SONDERPUBLIKATION Nr. 005

Global Lakes and Reservoirs

An investigation to which extent dynamic water body shapes have an impact on the estimates of the total water storage derived from GRACE

Annika L. Walter

DHyG-Sonderpublikation
Nr. 005
November 2024

Herausgeber:
Deutsche Hydrographische Gesellschaft e. V. (DHyG)

DOI: 10.23784/DHyG-SP_005

DHyG-SONDERPUBLIKATION

Nr. 005

Global Lakes and Reservoirs

An investigation to which extent dynamic water body shapes have an impact on the estimates of the total water storage derived from GRACE

Annika L. Walter

Table of Contents

List of Figures

List of Equations

Abstract

The satellite mission Gravity Recovery and Climate Experiment (GRACE) measures variations of the gravity field of the earth which are caused by the redistribution of masses across the atmosphere, the continents and the oceans. Over the continents, those mass redistributions are directly linked to changes in the total water storage (TWS), which are expressed in terms of equivalent water heights (EWH). The derived observations have been frequently used for water cycle studies, including the improvement of hydrological models in terms of calibration, data assimilation and validation. The problem herewith is, that the respective gravity field models have a low spatial resolution, which means that spatially localized changes concerning the water storage of for instance lakes and reservoirs, cannot properly be represented in the GRACE estimates. Since those surface storage changes can represent a large part of the total water storage, the leakage effect assimilates the surface water signal into the neighbouring water storage compartments. This means, that the observations, which were derived from GRACE, cannot be used to investigate the influence of regional and grid-based water storage changes on the total water storage. Furthermore, also non-hydrology related phenomena, such as earthquakes, which also cause a redistribution of the mass, hamper the usage of observations derived from GRACE for hydrological studies in the respective regions.

To counteract this tendency, this study presents an approach to which satellite altimetry and remote sensing data were used to forward model surface water volume estimates which can then be subtracted from the initial GRACE observations to remove their influence from the mass estimates. In order to do so, static as well as temporally variable and thus dynamic surface area extents were used.

It will be discussed, that using a dynamic instead of a static surface area extent (1) will change the equivalent water height values of the corrected GRACE signal in a magnitude between 0.006 cm and 0.243 cm, (2) causes the largest deviation for the Lake Mead which does not indicate any specific features and (3) that the question whether a dynamic or a static water body shape should be considered is driven by the interaction of various parameters. A first comparison of the retrieved results to an existing work confirms the derived observations.

1 Introduction

Water is the source of all life on earth. It is the only substance which can exist in a gaseous, in a liquid or in a solid state. Even if the total amount of water on the earth does not change, water constantly circulates between the lithosphere, the hydrosphere, the biosphere and the atmosphere. This cycle is denoted as the global water cycle (Erkin, 2013).

Since this cycling of water is intimately linked with the exchange of energy among the atmosphere, the ocean and the land, it also influences the natural climate variability and thus also the quality of human living on the earth (Nasa Science, n.d.). Subsequently, a profound understanding of the global water cycle is not only important to comprehend the ecosystem of the planet earth, but also to identify, to monitor and to predict environmental challenges and weather patterns.

In order to do so, hydrological models, which provide spatially and temporally distributed information not only concerning the different water storage compartments of the global water cycle, but also concerning the prevailing flow patterns between those compartments, can be used. Since hydrological models can be used on a local as well as on a global scale, they also help to increase the understanding of the available water resources and their flow patterns in areas where the availability of sufficient data is scarce (Ruhr Universität Bochum, n.d.).

Nevertheless, due to the general limitation of available data and the simplification of meteorological and physical processes, hydrological models only have a limited reliability (Soltani et al., 2021). To increase their reliability and their credibility, independent observations are required (Scanlon et al., 2018). On a global scale, these observations can be derived from different satellite missions, such as for instance Landsat.

While Landsat observations help to gather information concerning the surface extent of a water body (Ogilvie et al., 2018), altimetry satellites, such as the Environmental satellite (Envisat), have the potential to measure the water level of lakes, reservoirs, rivers and wetlands (Deutsches Geodätisches Forschungsinstitut, n.d.). Besides, data from the Soil Moisture Active Passive satellite mission (SMAP) and the Soil Moisture and Ocean Salinity satellite mission (SMOS) can be used to obtain an information concerning the prevailing soil moisture (Blank et al., 2023). Finally, observations from the satellite missions GRACE and its successor mission GRACE-Follow-On can be utilized to acquire an estimation of the total water storage and its changes (Deggim et al., 2021).

The advantage of using GRACE data is, that the total water storage refers to the sum of all water storage compartments, which are situated above and below the surface. Hence, the data does not only include lakes and rivers, but also canopy water, groundwater and soil moisture. Since this data is provided as column-integrated data in terms of equivalent water height values, it represents the dynamic and the interaction of the prevailing hydrological processes very accurate (Deggim et al., 2021).

To use the data derived from GRACE to improve hydrological models, mass variations, which are caused by the influence of global surface water bodies, have to be removed. The relevance of this will be further elaborated in the following chapter 2 MOTIVATION. In order to remove those mass variations, the volume of the considered surface water bodies, has to be computed. While previous studies have focused on a volume calculation based on static water body shapes (Deggim et al., 2021), this study will introduce dynamic water body shapes and assess to which extent the consideration of static or dynamic water body shapes is relevant when removing the influence of surface water bodies from the GRACE observations.

In order to do so, the chapter 2 MOTIVATION will outline and further investigate the importance and the problems of using GRACE data for hydrological models. The following chapter 3 THEORETICAL PRINCIPLES will emphasis on the measurement methods which were used to acquire the necessary input data. Hence, not only the working principle of satellite remote sensing and satellite altimetry, but also their individual strengths and weaknesses, will be further elaborated. In addition, also frequently used competitive methods, including their strengths and their weaknesses, will be outlined and discussed. Continuing, the chapter 4 DATA BASIS will introduce the data basis from which the required input data was derived. By means of that, not only the processing strategy of the individual input datasets, but also their validation and the current data availability, will be presented. Besides, the input data was also used to perform quantitative statistical analysis which was then used to determine possible focal points of this study. The carried out statistical analysis will also be presented in the chapter 4 DATA BASIS. Further on, the processing of the input data and the retrieved results, which were achieved under the consideration of static and dynamic water body shapes respectively, will be presented in the chapter 5 METHODS AND RESULTS. Continuing, a final conclusion whether a differentiation between static and dynamic water body shapes is relevant for the computation of the GRACE correction, will be given in the chapter 6 CONCLUSION. Finally, the results will be discussed in the chapter 7 DISCUSSION AND OUTLOOK. This chapter will also include an outlook, which finalises this study.

2 Motivation

The usage of hydrological models to gather a profound understanding of the global water cycle and its storage compartments, has become a key tool in the last decades (Ruhr Universität Bochum, n.d.). To improve the credibility and the reliability of hydrological models on a global scale, observations derived from various satellite missions, have become crucial.

Subsequently, the derived data can be used to tune the parameters of hydrological models. An example for such a model would be the WaterGAP Global Hydrology Model, which comprises about 30 different parameters. These parameters describe for instance the characteristics of the soil and thus help to quantify the hydrological storage processes and their flow patterns (Werth & Güntner, 2010). In the original version of the WaterGAP model, only the runoff parameter was tuned, meaning that all of the other parameters were either assigned to empirical values or to physical values (Döll et al., 2003). Considering that snowfall can be for instance neglected in the Amazon basin, an adjustment of the underlying parameters is crucial. Consequently, satellite observations can be used to tune the parameters of the hydrological model equations in a way, that they best agree with the observations (Dembélé et al., 2020). This process is also denoted as calibration.

Furthermore, the observations can also be used to validate the computed output of a hydrological model. In order to do so the time series, which were derived from the observation output, have to be compared with the time series of the hydrological model output (Alfieri et al., 2022). To obtain a result, both time series can be merged to a weighted mean. This concept of merging observation data with the data derived from hydrological models is also denoted as assimilation (Alfieri et al., 2022). It further helps to increase the reliability of a hydrological model and to improve it respectively.

Consequently, satellite observations cannot only be used for calibration, but also for validation and for assimilation purposes. In accordance to that, satellite missions make a contribution to further increase the accuracy and the reliability of hydrological models. Nevertheless, not only the calibration, but also the assimilation of hydrological models, through data which were derived from satellite missions, is a challenging task. For the satellite mission GRACE and thus the introduction of total water storage data, there are two main challenges.

First of all, it has to be considered, that the computed gravity models refer to a monthly solution, which means, that only monthly averages of mass changes are visualized. The problem with this is, that the gravity field continuously changes. Hence, there are a lot of unmodelled variations, which are not captured by the model. This undersampling of short-term variations is denoted as aliasing (Hauk & Pail, 2018). In addition to that, little detailed structures are strongly dampened throughout the upward continuation. As a result, only a small portion of the signal can be sensed. Thus, it is very difficult for GRACE to observe detailed structures (Ramillien et al., 2021). Moreover, the data which is actually available, is highly corrupted by spatially correlated noise. This can be attributed to the fact, that GRACE is flying in a polar orbit and that the observations are conducted along the orbit. Hence, there is a high measurement accuracy along the track. Besides, the observation of neighbouring arcs requires a certain amount of time. For GRACE-Follow-On, it takes about 99 minutes to complete one orbit (Jet Propulsion Laboratory, n.d.). This means that unmodelled short-periodic effects might have changed completely between the observation of neighbouring arcs. Consequently, the gravity field models are strongly corrupted by spatially correlated noise. To reduce this noisy behaviour the signal, or to be more precise, the spherical harmonic coefficients, have to be filtered. Nevertheless, filtering leads to a signal loss and to the occurrence of the leakage effect. The leakage effect causes a smearing of the GRACE signal and thus assimilates the surface water mass change into the neighbouring grid cells. This does not only mean, that the mass changes of for instance natural lakes or human-controlled reservoirs cannot be directly assigned to their location of origin and with their correct magnitude, but it also means, that those large water bodies extremely distort the mass variation estimates of their neighbouring grid cells. Since the filtering further decreases the resolution of the gravity field models to a few hundred kilometres, this hampers the representation of concatenated and sub-scale water storage changes. Consequently, small scale mass variations, which can have a strong influence on the total water storage signal, cannot be sufficiently modelled (Frappart et al., 2012).

In order to counteract this tendency, the Regional COrrections for GRACE (RECOG), which is a global correction product, can be used. Hence, the application of this correction product allows to relocate a change of mass to its exact location of origin (Deggim et al., 2021).

The second challenge is, that the gravity observations derived from GRACE also contain non-hydrology-related mass variations. Although the majority of the monthly observed gravity changes are indeed caused by changes concerning the water storage in hydrological reservoirs, some changes in gravity can also be related to mass redistributions which occur within the solid earth. This can include mass redistributions which are caused by large earthquakes or which follow a glacial isostatic adjustment (Jet Propulsion Laboratory, n.d.). To still use GRACE observations for the calibration and the assimilation of hydrological models, the non-hydrology and the hydrology related mass variations have to be separated from each other. In accordance to that, it has to be considered, that GRACE delivers column-integrated total water storage changes. This means, that even the hydrology related mass variations are composed by mass variations which are caused by for instance groundwater, soil moisture or water bodies such as lakes and reservoirs (Deggim et al., 2021). If the focus of interest refers to groundwater related mass variations only, the other impacts have to be removed. Hence, the signal has to be processed in a way, that only the relevant sources of mass variations can be extracted.

This can either be realized by subtracting available reference data from the initial observations and thus removing its impact, or by decomposing the signal into its individual components. While the former can be realized by forward modelling the unwanted mass variations and then subtracting them, a proper decomposition can be performed for example by the independent component analysis (ICA). The ICA separates the individual components of a signal based on an assumed statistical independence by using higher-order statistical information. The unwanted components can then be removed from the GRACE signal (Forootan & Kusche, 2011).

For the application of hydrological models, the relevance of such a signal separation can predominantly be related to the fact, that many global hydrological models do not contain a surface water storage compartment, which solely represents the water storage of inland surface water bodies such as lakes and reservoirs. As a result, an assimilation of the total water storage data derived from GRACE into a model, which does not explicitly include surface waters, would inevitably distort other storage compartments including for instance groundwater and soil moisture (Deggim et al., 2021). Despite of that, hydrological models which actually do include a surface water compartment might not sufficiently present the behaviour of for example a human operated reservoir. Hence, also for those hydrological models, it might be preferable to exclude the water storage, at least for reservoirs, from the assimilation procedure (Deggim et al., 2021).

Since previous studies have used a static defined surface area extent to model the water storage of surface water bodies, this study aims to depict the characteristics of surface water bodies, including their varying surface area extent, in greater detail. This could be achieved by introducing a dynamic surface area extent. Since the consideration of a dynamic surface area extent changes the forward modelled equivalent water height values and thus also the mass estimates, it does not only impact the data which will be used for the hydrological models, but it also directly influences the estimates of the total water storage.

Consequently, a meaningful application of the GRACE signal, whether this includes the calibration and the assimilation of hydrological models or estimates of the total water storage, does not only require a sufficient separation of the signal itself, but also an investigation whether forward modelling procedures should be carried out under the consideration of a dynamic or a static surface area extent respectively.

3 Theoretical principles

Since this study requires input data from various sources, this chapter will focus on the collection of the data and the underlying measurement principles. For this purpose, the fundamental principles of remote sensing and satellite altimetry, including their strengths and their weaknesses, will be presented. Furthermore, a short explanation of how remote sensing and satellite altimetry can be combined to derive volume variation values, will be outlined.

3.1 Satellite Remote Sensing to derive shoreline polygons

Remote sensing means, that information is obtained from space, including the measurements from extremely high-flying aircrafts, spacecrafts and satellites. In contrast to other measurement principles such as satellite altimetry, remote sensing focuses less on the derivation of geometrical parameters but more on the investigation of the physical properties of objects and the conditions on the surface of the earth. In order to do so, satellite remote sensing uses multispectral sensors which measure the emitted and the reflected radiation at a given distance (Witte & Sparla, 2015). While passive sensors measure the radiation, which was emitted from the sun and reflected on the surface of the earth, active sensors emit the radiation themselves. Since active sensors do not rely on the presence of the sun, they can be used during any season and at any time of the day. Both, active and passive sensors can measure the reflected signal at several spectral bands of the electromagnetic spectrum simultaneously. By doing so, colour images, hyperspectral images or multispectral images, from which properties such as the surface temperature can be derived, can be created (Skyora, 2021). Furthermore, remote sensing images cannot only be used to extract information concerning water bodies, but also to extract their boundaries polygons, which is crucial for the course of this study (Neema, 2022).

3.1.1 Strengths and Weaknesses of Satellite Remote Sensing

One strength of satellite remote sensing to extract boundary polygons of surface water bodies is, that the respective satellite missions are all placed in repeat orbits. This becomes especially handy, when data is collected on dynamic themes such as water bodies. Hence, the surface area extent of multiple water bodies can be systematically monitored over long periods of time. By means of that, also seasonal and interannual variations can be monitored. Another strength is, that remote sensing data is globally available, which means that also information from remote areas can be gathered. Since the derived images can be automatically processed and analysed, the extraction of surface water bodies is comparably simple (Spatialpost, 2023).

One weakness of remote sensing is, that the analysis of the derived images requires a special kind of training. This can for instance be related to the fact, that some land surfaces, such as basalt fields, share similar spectral characteristics with water. As a result, an overestimation of the water resources may occur. In addition, the relative motion of the sensor in relation to the source may cause distortions in the resulting images which has to be accounted for in the pre-processing procedure. Another weakness is that remote sensing is a costly technique, which means that it is only profitable for the analysis of large areas. Besides, remote sensing requires, such as any other measuring technique, cross verification with additional, for example ground field, data (Spatialpost, 2023).

3.1.2 Comparison to other measurement techniques including their strengths and their weaknesses

Another option to derive the outline polygon of a water body would be to perform in-situ measurements. In-situ measurements can be realized through measurements which involve the global positioning system. Hence, receivers can be used to accurately measure the coordinates of points along the shoreline of a water body. By collecting a series of points, a shoreline polygon can be derived. While those measurements achieve a very high accuracy, they are also work intensive and time consuming. In addition, it might be difficult to measure shorelines in inaccessible environments such as marshlands and tidal flats. Furthermore, those measurements always require a clear view to the sky, which may not be given when the shoreline is lined by trees and other dense vegetation (Braga et al., 2023).

Another option in terms of in-situ measurement involves the usage of a total station or the performance of a differential levelling procedure. Hence, those field survey techniques can also be used to measure the position of points along the prevailing shoreline and thus to create a shoreline polygon (Braga et al., 2023). The strength of total station and levelling measurements to derive a shore line polygon is, that the acquired data has a very high accuracy. Furthermore, the data collection process is, similar to the measurement with a receiver, directly controlled by the surveyor. This control ensures that specific areas of interest or certain features are accurately captured. Hence, it reduces the risk of missing important details. The weakness is, that in-situ total station and levelling measurements are time consuming, work intensive and that they are always related to a limited coverage (Witte & Sparla, 2015).

Moreover, hydrographic surveys can also be used to directly map the shape of the coastline of a water body. Hydrographic surveys have the strength, that they provide highly accurate and precise measurements of the shoreline. Apart from this, hydrographic surveys can be conducted in various water depths. This means that shoreline polygons can be created for different coastal environments. The weakness of this procedure is, that it is costly and time consuming. In addition, hydrographic surveys highly depend on the prevailing weather conditions. Besides, they are usually conducted along specific survey lines, which means that they may not cover the entire coastline. The resulting limited coverage then leads to gaps or missing information in the derived shoreline polygon (Hinds, n.d.).

In terms of remote sensing, not only satellite imagery, but also aerial photography, can be used. Hence, similar to satellite images, aerial photography can also be used to visually identify the shoreline and to trace its outline. The strength of aerial photography is, that it provides a good spatial coverage. Meanwhile, the weakness of aerial photography is, that the temporal coverage depends on the site and thus it might be the case that changes concerning the surface area extent and thus also concerning the shoreline polygon, are not sufficiently captured. Besides, aerial photography also implies a high cost of image acquisition and time-consuming elaborations. Hence, aerial photographs are usually distorted, which means that those distortions have to be corrected before the images can be used to determine a shoreline (Boak & Turner, 2005).

Despite the individual strengths of each presented alternative measurement technique, satellite remote sensing mainly convinces through its global data acquisition. Since this study investigates several surface water bodies which are distributed all over the earth, it is crucial to have shoreline polygons for a variety of different water bodies which are all situated in different environments and which all have different sizes.

3.2 Satellite Altimetry to derive water level height values

Although satellite altimetry has also been applied to non-ocean surfaces, it was initially designed for an accurate measurement of the sea surface height. Hence, satellite altimetry can be used to measure the water level of a water body from space. Therefore, the altimeter satellite is equipped with a sensor that transmits a radar pulse. By measuring the travel time of the radar pulse from the antenna of the altimeter satellite to the surface of the water body and back to the receiver of the altimeter satellite, the height of the water body above the ellipsoid can be determined (Vuglinskiy, 2009).

In order to do so, the measured round-trip travel time of the radar signal has to be multiplied with the speed of light. Since the derived product refers to the round-trip distance, one-half of this round-trip distance is approximately equal to the distance between the altimeter satellite and the surface of the respective water body. While the altitude of the altimeter satellite above the global ellipsoid can be derived from an orbit computation and is thus known, the difference between the altitude of the altimeter satellite and the derived altimeter range refers to the height of the water body with respect to the same ellipsoid. Hence, each returned height value is an average of all the water surface height values which are situated within the footprint of the altimeter. Since each satellite has a certain repeat orbit, the more or less same point will be revisited after a certain number of days. As a result, time series of water height changes for a particular location along the ground track of the respective satellite, can be realized. Nevertheless, since the travel time of the radar pulse and thus also the obtained surface height of the water body is influenced by factors such as the refraction within the Ionosphere and the Troposphere, the instrumental biases and the overall state of the sea, including the occurrence of waves, such effects have to be corrected. In order to do so, different models can be applied (Sánchez et al., 2003). Overall, the diameter of the footprint depends on the roughness of the surface and thus it varies between 200 m for calm water conditions and a few kilometres for open waters with surface waves (Vuglinskiy, 2009).

Since this study focuses on the evaluation of inland surface water bodies, it is important to mention, that altimetry satellites can only measure in nadir direction and thus, it is crucial that the satellite directly crosses the water body. To ensure that the majority of the water bodies is covered by at least one satellite track, water level time series are nowadays usually based on merged data from different altimeter satellite missions including for instance Topex / Poseidon, Jason - 1, Jason - 2, ETS2 and Envisat (Deutsches Geodätisches Forschungsinstitut, n.d.).

3.2.1 Strengths and Weaknesses of Satellite Altimetry

One strength of satellite radar altimetry is, that it can be operated during the day and during the night without any constraints concerning the prevailing weather situation. In addition, the measurement principle is not influenced by any canopy or vegetation cover. Besides, the surface heights have all one common reference frame. Furthermore, the altimeter satellites are placed in repeat orbits, meaning that the respective water bodies can be systematically monitored over long periods of time. By means of that, also seasonal and interannual variations can be monitored. Another strength is, that satellite altimetry data is globally available. Hence, satellite altimetry has the ability to gather water level information of remote areas which do not provide any local infrastructure and also of areas where traditional gauge data may be absent (Vuglinskiy, 2009). Finally, different altimeter systems can be combined and thus, not only the temporal and the spatial resolution, but also the length of the respective time series can be increased. Subsequently, satellite altimetry can provide water level time series which are longer than two decades (Schwatke et al., 2015).

One weakness of satellite radar altimetry is, that the measurement geometry provides observations along specific ground tracks. This means, that water bodies are only touched by chance. Therefore, large bodies of water have a higher probability of being crossed than smaller ones (Schwatke et al., 2015). When a water body is crossed, the retrieved height also only refers to an “average” of the topography which is situated within the footprint of the satellite. Additionally, those values are further averaged in the direction of the satellite track, meaning that there is for instance one final height value every 580 m for the satellite mission Topex / Poseidon or one final height value every 350 m for the satellite mission ERS. Moreover, altimeter instruments are usually designed to operate over uniform surfaces. Hence, quickly changing water levels may cause a data loss or a non-interpretation of the received data. By means of that, heavy precipitation, major wind events, the presence of ice and tidal effects will influence the accuracy and thus also the quality of the data. On top of that, the height accuracy does not only depend on the knowledge of the satellite orbit, but also on the precision of the altimeter range as well as on the size and the type of the target. Another challenge concerning inland altimetry is, that large footprints capture different reflections such as land, water et cetera. Consequently, the shape of the altimeter waveform, depending on the different reflections from the prevailing surface, varies. This variation has to be considered when retracking the waveforms (Schwatke et al., 2015). Following this, the orbit of the satellite and the size of the target also set the spatial and the temporal resolution (Vuglinskiy, 2009). Subsequently, the repeat orbit configuration only allows a temporal resolution of 35 days for the satellite altimeter missions ERS - 2, Envisat and SARAL / AltiKA or 10 days for Jason - 1, Jason - 2 and Topex / Poseidon. Nevertheless, this temporal resolution only accounts for single altimeter missions (Schwatke et al., 2015).

3.2.2 Comparison to other measurement techniques including their strengths and their weaknesses

Another option to derive the water level height values would be to perform in-situ measurements. In-situ measurements of the water level are usually performed with the help of gauges. To avoid the influence of drawdown, gauges are usually situated with a sufficient upstream, but still close to the outlets of lakes and reservoirs. Thus, there are different types of gauges, including non-recording gauges and recording gauges. While non-recording gauges solely indicate the water level, meaning that they are not able to indicate when the water level started to incline or to decline, recording gauges continuously record the state of the water level (Vuglinskiy, 2009). The strength of using gauges is, that they are convenient and simple to use. In addition, they have a long service lifetime, which means that they can be used to provide accurately long-term records of even subtle water level changes. Besides, the water level sensor can also be coupled with a digital display unit and thus, the measured water level values can be displayed in real time. This does not only allow for a timely detection of changes, but it also enables a fast decision-making. One weakness of using gauges is, that they are usually installed to specific locations and thus, they have a limited spatial coverage. Additionally, gauges require a regular calibration and maintenance, which can be costly and labour-intensive (Vath, 2021).

Despite the fact that gauges offer the highest available accuracy of water level values, satellite altimetry offers freely available data for the whole earth and thus also for remote areas. Moreover, a comparison between satellite altimetry measurements and measurements derived from gauges for the Great Lakes has shown, that satellite altimetry can deliver accuracies in the range of 3 cm to 5 cm root mean square (Shum et al., 2002). Since this study requires water level values for a variety of different water bodies across the planet earth, satellite altimetry is the only convenient option to choose.

3.3 Satellite Remote Sensing and Satellite Altimetry to derive volume variation values

The most common approach to derive volume variation values involves the multiplication of a surface area extent, derived from satellite remote sensing images, and water level values retrieved from satellite altimetry. Nevertheless, the individual data sources and the coupling methods can greatly differ (Schwatke et al., 2020).

The first option would be to combine surface areas derived from for instance Landsat images with satellite altimetry data by applying a polynomial function of degree two. As a result, a hypsometric curve, which illustrates the relationship between a surface area size, which is denoted on the x-axis, and the water level value above a given datum, which is represented by the y-axis, can be estimated (Schwatke et al., 2020).

The second option would be to combine a surface area information, derived from a satellite sensor such as a moderate resolution imaging spectroradiometer, with satellite altimetry data. Here, the relation between the surface area and the water height value can also be drawn by applying a linear hypsometry model (Schwatke et al., 2020).

The third option would be to use surface images from the Landsat satellite mission and link those to the matching water level values derived from the Ice, Cloud and Land Elevation Satellite (ICESat) mission (Schwatke et al., 2020).

In another study, a hypsometric model was derived by combining Landsat images with satellite altimetry data provided in the Hydroweb database. In order to do so, polynomial functions of degree one, two or three have to be applied. Hereby, the best suiting degree depends on the prevailing relationship (Schwatke et al., 2020).

Furthermore, time series of volume variations can also be derived by applying a pyramidal approach and hence assuming a pyramidal bathymetry of the prevailing water body (Schwatke et al., 2020).

Finally, monthly land water masks from the Joint Research Centre Global Surface Water dataset, which are also based on Landsat images, can be combined with the water level time series which are provided in the Database for Hydrological Time Series of Inland Waters (DAHITI). In this case, the volumes are solely calculated for water bodies which indicate a linear relationship between their surface area extent and their water level. In this context, the volume variation values are estimated for consecutive changes in the surface area extent and the water level (Schwatke et al., 2020).

3.3.1 Strengths and Weaknesses of Satellite Remote Sensing in combination with Satellite Altimetry

One strength is, that satellite altimetry has been around since the 1990s and that it provides a more or less continuous measurement of the water surface height since then. By combining several altimeter missions, not only the spatial, but also the temporal resolution of global inland water bodies, can be increased. Another advantage is, that the combination with optical images incorporates information concerning the dynamic surface area extent. Hence, changes concerning the shape of the water body and thus also concerning the surface area extent, which might be related to anthropogenic or natural factors, are also captured within the satellite images and can subsequently be incorporated in the computation of the volume variation values. Furthermore, satellite missions operate on a global scale. Hence, not only altimeter satellites, but also those satellite missions which are used to retrieve the optical images, overcome the need of manual measurements which can be very time consuming. Next to the time related factor, satellite observations also allow to compute volume variation values of water bodies which are difficult to access with traditional methods. Thus, also volume variation values of remote or inaccessible regions, can be derived. Furthermore, the usage of a hypsometric curve to derive water level values from surface areas leads to the fact, that water level errors from satellite altimetry can be minimized (Schwatke et al., 2020).

One weakness is, that satellite measurements are not as accurate as ground measurements. Subsequently, also the computed volume variation values are less precise. In addition, the available temporal resolution does usually not allow to monitor volume variations on very short-terms. Hence, satellite observations cannot be used to detect very rapid changes within a water body. Furthermore, the disadvantage of using a hypsometric curve is, that additional errors due to extrapolation or time-dependent changes of the bathymetry, may occur (Schwatke et al., 2020).

3.3.2 Comparison to other measurement techniques including their strengths and their weaknesses

Theoretically, volume variation values can be retrieved by any combination of the under 3.1 SATELLITE REMOTE SENSING TO DERIVE SHORELINE POLYGONS and 3.2 SATELLITE ALTIMETRY TO DERIVE WATER LEVEL HEIGHT VALUES presented techniques. In order to be not repetitive, this chapter will focus on combinations, which are actually carried out to derive volume variation values. Hence, the first option would be to perform ground measurements.

In this context, ground measurements refer to a combination of hydrographic surveys and water level observations from in-situ gauge stations. This approach is for instance carried out by the Texas Water Development Board. Hence, the Texas Water Development Board has processed volume variation values for approximately 120 lakes and reservoirs that are located within the state Texas of the United States of America (Schwatke et al., 2020). One strength of ground measurements is, that the resulting data sets are very accurate and thus they can also be used to validate volume variation values which were retrieved on the basis of remote sensing approaches. Meanwhile, one weakness of ground measurements is, that the required bathymetric surveys are not only costly, but that they are also time consuming. In addition, both, hydrographic surveys as well as in-situ gauge measurements, are usually difficult to carry out in remote areas (Schwatke et al., 2020).

Another option would be to combine digital elevation models with satellite altimetry data. Since a digital elevation model represents a continuous topographic elevation surface through a series of grid cells, each grid cell indicates the estimated height above a certain reference level. Subsequently, a digital elevation model can also be used to compute topographic slopes. The derived shoreline polygon can then be multiplied with water level values to compute volumes and thus also volume variations (Zhu et al., 2019). One strength is, that a digital elevation model provides a detailed representation of the surface of the earth and thus it allows for a precise computation of the shoreline polygon. Furthermore, a digital elevation model has the advantage, that hydrological features such as lakes and reservoirs can automatically be extracted. Especially in comparison to traditional methods, which are based on field surveys, image interpretations and topographic maps, this automatic extraction offers direct advantages in terms of accuracy assessment, cost effectiveness and processing efficiency (Zhu et al., 2019). Hence, the combination of a digital elevation model and satellite altimetry data allows for a precise estimation of volume variation values. One weakness is, that the accuracy of the computed volume variation values relies on the quality of the underlying digital elevation model and the accuracy of the water level measurements. Subsequently, not only inaccuracies, but also artefacts, data gaps or interpolation errors within the digital elevation model influence the volume calculation and thus also affect the reliability of the retrieved results. Accounting to that, the accuracy of the computed volume variation values also depends on the resolution of the digital elevation model. Consequently, a digital elevation model with a low resolution may not capture small-scale changes very accurate (Zhu et al., 2019).

Finally, also data from the satellite mission GRACE, which measures the total water storage, can be used to assess mass variations and thus to proportionally track volume variations of water bodies (Swenson, 2023). One strength of using data from the satellite mission GRACE is, that the data has a temporal resolution of one month. In addition, the relationship between the gravity field and the surface mass, which is also known as Newton's Law of Gravity, is considered as fairly robust. Subsequently, no empirical parametrizations, as it is for instance the case with some radiometric remote sensing products and which demand a calibration with in-situ observations, are required (Swenson, 2023). One weakness of using GRACE data is, that the temporal resolution of the provided datasets is relatively coarse. Consequently, the pixel size varies between 300 km and 400 km. To retrieve a useful combination of accuracy and resolution, the data must be filtered. The difficulty herewith is, that the nature and the effects of the various filtering strategies can be difficult to trace (Swenson, 2023). Furthermore, GRACE observations also contain non-surface water body related phenomena, which have to be removed (Deggim et al., 2021).

Since this study uses satellite remote sensing images to retrieve shoreline polygons and satellite altimetry to capture water level values, a combination of those two products was the simplest and also the most convenient option to derive volume variation values.

4 Data Basis

Against the background of the different methods to collect the required data, this chapter will focus on the selected data bases. For this purpose, the applied processing strategy, the validation procedure and the current amount of available data, will be outlined. Furthermore, the retrieved data was also used to perform quantitative statistical analysis which then helped to assess possible focal points of this study. Hence, the respective results of this analysis will also be presented.

4.1 Shoreline polygons from Global WaterPack

Global WaterPack is a project which aims to map the available global surface water bodies on a daily scale (German Aerospace Center, n.d.). In order to do so, Global WaterPack uses data from the moderate resolution imaging spectroradiometer instrument of the two satellite missions Aqua and Terra, which deliver data since July 2002 and February 2000 respectively. Consequently, Global WaterPack uses the spectral characteristics of the water, to distinguish between land and water masses. In order to do so, several processing steps have to be applied.

4.1.1 Processing

The processing strategy involves five major steps which are also fully explained in Klein et al., 2017.

In the first step, the input data, which was derived from the moderate resolution imaging spectroradiometer instrument, is processed. In addition, further layers are generated. An example for such a layer would be the local surface and ambiguous surface layer, which addresses misclassification errors related to shadows caused by buildings and topography. In addition, also a layer to reduce the risk of water overestimation, is generated. As already mentioned in the chapter 3.1.1 STRENGTHS AND WEAKNESSES OF SATELLITE REMOTE SENSING, some land surfaces, such as basalt fields, dark soils or volcanic ashes have similar spectral characteristics to water. To reduce the potential of misclassifications, WaterPack uses annual cycle parameters from the annual gap free land surface temperature product provided by Bechtel (Bechtel, 2015) and another spectral information product to compute this layer (Klein et al., 2017).

In the second step, an automatic selection of training pixels, based on defined criteria, is performed. Hence, pixels which are assigned as inland water are considered as training pixel candidates. Nevertheless, only when those pixels are not covered by for instance clouds or snow, they will finally be used as training pixels. Based on the remaining training pixels, a dynamic threshold, which is used to delineate between water and non-water pixels, is calculated (Klein et al., 2017).

Based on the threshold computed from the selected training pixels, the third step involves the computation of dynamic thresholds for daily water classification purposes. Besides, the individual datasets of the Aqua and Terra observations, which were acquired on the same day, are combined (Klein et al., 2017).

In the fourth step, the created mask layers and the dynamic thresholds are used to classify the combined daily datasets. Hence, each dataset is classified into water and non-water. Whenever a pixel contains feature values which are below the dynamic threshold, it is assigned as water. All pixels which are classified as non-water, but which contain cloud or ocean features, are labelled as such. The remaining pixels are assigned as land. Whenever the mask layer indicates a high probability of misclassification due to for instance building and relief shadow, the pixel will be re-classified to non-water (Klein et al., 2017).

The fifth processing step involves the temporal analysis of the daily water mask time series. Based on this time series analysis, data and cloud gaps will be interpolated. Furthermore, also pixel, which only indicate water or land on one isolated day, will be reinterpreted to the class that has been detected before and after (Klein et al., 2017).

The final product comprises daily gap free water masks and a layer of confidence.

Finally, Deggim et al., used these daily water masks to examine the maximum surface area extent of 282 water bodies within the time frame of 2003 to 2016. To identify coherent water bodies, Deggim et al., applied a pixel-based region-growing algorithm. Thus, each water pixel within the aggregated Global WaterPack raster layer, which spatially overlapped with temporal static datasets from HydroLAKES, was assigned to the water body ID provided by the HydroLAKES database. Subsequently, a seed point in every designated water body was determined. Based on this seed point, an eight-pixel large search window was used to identify the neighbouring water pixels. This procedure ensured, that water bodies were only represented by coherent pixel groups. The final result was vectorized and hence, a polygon which depicted the maximum size of each considered water body, was derived (Deggim et al., 2021). These polygons were also used for the purpose of this prevailing study.

4.1.2 Validation

The currently available daily water masks were validated on the basis of 321 Landsat reference classification datasets. Hence, 10.000 water and 10.000 land pixels were randomly selected from each scene and cross compared with the pixels from the Global WaterPack product. Hereby, only Landsat-based reference pixels, which had a sub-pixel fraction of more than 50 % water, were considered as water validation samples. The same accounts for the land validation samples. Besides, masks from the year 2014 were also compared to three major flood events, which occurred throughout that year (Klein et al., 2017). Consequently, the validation of the masks has shown, that the masks capture the spatial and the temporal patterns from the high-resolution reference data very well. Nevertheless, the validation has also outlined, that very small lakes and narrow rivers can face an underestimation. Finally, an overall accuracy of 96.3 % for 250 m pixels with a sub-pixel water fraction of 100 %, could be derived. For reference pixels with a sub-pixel water fraction of 75 % to 99.9 %, an overall accuracy of 90.1 % could be achieved. Generally, it was observed that the accuracy decreased with a decreasing sub-pixel water fraction (Klein et al., 2017).

4.1.3 Data availability

So far, the Global WaterPack product contains over five million individual images between the years 2003 and 2020, which have been processed and analysed (Klein et al., 2017).

4.1.4 Further statistics

Driven by the intersection of the available polygons and the number of available volume variation time series from DAHITI, which will be further elaborated in the chapter 4.3 VOLUME VARIATION TIME SERIES FROM DAHITI, this study focuses on 29 water bodies. An overview of the water bodies, including their location, their type and their surface area extent, can be derived from the chapter 9 APPENDIX. Furthermore, the location of the 29 considered water bodies is also depicted in the Figure 1 below.

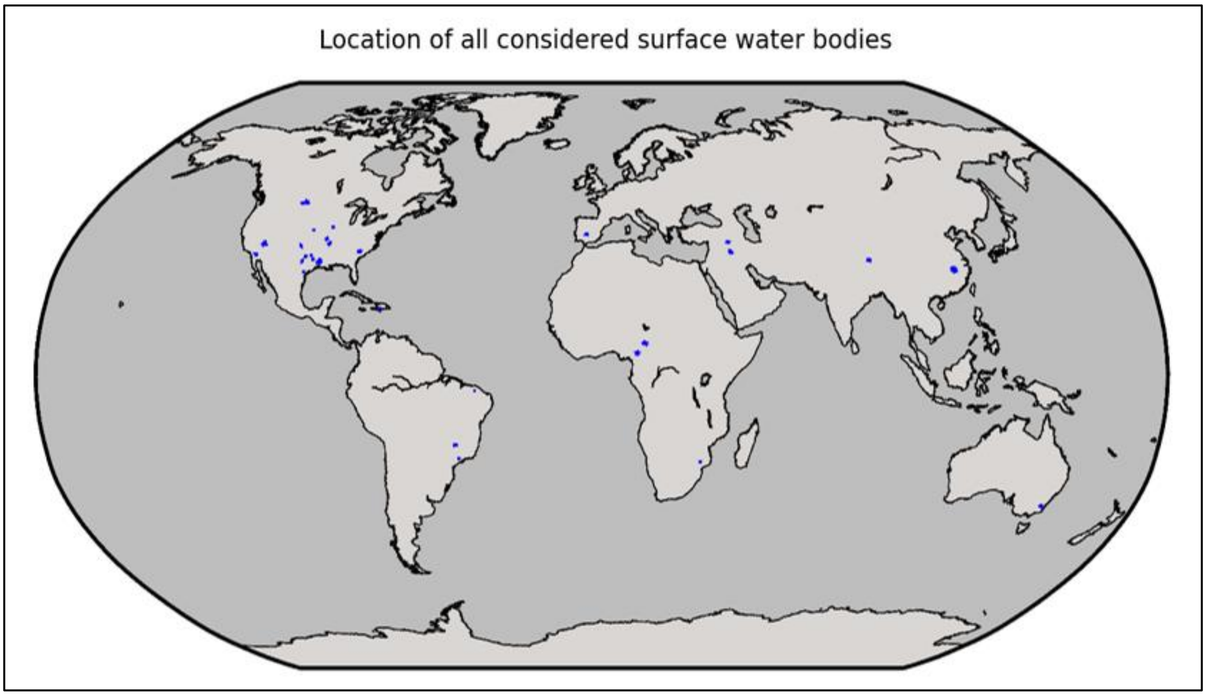

Figure 1: Map of all 29 considered surface water bodies

Source: Own representation in GROOPS and in Python

Consequently, the Figure 1 shows, that the majority of the considered water bodies, 17 to be precise, are located in the United States of America, whereas most of the lakes and reservoirs are situated in the State of Texas. In addition, three water bodies are located in South America and another three are situated in Africa. Besides, it can be seen, that Spain contains the only water body which belongs to continent of Europe. In contrast to that, four of the investigates water bodies are placed in Asia. Finally, another water body is located on the south - east coast of Australia.

To assess which of these 29 considered water bodies might be worth to investigate in-depth throughout the course of this study, the surface area extent of the respective polygons was computed. Hence, the Figure 2 illustrates, that the surface area of all considered water bodies varies between 21.204 km^2 for the Lake Grapevine and 2105.407 km^2 for the Lake Poyang.

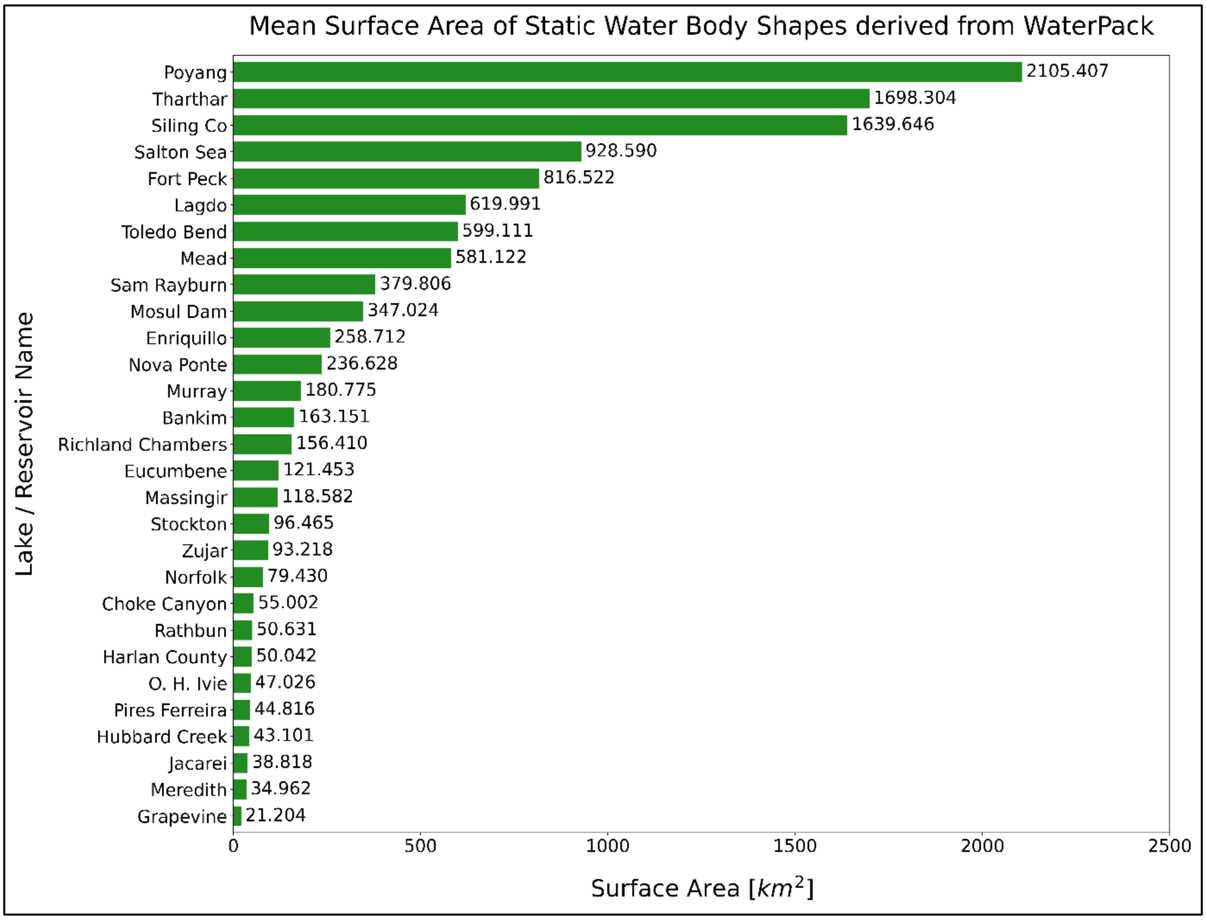

Figure 2: Mean surface area of static water body shapes

Source: Own representation in Python based on data retrieved from WaterPack

This computed surface area of the individual static water shapes was then compared to the mean surface area extent which could be derived from the surface area time series product of the DAHITI database. The DAHITI database itself will be further explained in the following chapter 4.2 WATER LEVEL TIME SERIES FROM DAHITI. The computed mean surface area extent for the selected 29 water bodies is graphically illustrated as a bar chart in the Figure 3 below. Hence, the comparison between the Figure 2 and the Figure 3 shows, that the surface area information varies. While the surface area extent values in the Figure 2 vary between 21.204 km^2 for the Lake Grapevine and 2105.407 km^2 for the Lake Poyang, the values in the Figure 3 vary between 19.137 km^2 for the Lake Meredith and 2365.353 km^2 for the Lake Siling Co. That the values depicted in the Figure 2 and the Figure 3 differ can be related to the varying source information and the alternating applied processing procedures. Since an in-depth description of the processing strategy of the surface area time series, which were derived from the DAHITI database and which will not be further used throughout the course of this study, would exceed the frame of this study, it will not be further elaborated.

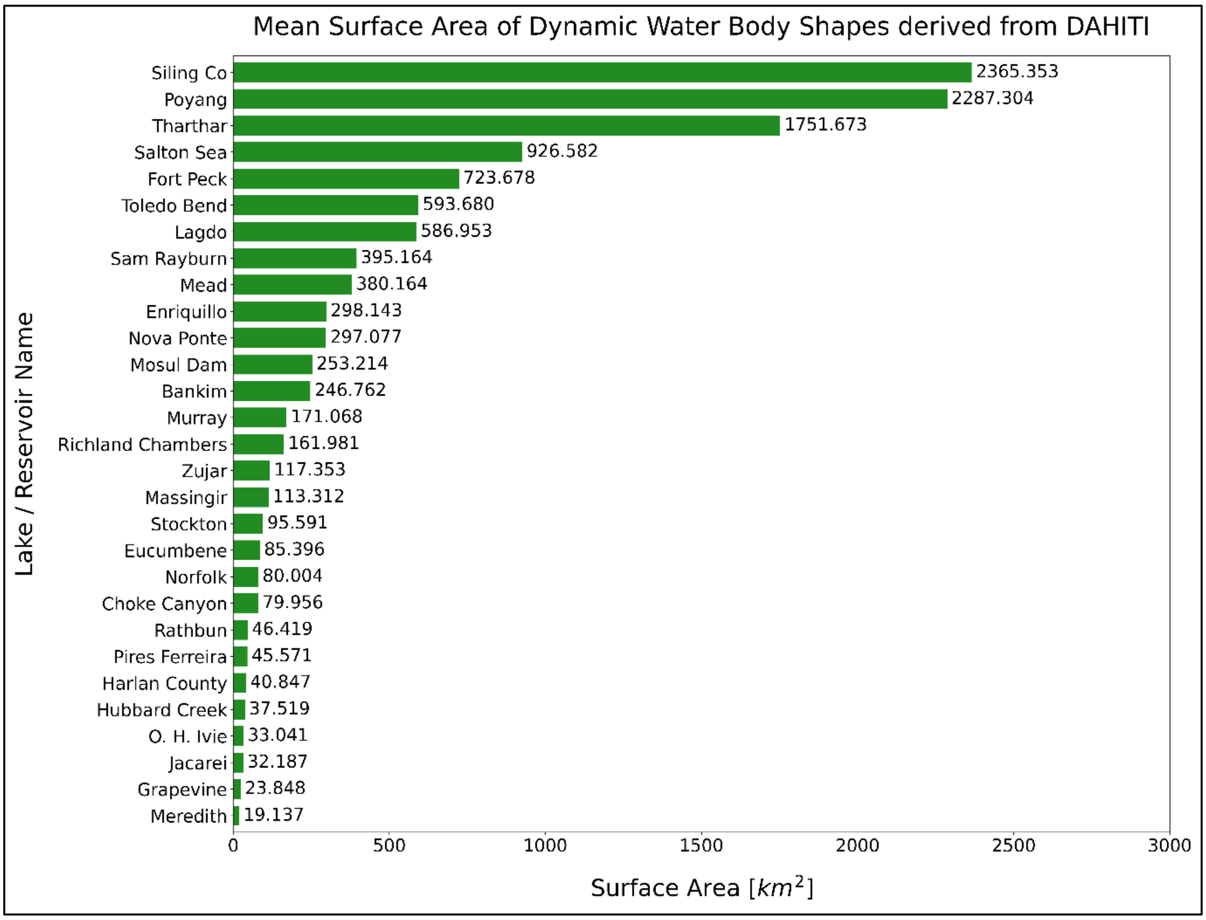

Figure 3: Mean surface area of dynamic water body shapes

Source: Own representation in Python based on data retrieved from DAHITI

To gather an overview up to which magnitude the surface area derived from the WaterPack polygons and the computed mean surface area extent of the DAHITI time series differ from each other, the respective values were subtracted from each other and the absolute value was sorted in a descending order. The result is depicted in the Figure 4. Subsequently, the Figure 4 shows, that the Lake Siling Co accounts for the largest surface area extent difference. In this case, both surface area extents differ by 725.707 km^2. Considering that the Lake Siling Co has a surface area extent of 1639.646 km^2 or 2365.353 km^2, depending on which data source is considered, this difference amounts 44.260 % to 30.681 % of the total surface area extent of the Lake Siling Co. The smallest difference was computed for the Reservoir Norfolk. It amounts 0.574 km^2. Taken into consideration, that the Lake Siling Co is the third largest water body according to the Figure 2 and the largest water body according to the Figure 3, it can generally be said, that the potential of a larger difference increases with an increasing surface extent of the water body. This thesis is further supported when considering that the Lake Norfolk has, according to the Figure 2 and the Figure 3, the tenth smallest surface area extent of all 29 investigated water bodies.

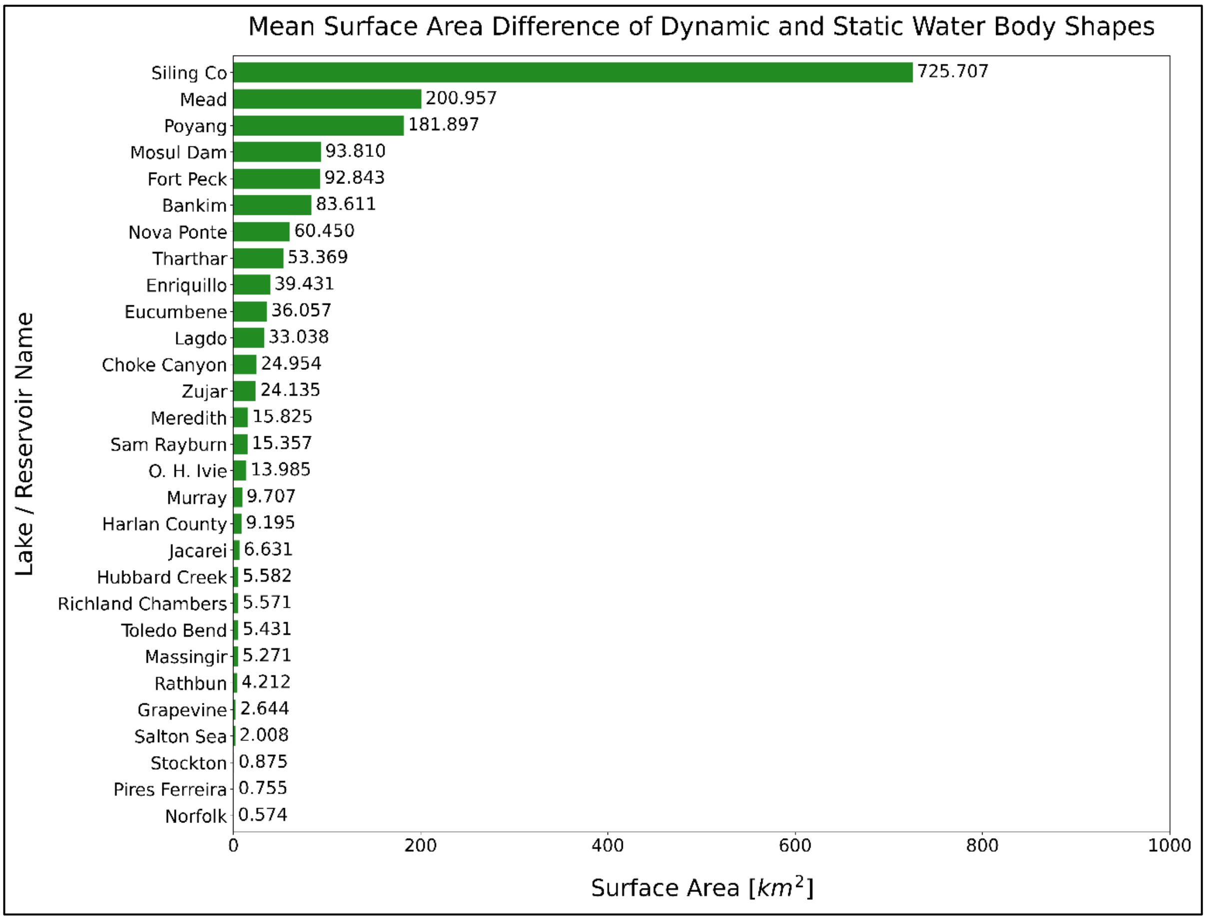

Figure 4: Mean surface area difference of dynamic and static water body shapes

Source: Own representation in Python based on data retrieved from DAHITI and WaterPack

To assess the computed difference against the background of the temporal variability of the surface area time series for one exemplarily water body, the Figure 5, was generated. Hence, the static surface area extent derived from the polygon of the Lake Siling Co was plotted against the surface area time series derived from the DAHITI database. Subsequently, it can be seen, that the estimated surface area extent, derived from the polygon of the Global WaterPack product, does not coincide with the temporal variation of the surface area time series derived from the DAHITI database. Hence, the estimated surface area extent derived from the static polygon is on average too small. The same vice versa phenomena occurs for instance for the Lake Mead, which encounters the second largest difference value and for which the surface area extent derived from the polygon is constantly larger than the temporal variation of the surface area extent values derived from the DAHITI database. Although these differences seem large, it has to be considered, that both data products were derived under the application of varying processing procedures and that throughout the course of this study, only the static polygon shapes were considered. Consequently, the internal comparability between the achieved results, which will be further elaborated in the following chapter 5 METHODS AND RESULTS, is still guaranteed.

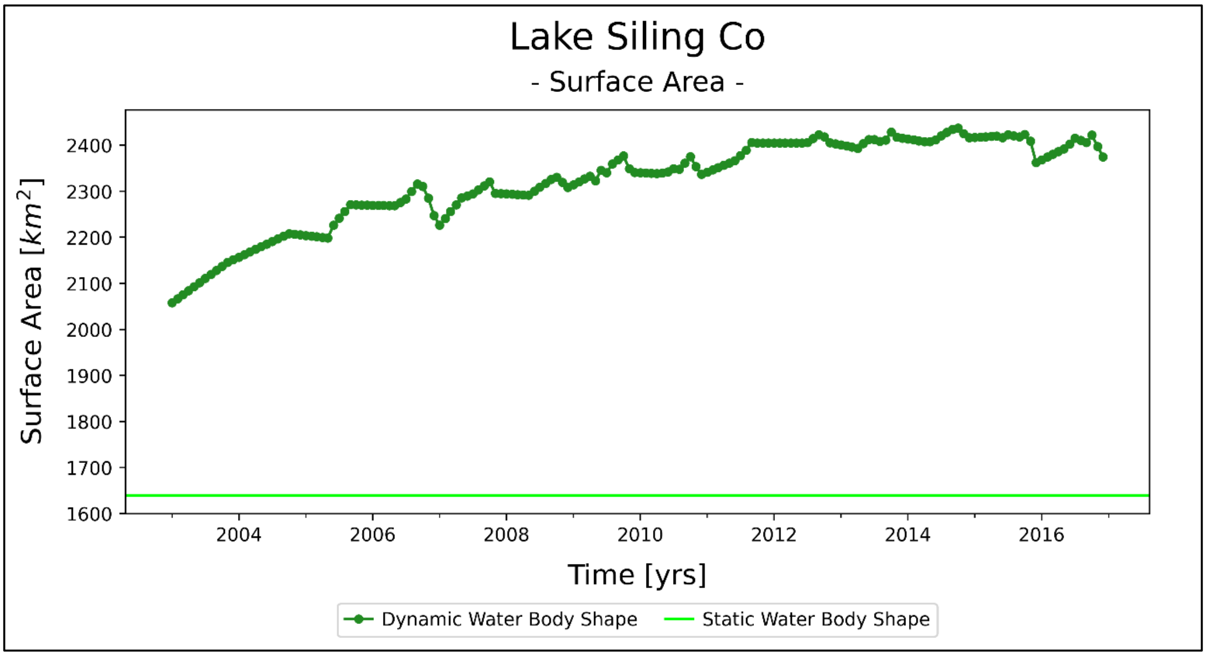

Figure 5: Surface area based on a dynamic and a static lake shape for the Lake Siling Co

Source: Own representation in Python based on data retrieved from DAHITI and WaterPack

Regardless of the computed differences, the surface area extent time series from the DAHITI database can still be used to analyse the maximum temporal variation of the surface area extent. Since this information cannot be derived from a static polygon, the maximum and the minimum surface area extent values of each surface area time series, were subtracted from each other. The derived difference represents the oscillation range of the time series and thus functions as an indicator which expresses how strong the time series, and subsequently also the surface area extent, fluctuates. The results are visualized in the Figure 6 below. Subsequently, the Figure 6 shows, that the difference between the minimum and the maximum surface area extent varies from 15.320 km^2 for the Lake Grapevine to 2709.380 km^2 for the Lake Poyang. Considering, that the Lake Poyang has, according to the Figure 3, an average surface area extent of 2287.304 km^2, this difference seems massive. Nevertheless, when evaluating the respective time series in the Figure 7, it can be seen, that the Lake Poyang is subject to a huge annual variation. Reasons for this variation will be elaborated in the chapter 5.5 RESULT FOR THE LAKE POYANG. By comparing the values from the Figure 6 with the surface area extent values from the Figure 2 and the Figure 3, it can be seen that an increasing surface area is usually conducted with an increasing surface area variation. An exception to this would be for instance the Lake Fort Peck, which has a smaller area size than the Lake Siling Co, but a larger surface area variation. Nevertheless, both lakes are still situated under the top five lakes with the largest surface area and the highest surface area variation. Hence, a general tendency, that large water bodies are conducted with higher surface area variation averages, emerges.

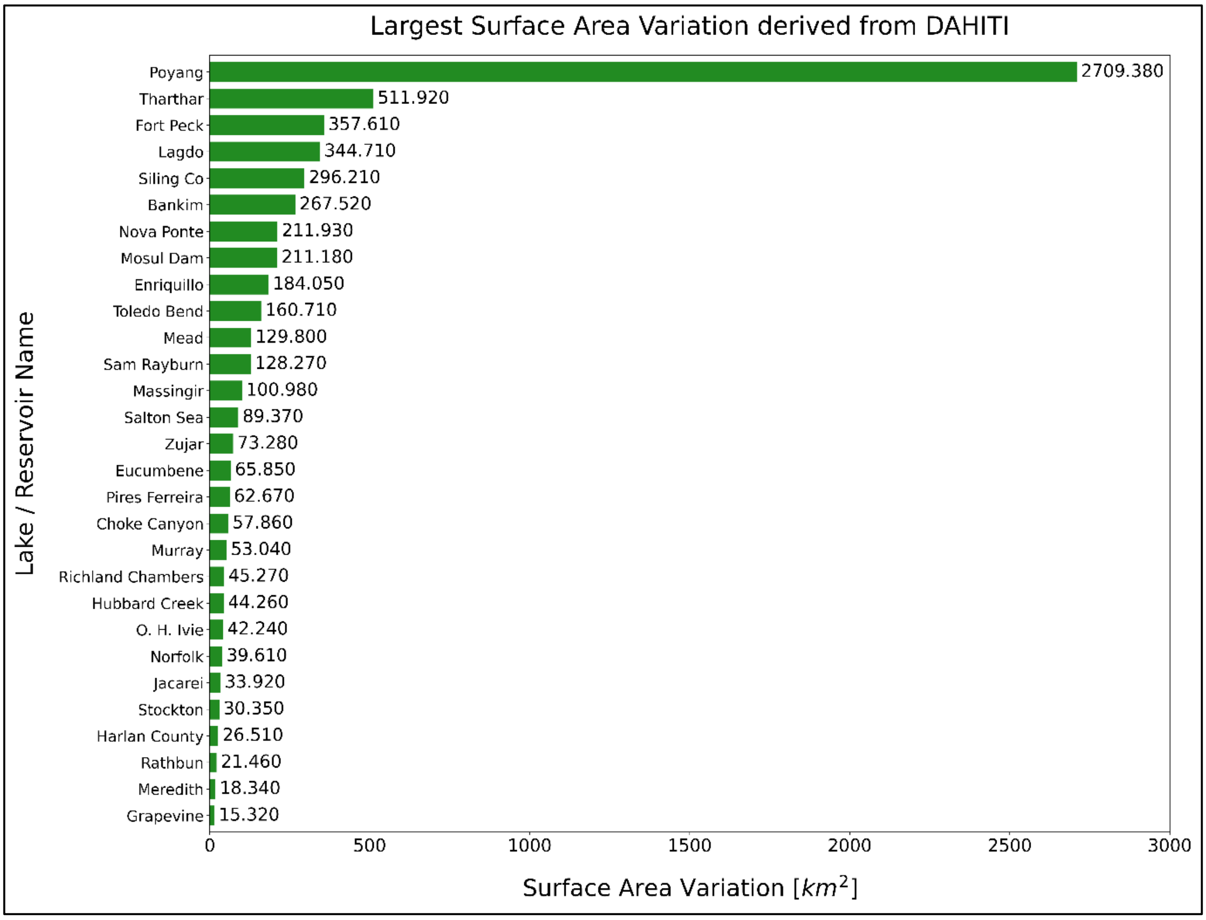

Figure 6: Surface area variation

Source: Own representation in Python based on data retrieved from DAHITI

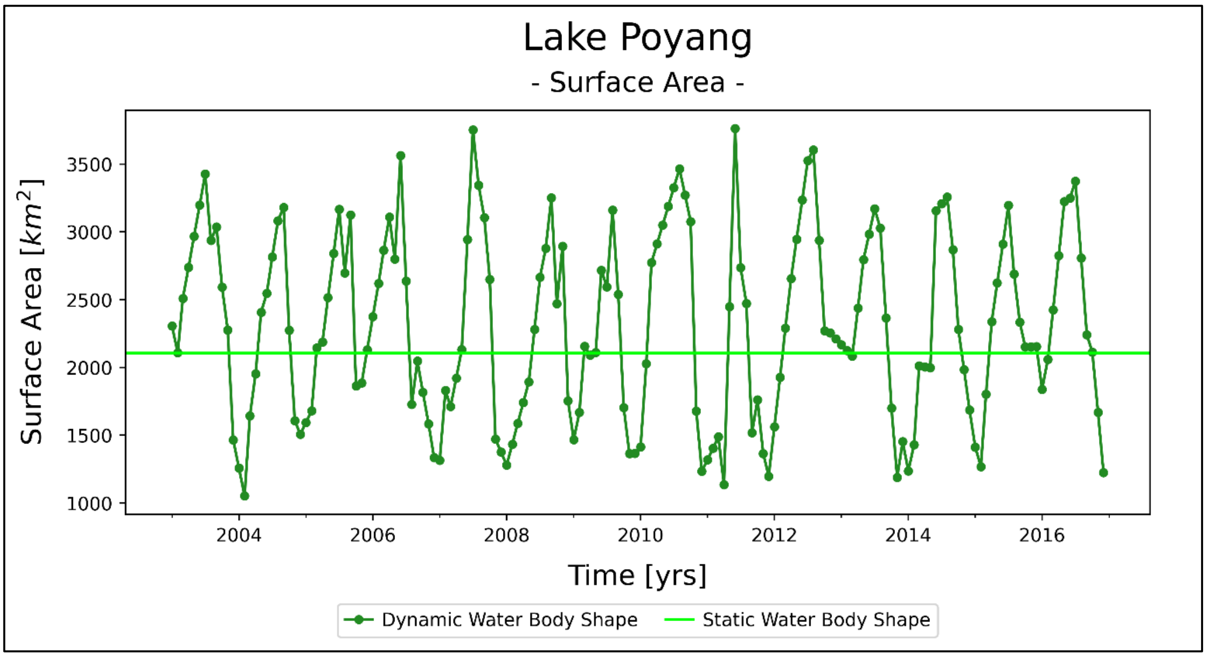

Figure 7: Surface area based on a dynamic and a static lake shape for the Lake Poyang

Source: Own representation in Python based on data retrieved from DAHITI and WaterPack

4.2 Water Level Time Series from DAHITI

As already mentioned in the chapter 3.3 SATELLITE REMOTE SENSING AND SATELLITE ALTIMETRY TO DERIVE VOLUME VARIATION VALUES, DAHITI is an abbreviation for database for hydrological time series of inland waters. Hence, DAHITI is a database which is operated by the German Geodetic Research Institute of the Technical University of Munich. The water level time series, which are provided within the DAHITI database, are generated on the basis of data which was retrieved from altimeter satellite missions.

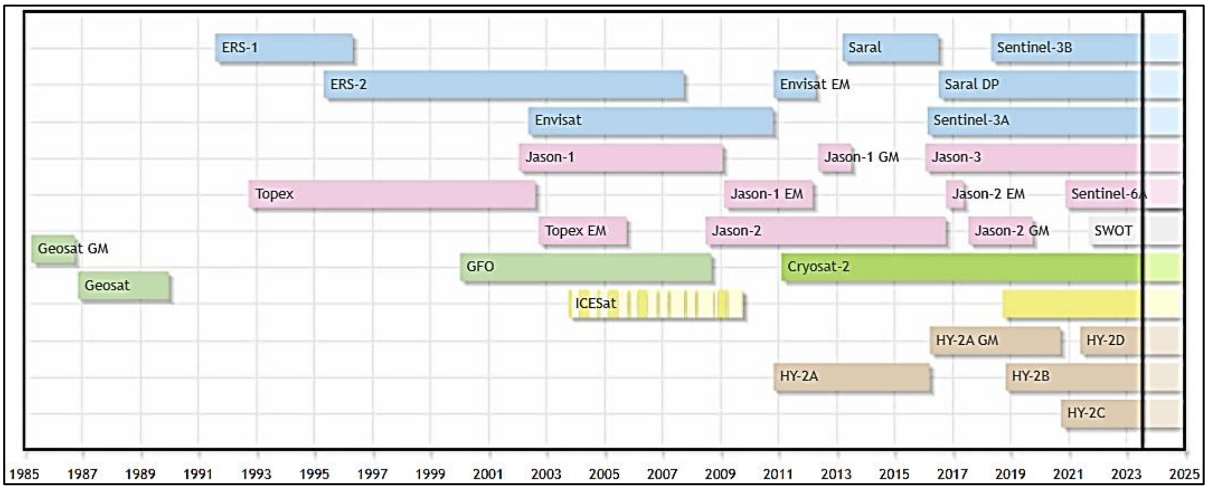

Figure 8: Overview of the altimeter satellite missions from 1985 onwards

Source: Deutsches Geodätisches Forschungsinstitut, n.d.

As already stated in the chapter 3.2 SATELLITE ALTIMETRY TO DERIVE WATER LEVEL HEIGHT VALUES, the temporal resolution of the water level time series depends on the used altimeter satellites. Hence, each water level time series, which is provided in the DAHITI database, is usually a combination of multi-mission altimeter data. An overview of the past, present and future satellite altimeter missions is given in the Figure 8 above. To use the respective satellite altimetry data to estimate the temporal variation of water level values, several processing steps, which will be further elaborated in the following, have to be carried out.

4.2.1 Processing

The processing strategy involves two major steps which are also fully explained in Schwatke et al., 2015.

The first processing step involves the pre-processing, which contains five major steps.

In the first pre-processing step, the altimeter waveforms of small inland water bodies such as lakes and reservoirs have to be retracked. By doing so, a more convenient altimeter range, can be achieved (Schwatke et al., 2015).

In the second pre-processing step, the range measurements, either original or retracked, have to be converted to water level values. In order to do so, the range has to be corrected by geophysical effects, including for instance the dry and the wet part of the tropospheric delay as well as the solid earth tide correction and the pole tide corrections. To eliminate inter-mission biases, the radial error of each altimeter measurement has to be corrected (Schwatke et al., 2015).

The third pre-processing step involves the calculation of heights. Consecutively, the ellipsoidal heights, which are provided by the altimetry measurements, have to be converted to normal heights (Schwatke et al., 2015). This can be related to the fact, that ellipsoidal heights have a pure geometrical origin and hence they cannot be used to predict where water will flow. Subsequently, the normal heights can be derived by subtracting a quasi-geoid model from the ellipsoidal heights.

The fourth pre-processing step includes the computation of height errors and thus an estimation concerning the quality of each measurement. For the purpose of that, an absolute deviation around the median value is estimated. This is done by using a sliding box along the altimeter track. Here, the size of the sliding box varies between ± 0.5 km for very small rivers and ± 1.5 km for small lakes and large rivers. A sliding box size of ± 3.5 km is usually used for very large lakes. The absolute deviation around the median value is then computed by estimating the median value of the water height values which are situated within the sliding box. This median height value is then subtracted from the prevailing water height value. The absolute value of the difference is considered as error of the altimeter measurement. In comparison to the estimated standard deviations, it is said that this approach is far more robust against corrupted water heights and topography close to the shores. Subsequently, it results in much more reliable errors. Finally, this measure of quality can be used to weight the individual data sets and to perform an error estimation within the Kalman Filter (Schwatke et al., 2015).

The fifth step within the pre-processing procedure involves the rejection of outliers. Hence, inaccurate water level values have to be rejected. To decide whether a water level measurement is accurate or not, several outlier criteria, including for instance an along-track outlier test, backscatter coefficient thresholds, a height error threshold, latitude thresholds and water height thresholds, can be applied. Since these outlier detection criteria are very flexible, they can be set according to the characteristics of the investigated water body. Furthermore, also a linear regression to reject altimeter measurements, which do not represent the flat water level of inland water targets, can be applied (Schwatke et al., 2015).

The second processing step involves the application of a Kalman filter.

The Kalman filter is a recursive filter algorithm which was developed by R. E. Kalman in 1960. Recursive means, that the state of the system is initialized with the help of an a-priori estimation and thus, the first correction is derived by the observations. Thus, the Kalman Filter uses input observations to constantly update the current state of the system and thus to predict the model of the following time epoch (Holst, 2017). In respect of the retrieved altimeter height values this means, that the system is updated each time a new altimeter track is available. Subsequently, the update of the interval mainly depends on the size and thus also on the data coverage of the investigated water body. Hence, the update rate can vary between 35 days if only the satellite mission Envisat crosses the target area and one day in case several altimeter mission tracks cover the target area. The predicted water height values of one update are then merged to one location. In order to do so, the information of a land water mask, which provides information concerning the surface area extent of the water body, is used. Finally, a time series of water level values and their respective errors, can be derived. Existing outliers, which can be attributed to for instance orbit manoeuvres and which then lead to an insufficient data quality, can be removed by performing an outlier rejection (Schwatke et al., 2015).

4.2.2 Validation

The available water level time series were not only validated by comparing them to in-situ data, but also by comparing them to time series which were provided by other research groups.

Although gauges offer water level time series with a very high accuracy, a direct comparison between water level height values derived from gauges and those derived from satellite altimetry, is usually difficult to perform. One reason for this is, that the location, the reference height and the vertical datum of a gauge is not always known and if, sometimes not very precisely known. Furthermore, it should be kept in mind, that almost no altimeter satellite track directly crosses a water body at the location of the gauge station. This leads to an additional offset between the water level time series which was derived from a gauge station and altimetry data. Consequently, only relative comparisons can be performed. Finally, the results from the DAHITI database and the gauge data differed by a root mean square of 4 cm to 36 cm, which corresponds to a difference of 8 cm to 114 cm. Hereby, it was observed, that the accuracy declined with an increasing extent of the water body and with an increasing ice coverage (Schwatke et al., 2015).

To compare the derived water level time series to water level time series from other databases, which also rely on altimetry data, three databases, namely Hydroweb, River & Lake and Global Reservoir and Lake Monitor, were evaluated. Nevertheless, it has to be kept in mind, that all those databases process water level time series in different ways. Hence, the time series are not only based on varying altimeter missions, but they were also computed in different ways. As a result, all the time series differed in respect of their time periods and their temporal resolution. Nevertheless, the final comparison to other databases has shown, that the DAHITI approach can improve the gauge consistency up to several decimetre for most of the evaluated targets (Schwatke et al., 2015).

Overall, the validation has shown, that the water level time series, which are provided within the DAHITI database, have a great consistency with available in-situ observations. Besides, also a clear advance in relation to already existing approaches for the processing of altimetry data, could be proven. Subsequently, the strongest improvements could be related to the rigorous outlier detection and the data retracking strategy. Despite of that, it could be identified, that the occurrence and the handling of inter-mission biases and retracking biases is the most important challenge. One idea to reduce the occurrence of retracking biases would be to combine different retracking algorithms depending on how the shape of the prevailing waveform looks like. Since this application remains a major challenge, it also offers an enormous potential for future works (Schwatke et al., 2015).

Consequently, the water level time series which are provided in the DAHITI database, can be considered as being reliable and as having a high accuracy.

4.2.3 Data availability

DAHITI currently provides 10396 water level time series which are distributed over all continents except the Antarctica. That there are no water level time series for the Antarctica can be traced back to the fact, that there is no target of interest (Deutsches Geodätisches Forschungsinstitut, n.d.).

4.2.4 Further statistics

To assess the water body which has the highest average water level, the following Figure 9 was generated. Hence, the Figure 9 illustrates the mean computed water level value of the water level time series which are provide in the DAHITI database. The computed mean values are given in the unit metre above sea level. While the mean water level value of the shallow and high saline Lake Salton Sea from the southern end of the state California is - 70.550 m below sea level, the Lake Siling Co lies on the northern Tibetan Plateau of China and thus indicates the with 4541.781 m above sea level highest mean water level height value. Nevertheless, since the Figure 9 illustrates the absolute mean water level with respect to the sea level, which means that the depicted value is mainly driven by the altitude of the water body itself, it does not provide any information of the water height within the respective water body itself. Hence, it has to be said, that the magnitude of the mean water level value depends on the location of the considered water body.

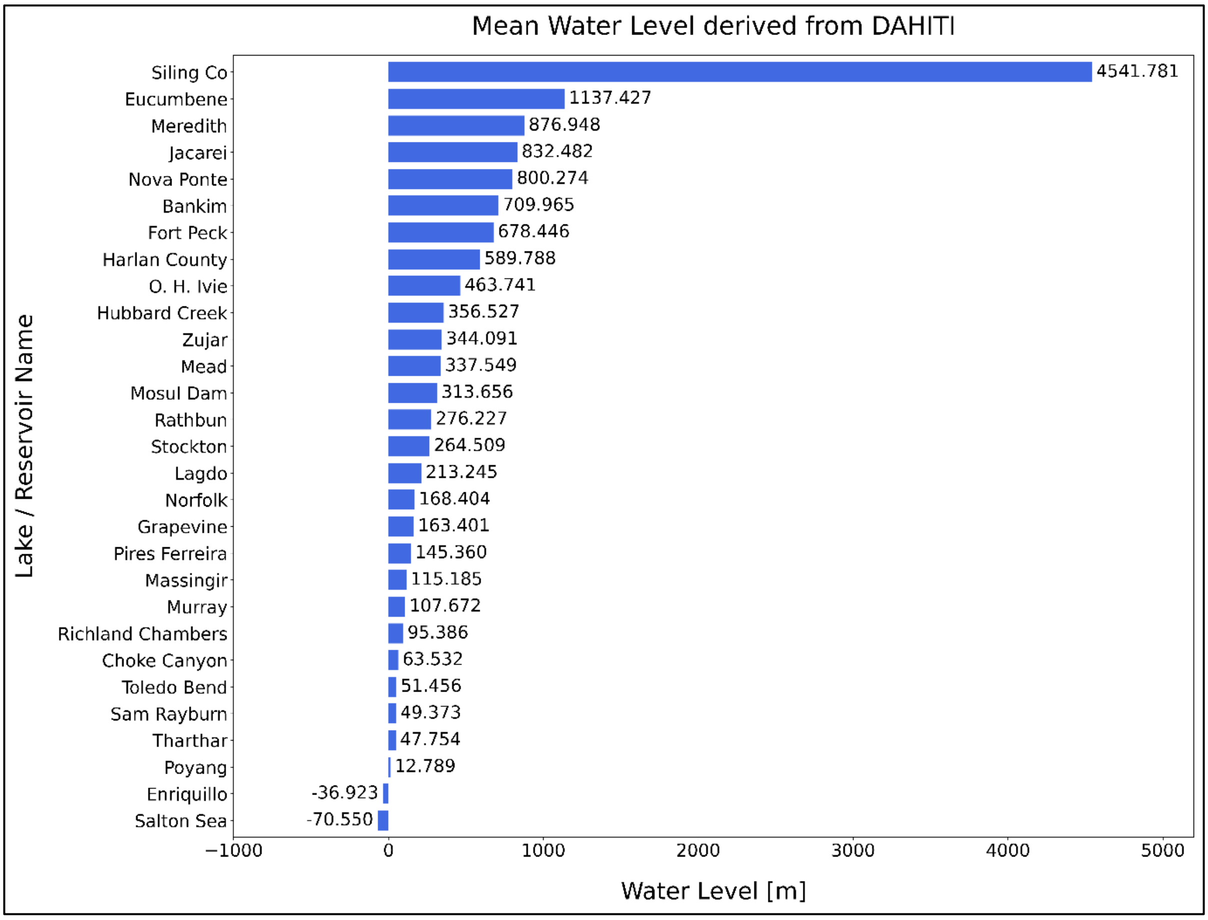

Figure 9: Mean water level

Source: Own representation in Python based on data retrieved from DAHITI

4.3 Volume Variation Time Series from DAHITI

As already mentioned in the chapter 4.2 WATER LEVEL TIME SERIES FROM DAHITI, DAHITI is an abbreviation for database for hydrological time series of inland waters and it is operated by the German Geodetic Research Institute of the Technical University of Munich. The volume variation time series, which are provided within the DAHITI database, are generated on the basis of data which is retrieved from remote sensing approaches only. While the surface area extents are computed from optical satellite images, the water level values are retrieved from satellite altimetry data. Nevertheless, since the full bathymetry of an inland water body cannot be measured by using remote sensing data only, the volume variation values are expressed with respect to the minimum observed surface area that was derived from optical satellite images.

To estimate volume variation values from the optical satellite imagery and satellite altimetry data, several processing steps, which will be elaborated in the following, have to be performed.

4.3.1 Processing

The processing strategy involves three major steps which are also fully explained in Schwatke et al., 2020.

The first processing step involves the estimation of a hypsometry model.

In hydrological applications, hypsometric curves can be used to illustrate the dependency between surface area values and water level values. Hence, each lake and each reservoir has a fixed area-height relationship. This area-height relationship depends on the bathymetry of the respective water body. The relationship itself can be described with the help of mathematical functions. In order to do so, an existing equation which describes a percentage hypsometric curve and which was developed in 1952 by the geoscience professor Arthur Strahler, was modified. This necessity for a modification can be traced back to the fact, that the original approach from Strahler was developed to analyse drainage basins with a known minima and a known maxima of the surface area values and the height values. Since the minima and the maxima values of both, the surface area values which are based on optical satellite images and the water level values which are derived from satellite altimetry, are usually not known, the original approach had to be revised. Finally, the derived hypsometry model can be used to compute water level values from surface areas and vice versa (Schwatke et al., 2020).

The second processing step involves the estimation of a bathymetry.

The bathymetry of a water body can be estimated in various ways. While simplified assumptions such as a pyramidal shape may be accurate enough for a water body with a more or less regular shape, those assumptions will reach their limitations in terms of reservoirs. Reservoirs experience large volume changes. Subsequently, the assumption of for instance a pyramidal shape may then lead to large errors regarding the volume change estimation. To overcome this problem, DAHITI uses an approach in which a bathymetry between the minimum and the maximum observed surface area is computed. To determine the minimum and the maximum surface area extent values, high resolution land-water masks, which are also provided within the DAHITI database, are used. Hence, the first step is to stack all land-water masks according to their water level. The second step is to analyse each pixel column individually and to compute the resulting water height value of the bathymetry. In order to do so, a median filter is applied to each pixel column. As long as the result of the applied median filter is water, the prevailing water height value is set for the pixel. This procedure continues until the result of the median filter is land. Then, the filtering is stopped. The resulting bathymetry has a spatial resolution of 10 m (Schwatke et al., 2020).

The third processing step involves the estimation of a volume variation time series.

To derive a time series of volume variation values, a pixel-wise intersection of the prevailing water level values and the related bathymetry, has to be carried out. As a result of this intersection, an information concerning the volume below the water level, can be derived. By accumulating the individual pixel volume values of the present water level, the value of the volume above the minimum observed surface area value, can be obtained. Since the volume value below that minimum observed surface area value is unknown, only time series of volume variation values, can be estimated. Finally, the surface area errors are converted into volume errors. This can be done by using the bathymetry information as well as the hypsometric curve (Schwatke et al., 2020).

4.3.2 Validation

While the surface area information can be validated by using time series from other databases, such as the Texas Water Development Board, water level time series can be validated by using gauge stations. To retrieve an in-situ volume value for validation purposes, bathymetry information from surveys have to be combined with water level values from gauge stations. Nevertheless, since usually more than one bathymetric survey is available, the resulting hypsometry and the retrieved volume values can differ. This may lead to inconsistencies such as offsets within the volume time series. Finally, the volume variation time series of 28 lakes and reservoirs, which are all located in the state of Texas within United States of America, were evaluated and the retrieved results were validated (Schwatke et al., 2020).

Throughout the validation procedure of the 28 targets, an average root mean square error of 0.025 km^3 was computed. This accounts for a root mean square error of 8.3 % with respect to the volume variation values and 3.1 % with respect to the overall volume. Further, the validation has also shown, that the quality of the volume variation time series strongly depends on the quality of the used input data. Hence, it was found out, that if the correlation coefficients between the surface area values and the water level values with the respective in-situ data are larger than 0.90, the resulting correlation coefficient of the volume variation values is also almost always larger than 0.90. For the selected targets within the state of Texas, the resulting correlation coefficients varied between 0.80 and 0.99. Hence it could be concluded, that using precise surface areas from optical imagery and precise water level values from satellite altimetry in combination with the modified Strahler approach, can lead to the estimation of very accurate volume variation time series. Since the method is solely based on remote sensing data, it can be used on a global scale and thus it can also be used to compute volume variation time series in remote areas (Schwatke et al., 2020).

4.3.3 Data availability

DAHITI currently provides 69 volume variation time series which are distributed over all continents except the Antarctica. Since there is no water level time series for the Antarctica, there are also no volume variation time series for this respective continent (Deutsches Geodätisches Forschungsinstitut, n.d.).

4.3.4 Further statistics

Since it might be the case that the difference between the consideration of a dynamic and a static water body shape is not driven by the size of a water body, but by its volume variation and thus in the last instance by its mass variation, the following Figure 10, was generated.

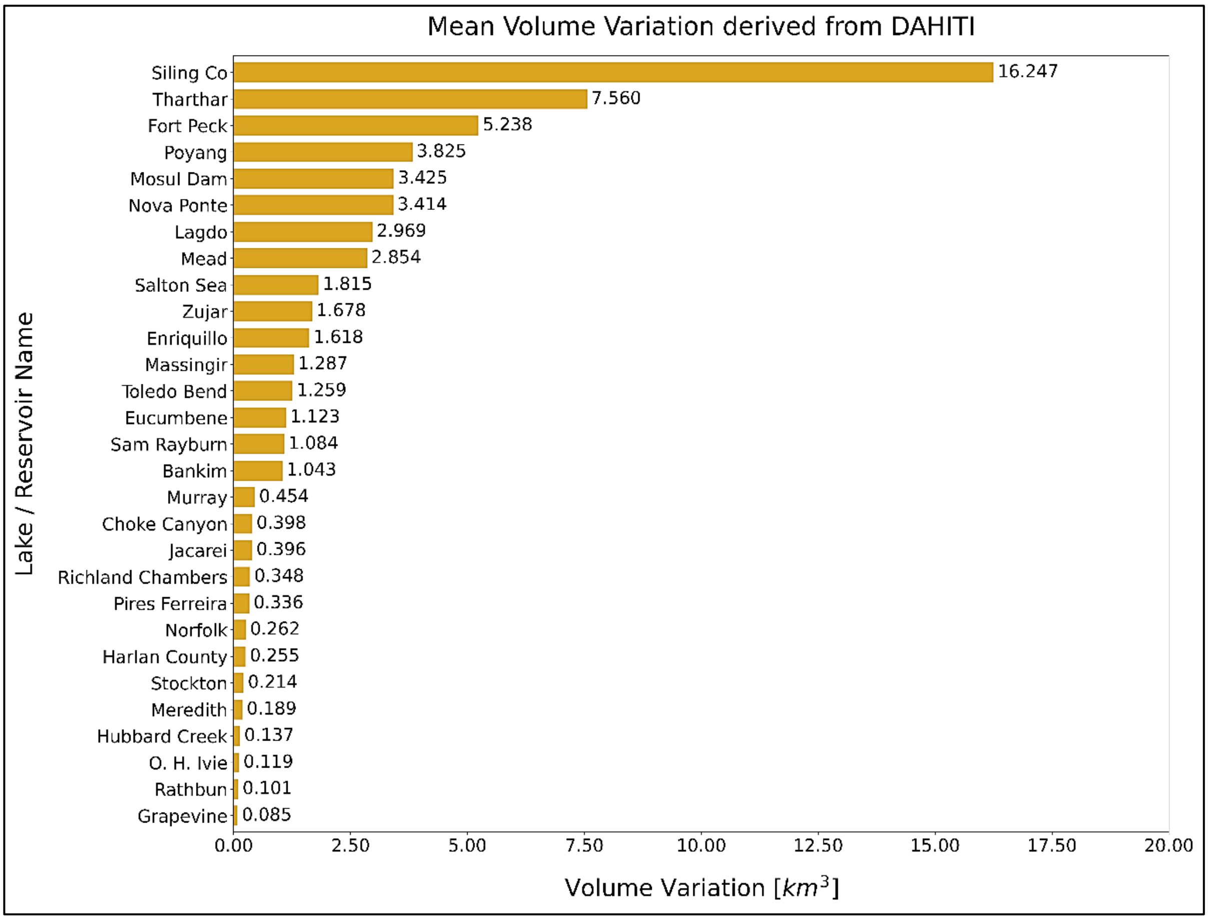

Figure 10: Mean volume variation

Source: Own representation in Python based on data retrieved from DAHITI

Hence, the Figure 10 illustrates the mean volume variation value with respect to the minimum observed surface area, which was derived from optical satellite imagery. It can be seen, that the mean volume variation values range from 0.085 km^3 for the Lake Grapevine to 16.247 km^3 for the Lake Siling Co. Subsequently, the Figure 10 also shows, that the largest water bodies do not necessarily indicate the largest volume variation values. Considering that the Lake Poyang is the lake which has the largest surface area extent, it can be seen that the Lake Poyang has only the fourth largest mean volume variation value. Besides, this mean volume variation value is with 3.825 km^3 also 76 % smaller than the mean volume variation value from the Lake Siling Co. Since GRACE measures the total water storage and thus also changes which are related to mass variations and in a last sequence also to volume variations, the Lake Siling Co is, next to the Lake Poyang, another water body which may be worth to further investigate.

Although the Figure 10 outlines, that the largest water body does not indicate the largest mean volume variation, the comparison to the Figure 2 and the Figure 3, which illustrate the mean surface area extent based on data derived from WaterPack and DAHITI respectively still shows, that an increasing surface area extent is generally also related to an increasing volume variation. To underline this behaviour, the temporal variation of the volume variation values and the temporal variation of the surface area extent values were plotted in one figure. An example for this can be seen in the Figure 11 below. In this case, the Lake Poyang, which was selected because it is subject to a high annual surface area variation, which will also be further elaborated in the chapter 5.5 RESULT FOR THE LAKE POYANG, is depicted. Hence, the Figure 11 clearly shows, that an increase of the volume variation is generally also conducted with an increase of the surface area extent and vice versa. Punctual contrary developments can either be attributed to errors within the original data or to the monthly averaging of depicted values.

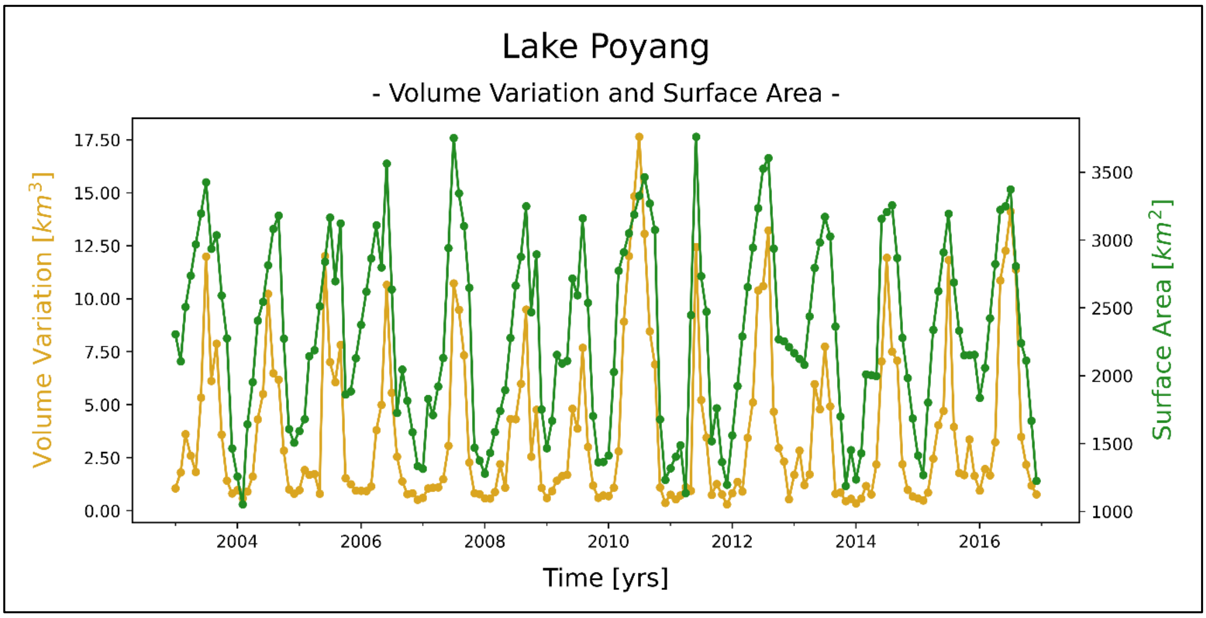

Figure 11: Temporal variation of the volume variation and the surface area for the Lake Poyang

Source: Own representation in Python based on data retrieved from DAHITI and WaterPack

To further assess to which extent a volume variation time series differs when a dynamic and a static water body shape are considered, the following Figure 12 was generated. Since the Lake Siling Co indicates, according to the Figure 10, the largest mean volume variation value, it was also selected for the purpose of this demonstration.

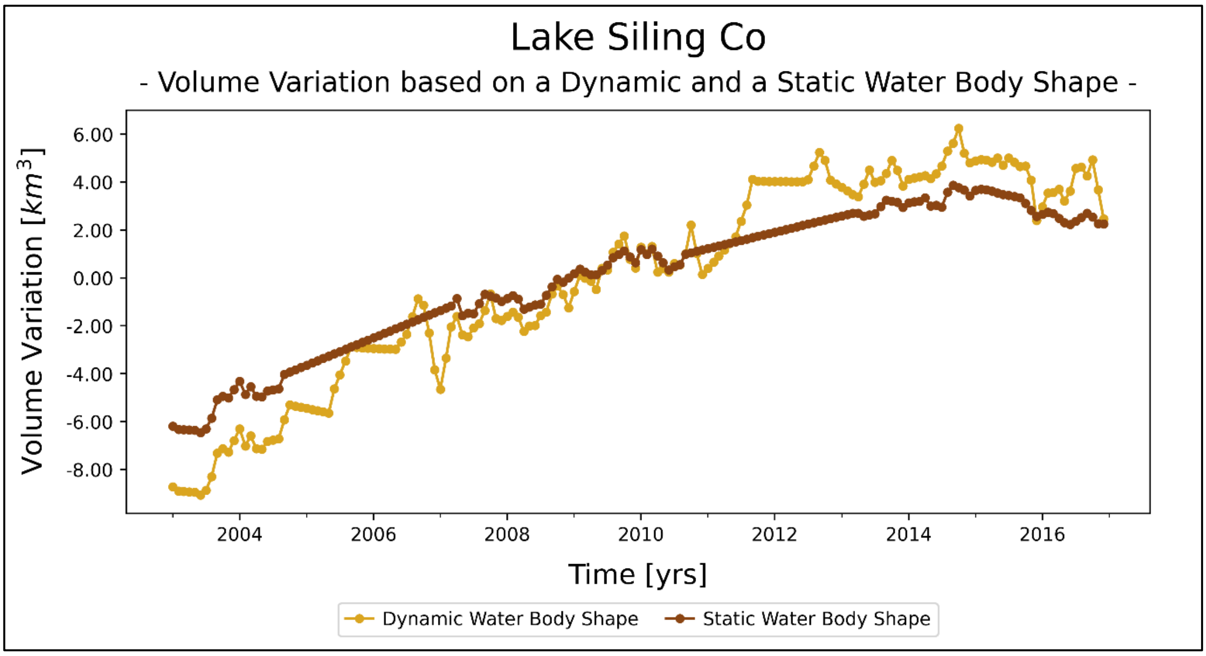

Figure 12: Volume variation based on a dynamic and a static water body shape for the Lake Siling Co

Source: Own representation in Python based on data retrieved from DAHITI and WaterPack

While the volume variation values based on a dynamic water body shape were directly retrieved from the DAHITI database and just averaged to monthly mean values, the curve which represents the volume variation based on a static water body shape was retrieved by multiplying the area extent value derived from the polygon of the WaterPack product by the mean water level value derived from the DAHITI database. Hence, the Figure 12 shows, that both time series differ from each other. Taken into consideration, that both time series were computed under the consideration of the water level time series provided in the DAHITI database, these differences can solely be attributed to the varying surface area extents. By means of that, the deviation of both time series is comparable large in the beginning and towards the end of the selected time frame. Hence, the largest compliance occurs between 2008 and 2011. Despite of that, both time series still indicate the same trend, which means that the volume variation increases over the course of the selected time frame.

To quantify the average deviation of both time series, not only for the Lake Siling Co, but also for the remaining 28 water bodies, the absolute mean difference between two related volume variation time series, was computed. In order do so, the mean value of the volume variation time series, which was computed on the basis of the dynamic water body shape, was subtracted from the mean volume variation value which was computed under the consideration of a static water body shape. The result is depicted in the Figure 13. Subsequently, the Figure 13 shows, that both volume variation time series encounter a difference which varies between 0.008 km^3

for the Reservoir Meredith and 1.673 km^3 for the Lake Mead.

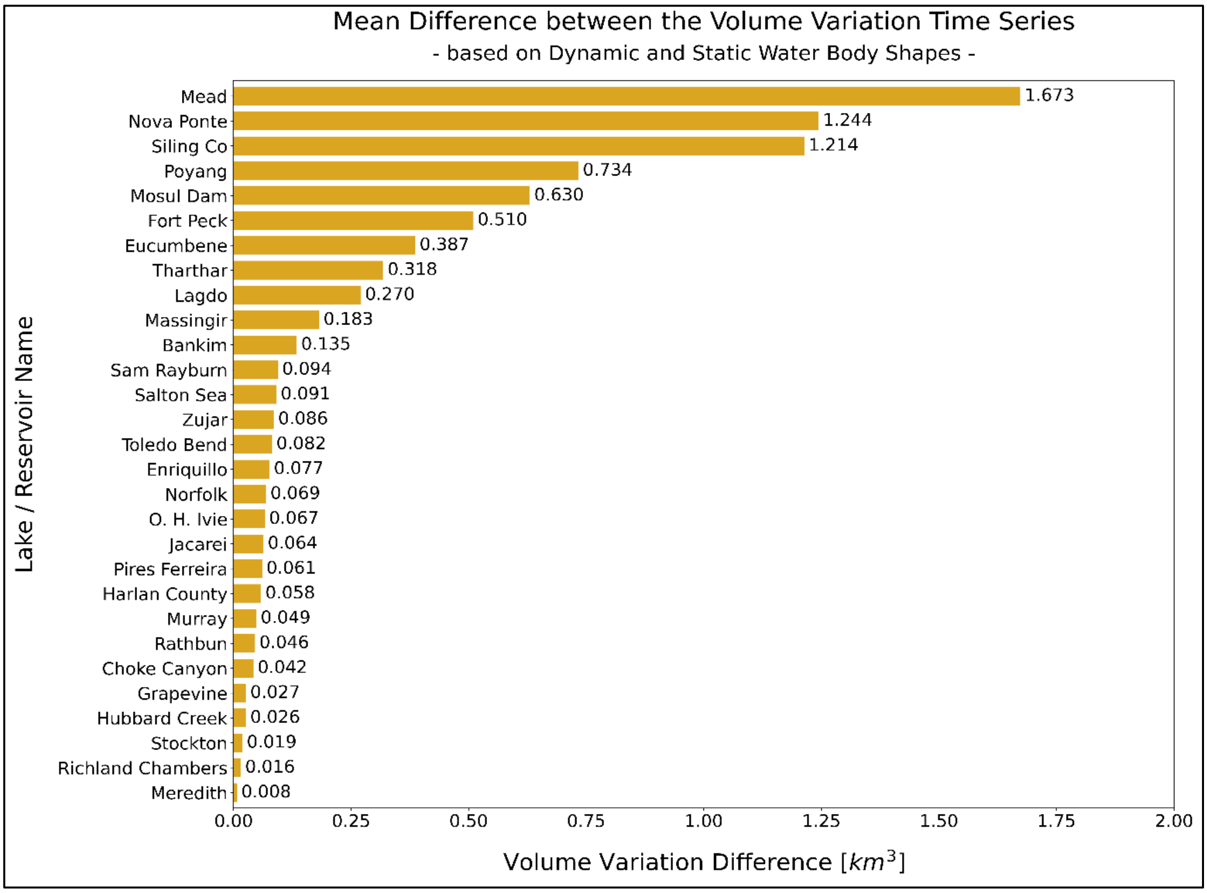

Figure 13: Mean volume variation difference based on dynamic and static water body shapes

Source: Own representation in Python based on data retrieved from DAHITI and WaterPack

To investigate the difference of the Reservoir Meredith, the following Figure 14 was generated.

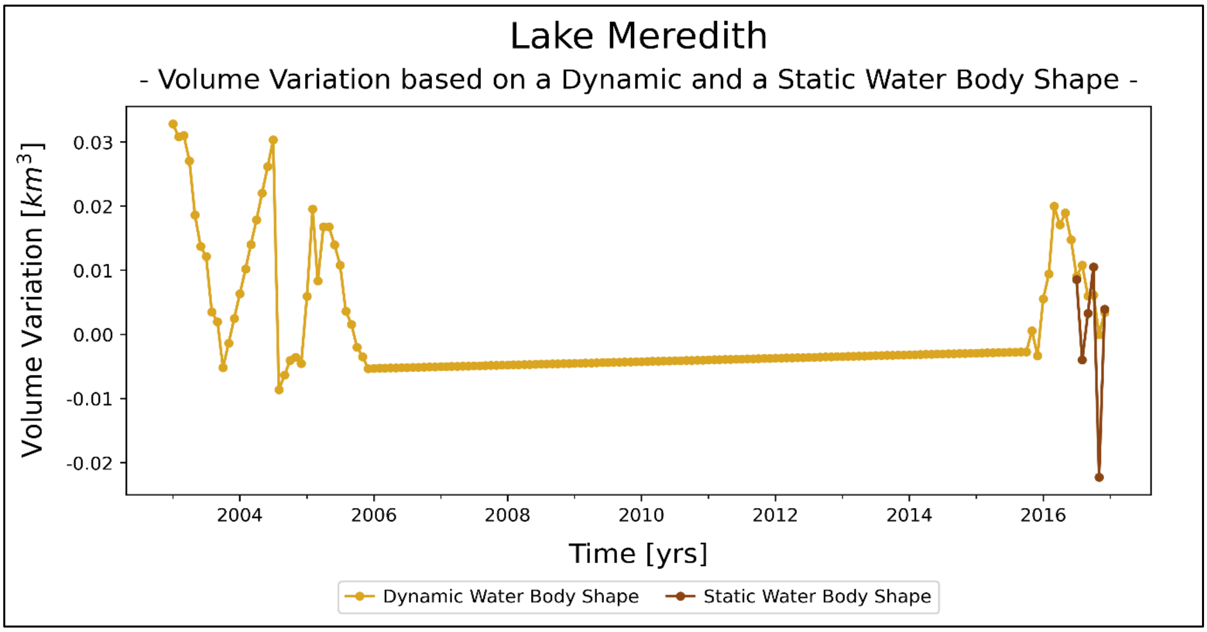

Figure 14: Volume variation based on dynamic and static water body shapes for the Reservoir Meredith

Source: Own representation in Python based on data retrieved from DAHITI and WaterPack

Hence, the particularly small mean difference for the Reservoir Meredith can be attributed to the fact, that the water level time series derived from the DAHITI database only delivers values from the summer of 2016 onwards. Hence, it can be seen, that both time series only overlap for five months, which means that the value depicted in the Figure 13 is also computed based on just those five points in time. Nevertheless, the Figure 14 still shows, that both volume variation time series indicate the same trend behaviour at least for those five months. Considering the magnitude of the scale, which indicates deviations in the magnitude of cubic metres, the depicted differences can be neglected.

Meanwhile, the Figure 15 illustrates the volume variation time series for the Lake Mead, which encounters the largest volume variation difference.

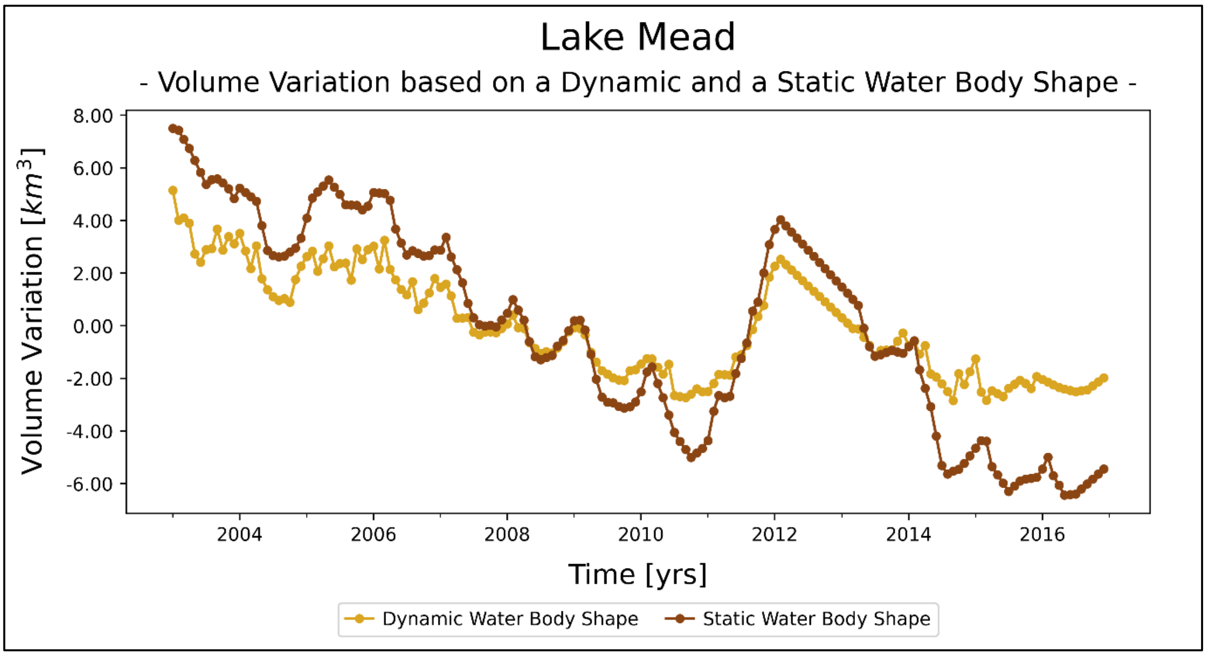

Figure 15: Volume variation based on dynamic and static water body shapes for the Lake Mead

Source: Own representation in Python based on data retrieved from DAHITI and WaterPack

Although both depicted time series indicate the same trend, meaning that the volume variation decreases over the course of the selected time frame, both time series also indicate a clear, non-static offset. Considering the magnitude of the y-axis, which depicts the volume variation in cubic kilometres, this non-static offset finally causes a mean deviation of 1.673 km^3, which is also depicted in the Figure 13.

Next to the volume variation time series and their differences based the consideration of dynamic and static water body shapes respectively, the volume variation difference itself, which refers to the deviation between the minimum and the maximum observed volume variation values, was further quantified. Therefore, the volume variation time series, which was computed on the basis of dynamic water body shapes and which could be directly retrieved from the DAHITI database, was used. Hence, the minimum as well as the maximum volume variation value of each considered water body was computed. By subtracting the minimum from the maximum observed volume variation value, the largest encountered volume variation difference, could be derived. The results were transferred to a bar chart, which is depicted below.

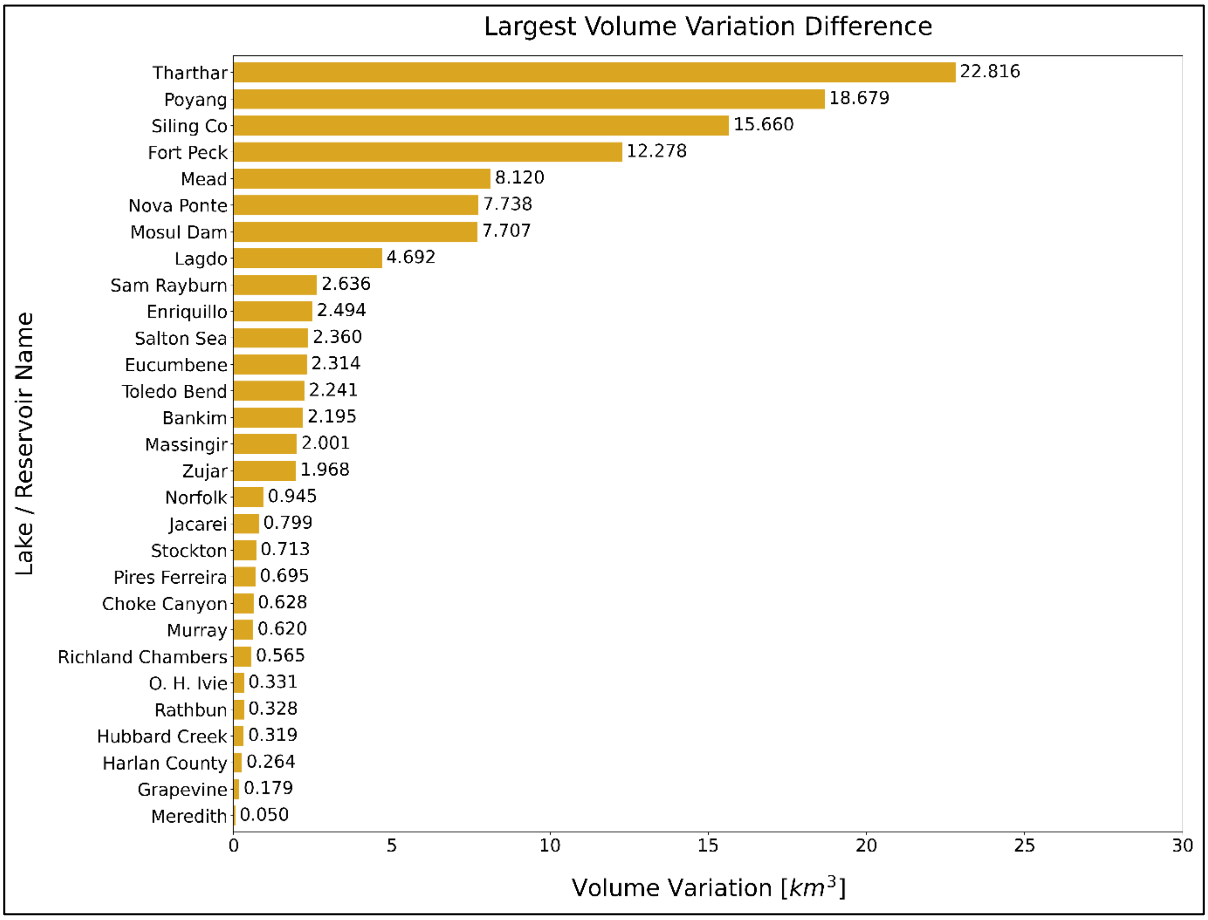

Figure 16: Largest volume variation difference based on dynamic water body shapes

Source: Own representation in Python based on data retrieved from DAHITI

Subsequently, the Figure 16 shows, that the largest encountered volume variation differences reach from 0.050 km^3 for the Reservoir Meredith to 22.816 km^3 for the Lake Tharthar. Thus, the Figure 16 also shows, that the water body Lake Siling Co which has, according to the Figure 10, the largest volume variation, does not necessarily also has the largest volume variation difference. Hence the question arises, whether only a large volume variation itself, or a large volume variation difference, plays a key role for the consideration of a dynamic and a static water body shape. To answer this question, not only the largest Lake Poyang, but also the lake which has the largest volume variation, being the Lake Siling Co, and last but not least also the Lake Tharthar, which indicates the largest volume variation difference, will be further investigated in the following chapters 5.5 RESULT FOR THE LAKE POYANG, chapter 5.6 RESULT FOR

THE LAKE SILING CO and chapter 5.7 RESULT FOR THE LAKE THARTHAR. Hence, those investigations will help to assess, whether the mass changes observed by GRACE are more sensitive to surface area variations or to volume variations and their differences.

5 Methods and Results

This chapter will focus on the pre-processing steps which were necessary to perform the forward modelling procedure. In addition, this chapter will also quickly introduce the applied filtering procedure and the required re-computation approach. Besides, the achieved results for the consideration of static and dynamic water body shapes will be compared and evaluated. Therefore, a special focus will be set on the Lake Poyang, the Lake Siling Co and the Lake Tharthar. Finally, a result for all 29 considered water bodies will be given and the driving factors of the achieved results will be investigated.

5.1 Pre-processing

To combine the various input data products, several pre-processing steps had to be carried out.

To match the temporal resolution of the monthly GRACE gravity field models, the object-oriented programming language Python was used to average the water level and the volume variation time series to monthly mean values. In addition, monthly data gaps were closed by applying a linear interpolation approach. To match the time frame of the GRACE observations, each time series was tailored to an investigation period reaching from January 2003 to December 2016. To allow for a better comparability, the time series were also reduced by their respective mean values. Since the volume variation time series refer to a dynamic surface area extent, a division by the respective static surface area extent allowed to express the volume in terms of equivalent water height values, which could then enter the forward modelling procedure.

Following, the Gravity Recovery Object Oriented Programming System (GROOPS), which is a software toolkit for gravity field recovery and GNSS processing (Mayer-Gürr et al., 2021), was used for further processing steps. Although these processing steps were performed based on a GROOPS script which was used by Deggim et al., the non-availability of certain functions within the newest version of GROOPS made it necessary to update the prevailing script and to replace missing functions by new ones. An in-depth explanation of the updated script, including a description of the used parameters and the retrieved output, can be derived from the chapter 9 APPENDIX. Hence, the updated script was used to discretise the surface water body shapes on a fine-resolution grid in which every grid cell had a size of 0.0025 ° x 0.0025 °. As a result, also long and narrow water bodies, which are for instance situated in valleys or between neighbouring mountain ranges, could be captured. After that, the surface water body shapes were multiplied with their respective water level height values. Hence, either the water level height values from the DAHITI database for the static approach, or the newly computed water level height values, which were derived from the volume variation time series, were used. Subsequently, an estimation concerning the temporal variation of the water volume values within each grid cell, could be derived. To reduce the computation time, the volume values were distributed over a lower resolution grid of 0.5 ° x 0.5 °. As a result, an information regarding the water level anomaly of each grid cell, which refers to the height of the body water over the mean sea surface (Copernicus, 2018), could be derived. These global water height anomaly values then entered a forward modelling algorithm (Deggim et al., 2021).

5.2 Forward modelling

Since the goal was to subtract the gridded surface water variation values from the monthly GRACE gravity field estimates, the resolution of the surface water variation values had to be converted to the spatial resolution of GRACE. In order to perform this forward modelling procedure, the gridded water level anomaly values were expanded into spherical harmonic coefficients. Therefore, the following Equation 1 was applied.

$$\begin{bmatrix}\Delta C_{nm}\\ \Delta S_{nm}\end{bmatrix} = \frac{R^2}{M}\cdot\frac{k_n+1}{2n+1}\int_0^{\pi}\int_0^{2\pi}\left(\Delta TWS(\theta,\lambda)\cdot P_{nm}(\cos\theta)\begin{bmatrix}\cos(m\lambda)\\ \sin(m\lambda)\end{bmatrix}\cdot\sin(\theta)\right)\cdot d\lambda\cdot d\theta$$

Equation 1: Spherical Harmonic Coefficients

Source: Deggim et al., 2021

Hence, the spherical harmonic coefficients ΔC_{nm} and ΔS_{nm} were expanded up to a degree (n) and an order (m) of 96. While R represents the radius of the earth, M refers to the mass of the earth. Meanwhile, k_n indicates the load Love numbers and ΔTWS (θ, λ) the change of the altimetry-derived water storage depending on the co-latitude θ and the longitude λ. Finally, P_{nm} represents the Legendre functions.

5.3 Filtering

The forward modelled spherical harmonic potential coefficients were then smoothed by applying a DDK3 filter. While DDK is an abbreviation for denoising and decorrelation kernel, the number 3 refers to the filter level. Hence, the DDK3 filter is a standard filter to filter GRACE data. It was developed by Kusche et al. in 2009. In comparison to the original Kusche filter from 2007, which involves a decorrelation and a smoothing method (Kusche, 2007), the new filter is a simplified version which follows an order-convolution approach. Therefore, the input is modified order-wise. While this order-convolution approach requires less coefficients that have to be stored, a higher resolution can be achieved at the same time (Kusche et al., 2009).

5.4 Re-Computation

The forward modelled and filtered spherical harmonic potential coefficients express the signal that GRACE would measure if the observations were only influenced by the changing mass of the respective water body. To obtain a grid-based solution, a re-computation had to be performed. In order to do so, the following Equation 2 had to be applied.

$$\Delta TWS^{F}(\theta,\lambda) = \frac{M}{4\pi R^2 \rho}\sum_{n=0}^{96}\sum_{m=0}^{n}\left(\frac{2n+1}{1+k_n}\cdot P_{nm}(\cos\theta)\cdot\left(\Delta C_{nm}^{F}\cos(m\lambda)+\Delta S_{nm}^{F}\sin(m\lambda)\right)\right)$$

Equation 2: Total Water Storage for every grid cell after filtering

Source: Deggim et al., 2021

Hence, the equation allowed to calculate the total water storage for every grid cell after filtering up to an order (m) and a degree (n) of 96. While M refers to the mass of the earth, R represents the radius of the earth. In comparison to the previous Equation 1, the Equation 2 also involves ρ, which refers to the density of the water and which allows to obtain the total water storage of the investigated water body in metres of equivalent water height values. Furthermore, k_n indicates the load Love numbers and P_{nm} represents the Legendre functions. Finally, ΔC_{nm}^{F} and ΔS_{nm}^{F} denote the filtered spherical harmonic coefficients.

5.5 Result for the Lake Poyang

Since the previous statistics of all 29 considered water bodies has shown, that the Lake Poyang is, according to the size of the considered polygon, the largest water body and that it has the largest surface area variation, it was further investigated. The derived results will be examined in the following.

To examine whether the consideration of a dynamic lake shape significantly influences the results, which were derived for Chinas largest freshwater lake, the Figure 17 and the Figure 18, were generated. Hence, each figure represents the first release of the monthly computed removal correction for 01/2003. The removal correction is expressed in terms of forward modelled equivalent water height values, which are indicated in the unit of centimetre. Accordingly, each figure visualizes the size of the forward modelled equivalent water height values that has to be removed from the GRACE signal in 01/2003. By subtracting the respective size from the GRACE signal, the impact, that the Lake Poyang has on the processed equivalent water height values, which were derived from GRACE observations, can be removed and thus the GRACE signal can be corrected. Consequently, each map functions as an indicator which shows how strong the Lake Poyang influences the mass change observed by GRACE. This information is, especially under the consideration of more than one water body, extremely helpful to make the estimates of GRACE more consistent with the output from hydrological models.

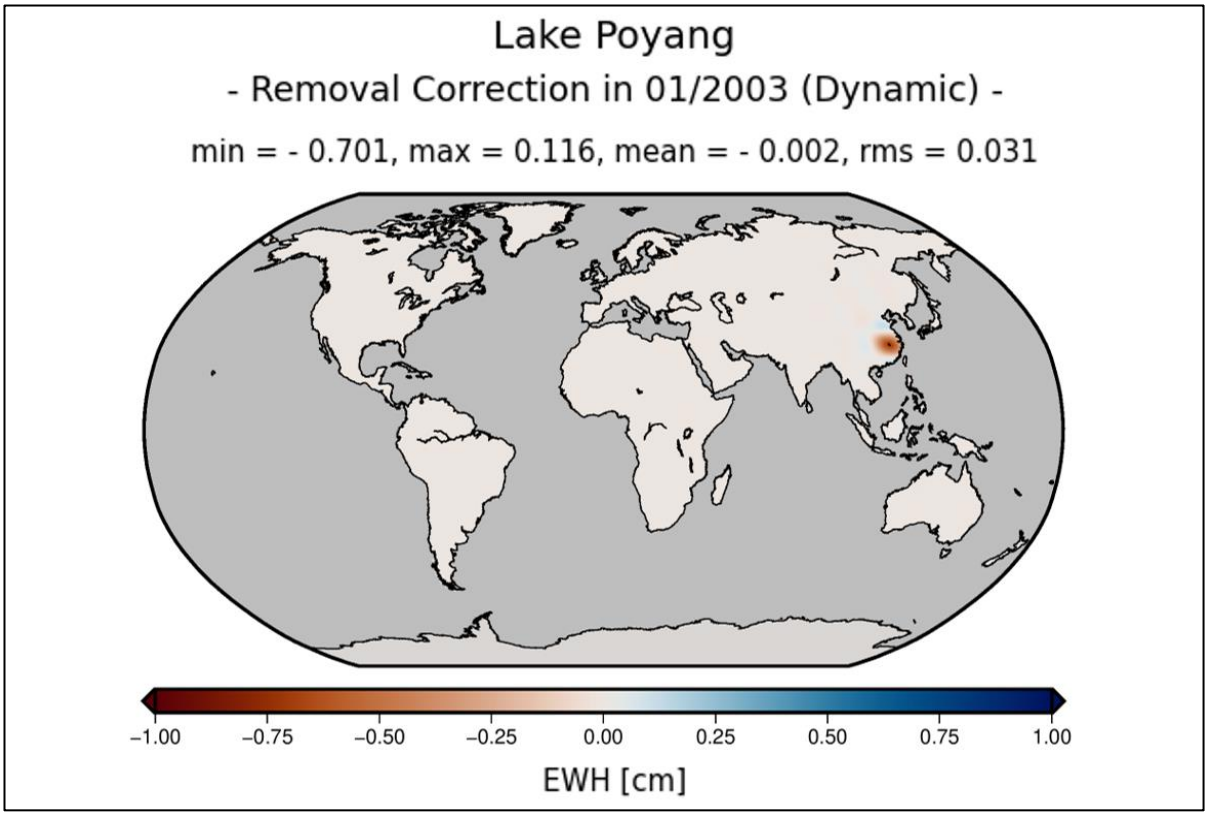

Figure 17: Removal correction in 01/2003 based on a dynamic lake shape for the Lake Poyang

Source: Own representation in GROOPS and in Python

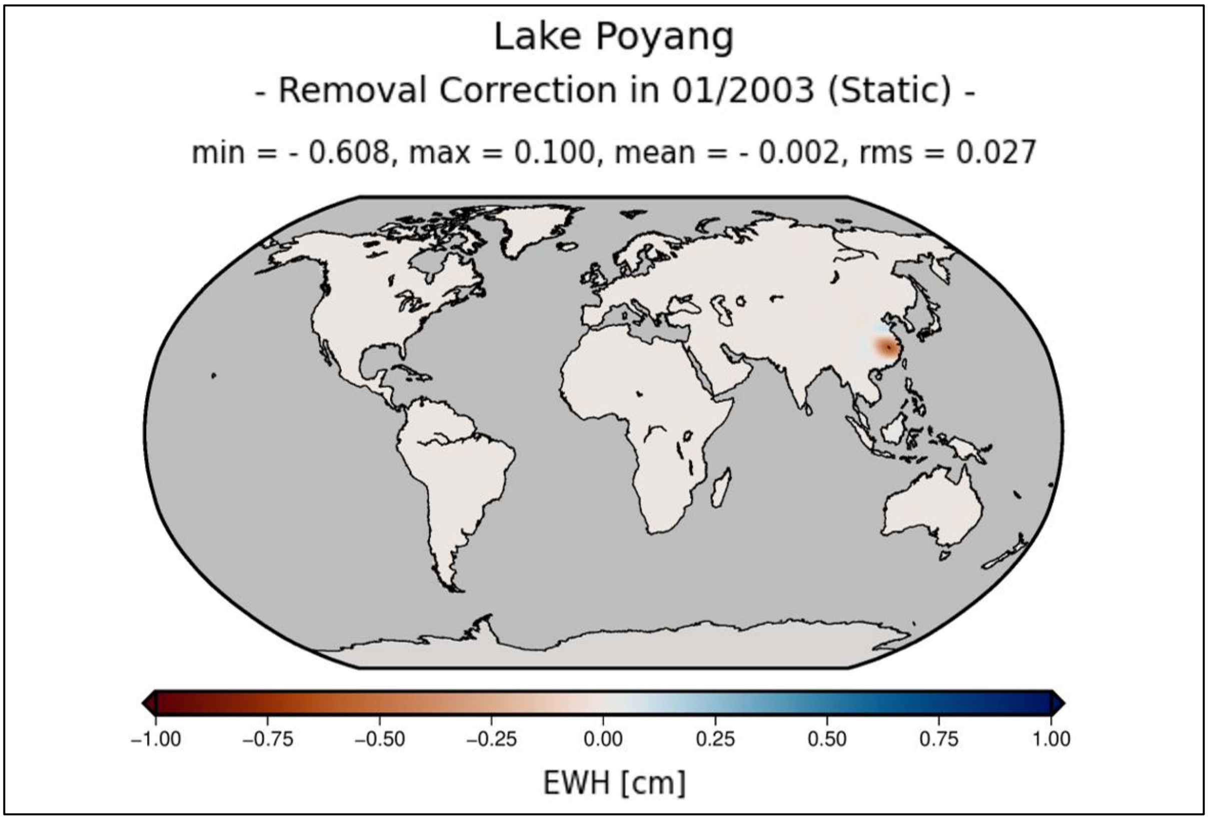

Figure 18: Removal correction in 01/2003 based on a static lake shape for the Lake Poyang

Source: Own representation in GROOPS and in Python

Consequently, the Figure 17 includes a dynamic lake shape for the Lake Poyang. This means, that the equivalent water height values were forward modelled on the basis of a dynamic lake shape. Meanwhile, the Figure 18 refers to a static water body shape. For the Figure 17, the forward modelled equivalent water height values range from - 0.701 cm to 0.116 cm. This results in an average equivalent water height value of - 0.002 cm. This means, that an average of - 0.002 cm equivalent water height would have to be removed from the GRACE signal in order to withdraw the influence of the Lake Poyang. The root mean square error indicates how much the values scatter around zero. This value is weighted according to the area sizes and it equals 0.031 cm.

For the Figure 18, the forward modelled equivalent water height values range from a minimum of - 0.608 cm to a maximum of 0.100 cm, which results in a mean value of - 0.002 cm and a root mean square error of 0.027 cm. As already mentioned, the only difference between these two figures is, that the Figure 17 contains a dynamic lake shape for the Lake Poyang. Hence, the statistical differences can only be attributed to the fact that the dynamic lake shape of the Lake Poyang was replaced by a static lake shape. Subsequently, the statistical information of the Figure 17 and the Figure 18 for the Lake Poyang shows, that both minimum values differ by - 0.093 cm. Meanwhile, the maximum values differ by 0.016 cm, which then results in a, to three digits rounded, deviation of the mean value of - 0.000 cm. Nevertheless, all of these numbers, including the difference, only refer to 01/2003.

To estimate the influence that the dynamic lake shape of the Lake Poyang and the respective difference to a static lake shape have over time, the following two figures, the Figure 19 and the Figure 20, were generated. Hence, the Figure 19 and the Figure 20 illustrate the temporal variation of the equivalent water height values for the Lake Poyang. The x-axis indicates the year and reaches from 01/2003 to 12/2016. Meanwhile, the y-axis indicates the equivalent water height values in the unit of metre. In total, both figures visualize three different curves. The first curve is coloured in red and it represents the forward modelled equivalent water height values which have to be subtracted from the GRACE signal in order to remove the mass variations caused by the Lake Poyang. This process of subtraction is also denoted as removal correction. The second curve is coloured in blue. It illustrates the processed equivalent water height values which were derived from GRACE observations. For this purpose, gridded total water storage anomalies were derived from the ITSG-Grace2018 spherical harmonic expansion up to a degree and up to an order of 96 (Mayer-Gürr et al., 2021). These gridded total water storage anomaly values were not only corrected for low degree coefficients (Swenson et al., 2008), but they were also corrected by applying a glacial isostatic adjustment (A et al., 2013) and a DDK3 filter

(Kusche, 2007). The third curve visualizes the difference between the forward modelled equivalent water height values and the total water storage anomaly grids which were derived from GRACE observations. It is coloured in green and refers to the corrected GRACE signal. The procedure of subtracting the forward modelled equivalent water height values from the processed equivalent water height values derived from GRACE, is denoted as removal approach.

Taking this into consideration, the Figure 19 and thus also the forward modelled equivalent water height values which are depicted in there, refer to the consideration of a dynamic lake shape of the Lake Poyang.

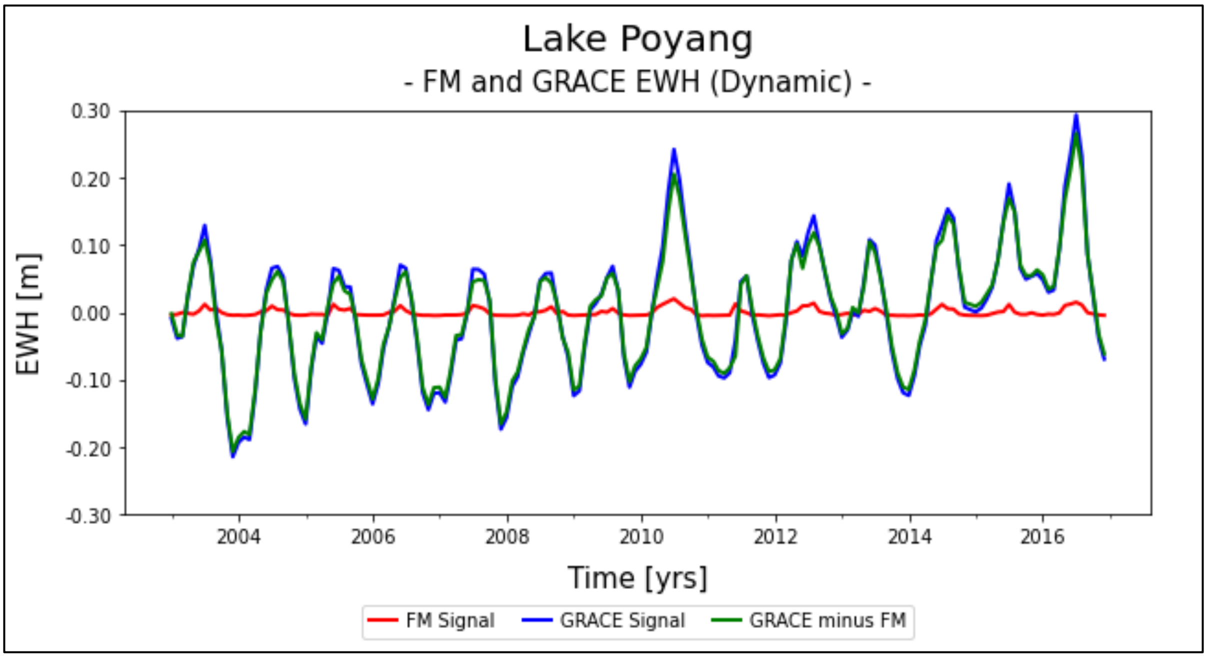

Figure 19: FM, GRACE and GRACE-FM EWH based on a dynamic water body shape for the Lake Poyang

Source: Own representation in Python

Hence, it can be seen, that the monthly forward modelled and red coloured equivalent water height values fluctuate around 0.000 m, reaching their minimum value in 12/2011 where the equivalent water height values reach - 0.005 m. Nevertheless, it can also be seen, that the forward modelled equivalent water height values slightly increase towards the middle of each year. The resulting small peaks can be attributed to the fact that the Lake Poyang is located in south - east China, where the precipitation is closely linked to the east Asian monsoon. Hence, the main rainy season lasts from April to June each year, resulting in an average annual precipitation of 1580.8 mm (Zhang, 2019). Consequently, those annual rainfall events cause the forward modelled equivalent water height values to increase to a maximum of 0.020 m in 07/2010. This annual increase can also be seen in the GRACE signal. Nevertheless, since the processed equivalent water height values, which were derived from GRACE observations, refer to the entire water column, meaning that the GRACE signal does not only contain the surface water body itself, but also other storage compartments such as groundwater or soil moisture, the magnitude of the signal and thus the magnitude of the annual peaks is much larger. Hence, the GRACE signal reaches its peak in 07/2016 where the equivalent water height values amount to 0.293 m. Meanwhile, the lowest processed equivalent water height values occur in 12/2003. In this month, the GRACE observation indicates, that every grid cell of the Lake Poyang has an equivalent water height value of - 0.214 m. Overall, it can be seen that the processed equivalent water height values, which were derived from GRACE observations, slightly increase over the course of the observed time frame. This increase can be related to an incline of the water level by 44.497 km^2 from 2003 to 2015 (Wang et al., 2020). Since this incline of the water level also increases the mass of the Lake Poyang, it also increases the processed equivalent water height values which were derived from GRACE observations. Hence, the increase is also visible in the Figure 19. After that period, the water level starts to decrease again, resulting in a decline of - 129.53 km^2 from 2015 to 2019 (Wang et al., 2020). The beginning of this decrease can also be seen in the Figure 19, where the peak from 07/2016 is followed by a steep decline of the processed equivalent water height values. The third and green coloured curve illustrates the corrected GRACE signal. Hence, it refers to the subtraction of the red curve from the blue curve and thus expresses the temporal variation of the GRACE signal if the influence of the Lake Poyang would be removed. Since the forward modelled equivalent water height values have a very small magnitude with a maximum of 0.020 m in 07/2010, the temporal variation of the GRACE signal and the corrected GRACE signal are almost identical. Nevertheless, it can be seen that the differences between the processed GRACE signal and the corrected GRACE signal, always occur in the local minimum and maximum points. Hence, the forward modelled equivalent water height values and thus also the removal correction, have a stronger influence whenever the Lake Poyang reaches its annual minimum and maximum water level and thus also its minimum and maximum mass. The global minimum of the corrected equivalent water height values is reached in 12/2003. Since December belongs to the dry period of the Lake Poyang, which always takes place from late autumn to winter (Zhang, 2019), the corrected equivalent water height values indicate a global minimum value of - 0.207 m. The highest corrected monthly equivalent water height value is 0.266 m and it appears in 07/2016.

When comparing the temporal variation of the three curves depicted in the Figure 19 and the Figure 20, which only differ in the aspect that a static shape was used in the Figure 20, it can be seen, that the overall temporal variation of all three curves is similar to the behaviour of the three curves depicted in the Figure 19. However, the forward modelled equivalent water height values slightly differ. While they reach a minimum value of - 0.005 m in 12/2011 and a maximum value of 0.020 m in 07/2010 in the Figure 19, the minimum value now accounts - 0.007 m and occurs in 10/2013. In addition, the maximum value does not occur in 2010 anymore, but in 2016. Besides, it is also by 0.003 m smaller and equals 0.017 m. Since the processed equivalent water height values, which were derived from GRACE observations, remain the same, the corrected equivalent water height values, which function as removal correction, also slightly differ. By means of that, the corrected equivalent water height values range from - 0.208 m in 12/2003 and increase to 0.262 m in 07/2016.

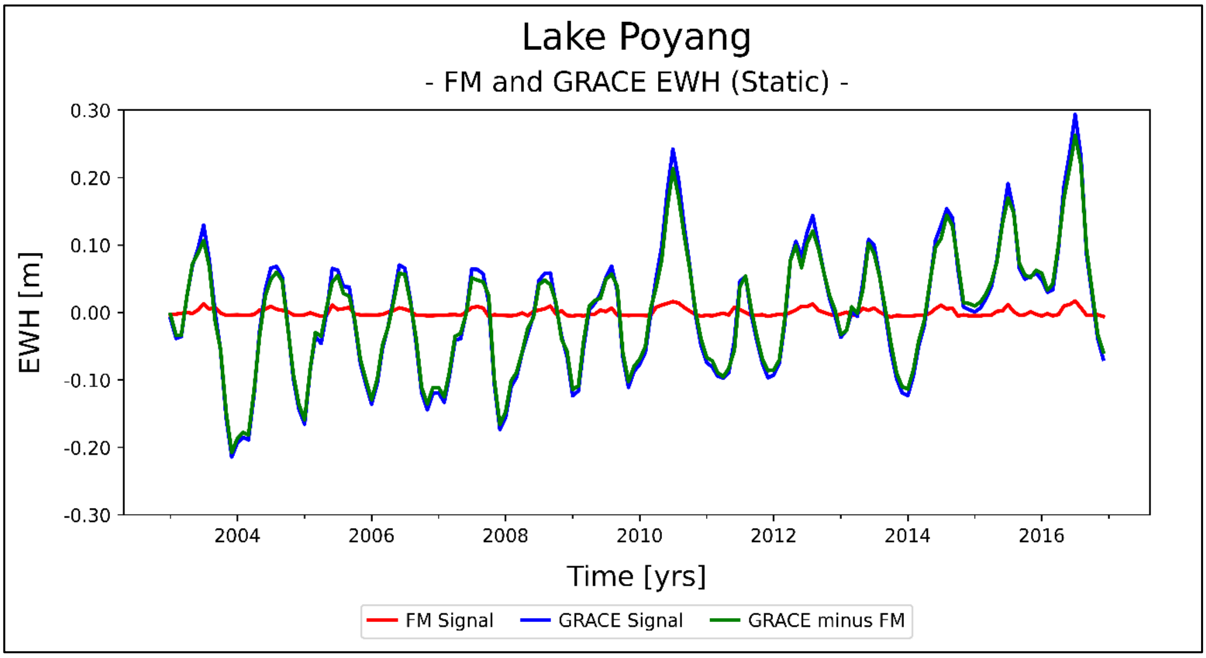

Figure 20: FM, GRACE and GRACE-FM EWH based on a static water body shape for the Lake Poyang

Source: Own representation in Python

Hence, the fact whether a dynamic or a static lake shape is used, slightly influences the temporal variation and the magnitude of the removal correction and thus also the corrected GRACE signal. To further quantify the difference and the influence that the consideration of a dynamic water body shape has in comparison to a static water body shape, the forward modelled equivalent water height values of both cases were plotted in an additional figure. Hence, the Figure 21 illustrates the temporal variation of the forward modelled equivalent water height values, which were computed on the basis of a dynamic and a static lake shape respectively. While the forward modelled equivalent water height values, which were computed on the basis of a dynamic lake shape, are coloured in orange, the forward modelled equivalent water height values, which were computed under the consideration of the static lake shape, are coloured in yellow. By changing the unit of the y-axis from metre to centimetre, it becomes even more evident, that the respective equivalent water height values only differ in the magnitude of millimetres. The exact magnitude can be derived from the black curve, which refers to the difference between the other two curves. Hence, the equivalent water height values, which refer to a static lake shape, are subtracted from those which refer to a dynamic water body shape. This difference faces a temporal variation. It has a global minimum value of - 0.368 cm, which occurs in 08/2006 and a global maximum value of 0.481 cm. This global maximum value is reached in 06/2011. The absolute mean value of the difference is 0.107 cm.

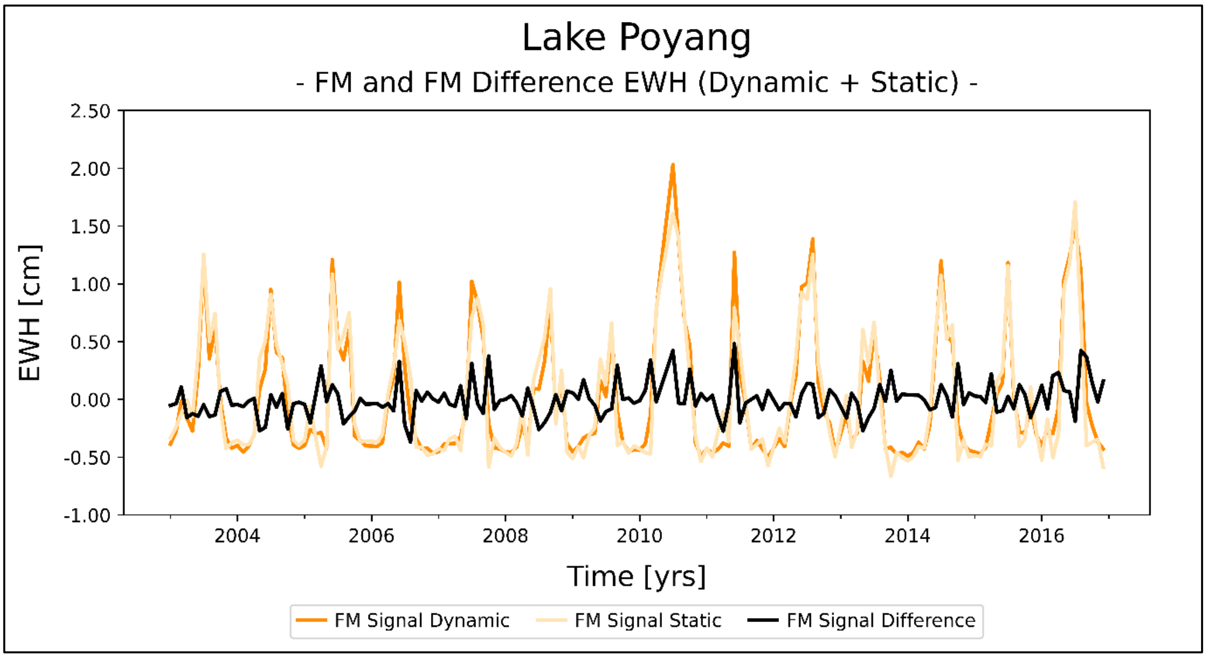

Figure 21: FM and FM difference EWH based on a dynamic and a static lake shape for the Lake Poyang

Source: Own representation in Python

Since the respective forward modelled equivalent water height values only differ on a small scale in the magnitude of millimetres, the influence on the processed equivalent water height values, which were derived from GRACE observations, is difficult to trace with the bare eye. This also becomes evident when evaluating the Figure 22, which refers to a comparison of both corrected signals. Hence, each correction signal is represented by equivalent water height values. Subsequently, the Figure 22 illustrates three curves, coloured in dark blue, light blue and black. The blue coloured curves illustrate the temporal variation of the corrected equivalent water height values. The corrected equivalent water height values refer to the difference between the processed equivalent water height values, which were derived from GRACE observations, and the forward modelled equivalent water height values, which function as removal correction. By subtracting the removal correction from the initial GRACE signal, the influence of the respective water body, in this case the Lake Poyang, can be removed. In this case, the Figure 22 shows, that the corrected equivalent water height values differ in a magnitude which reaches from - 0.009 m to 0.007 m and which results in an average absolute deviation of 0.002 m. Hence, the global minimum of the difference curve, which is coloured in black, occurs in 06/2011. Meanwhile, the global maximum occurs in 08/2006.

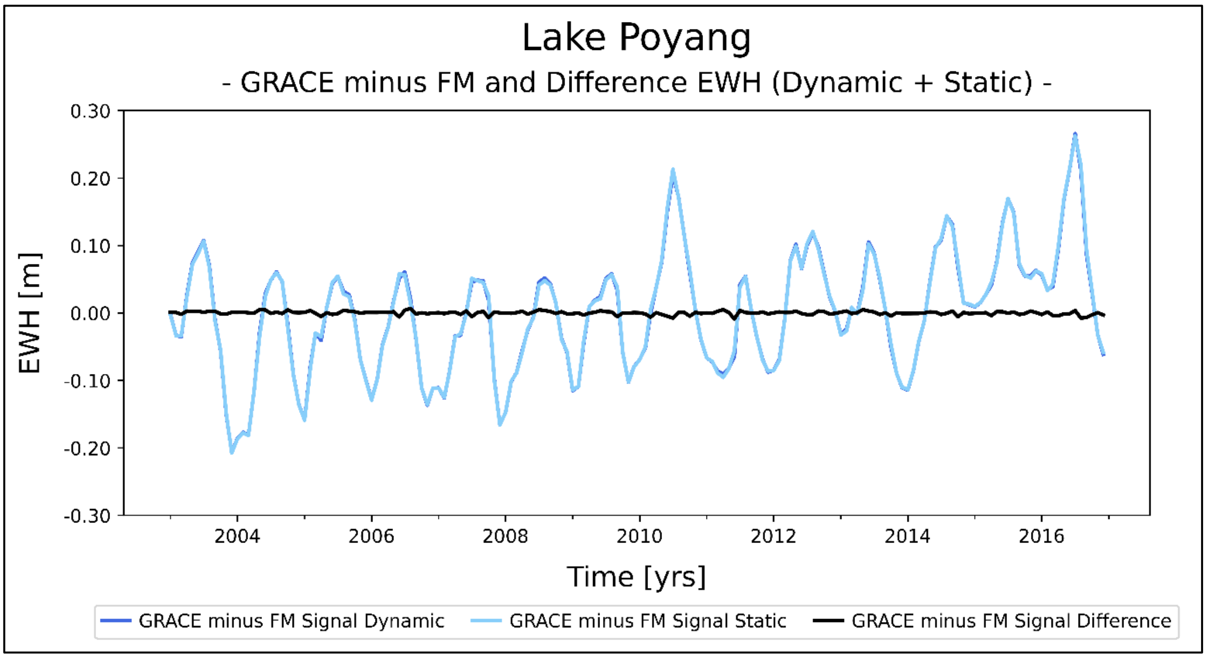

Figure 22: GRACE - FM and Difference EWH based on a dynamic and a static lake shape for the Lake Poyang

Source: Own representation in Python

To assess whether differences of the magnitude depicted in the Figure 22 can be seen from GRACE, the following Figure 23, was generated.

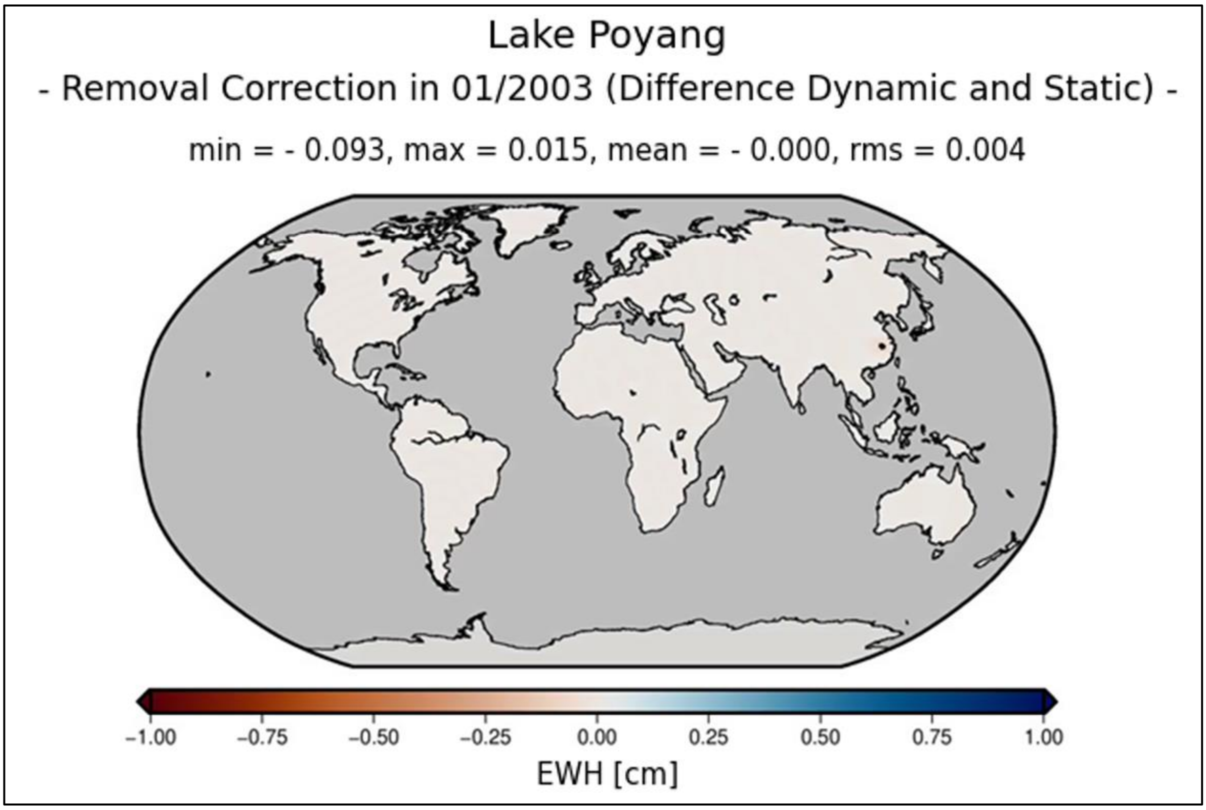

Figure 23: Removal correction difference in 01/2003 for the Lake Poyang

Source: Own representation in GROOPS and in Python

Thus, the Figure 23 illustrates the difference between the two removal corrections, which were computed from forward modelled equivalent water height values based on a dynamic shape of the Lake Poyang and forward modelled equivalent water height values based on a static shape of the Lake Poyang. As a result, the Figure 23 refers to the difference between the Figure 17 and the Figure 18 and although it only illustrates the respective difference for 01/2003, this month is representative for the remaining 167 months. Taken into consideration, that the satellite mission GRACE flies in an orbit that has an average altitude of approximately 450 km (Mohr, 2023), the Figure 23 shows, that the computed difference is at least not visible on a scale reaching from - 1 EWH [cm] to 1 EWH [cm]. Nevertheless, the statistical information on top of the figure indicates, that the two removal corrections for the Lake Poyang, which are presented by the forward modelled equivalent water height values, differ from - 0.093 cm to 0.015 cm. Those differences can be attributed to the fact, that the forward modelled equivalent water height values are computed for every single grid cell of the Lake Poyang. Thus, the values vary and as a consequence, the removal correction also fluctuates. Besides, the leakage effect also smears the signal, which means that the highest absolute forward modelled equivalent water height values occur in the center of the Lake Poyang and that their size decreases with an increasing distance. Despite of that, also a close-up look of the Lake Poyang, as it is shown in the Figure 24, only allows to gather a slight idea of the prevailing differences.

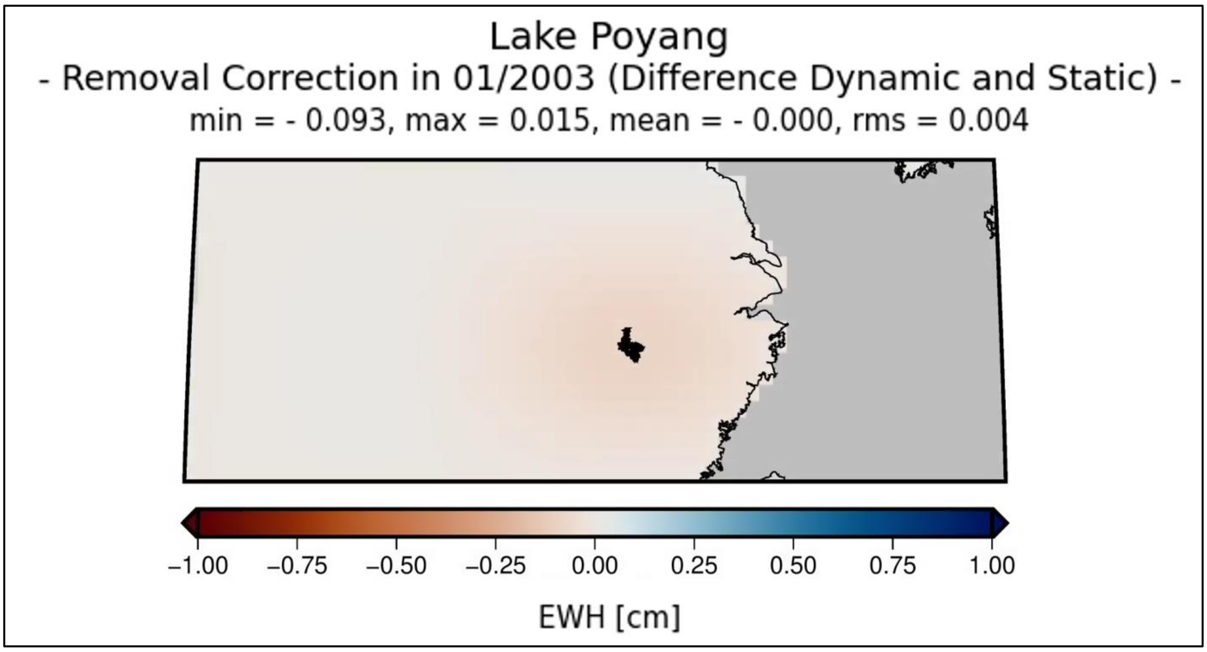

Figure 24: Close-Up of the computed removal correction difference in 01/2003 for the Lake Poyang

Source: Own representation in GROOPS and in Python

Hence, the differences between the two computed removal corrections can only be seen when the scale of the colour bar of the two figures is adjusted. In this case, the differences can be seen when adjusting the prevailing scale to - 0.10 EWH [cm] and 0.10 EWH [cm]. The results can be seen in the Figure 25 and the Figure 26. Thus, the leakage effect is also very well visible in both figures.

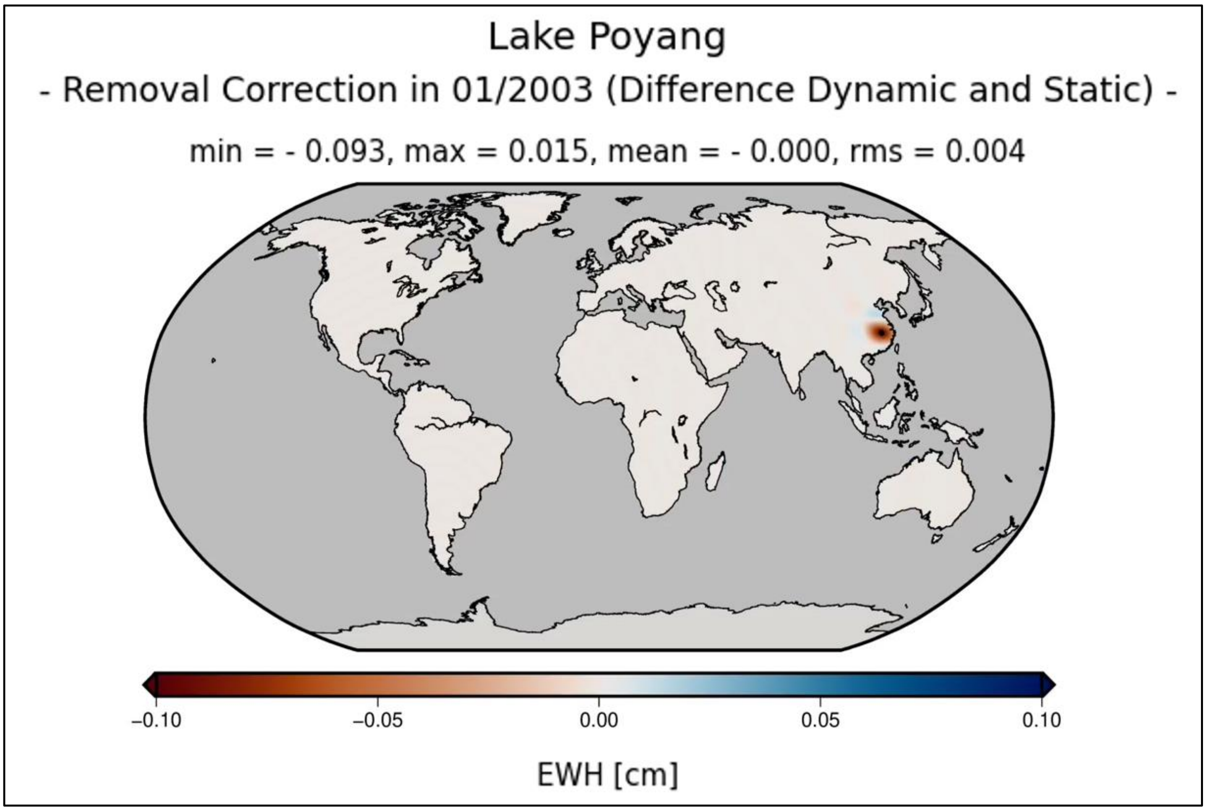

Figure 25: Removal correction difference in 01/2003 for the Lake Poyang with an adjusted scale of the colour bar

Source: Own representation in GROOPS and in Python

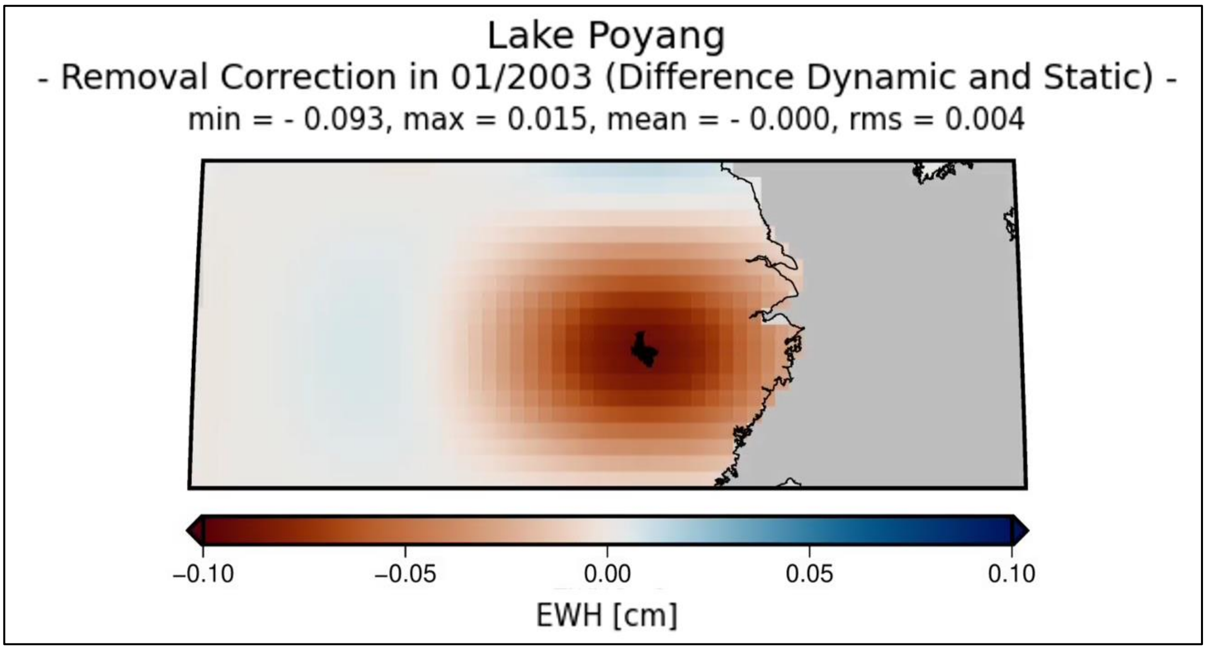

Figure 26: Close-Up of the computed removal correction difference in 01/2003 for the Lake Poyang with an adjusted scale of the colour bar

Source: Own representation in GROOPS and in Python

Hence, the consideration of a dynamic or a static water body shape influences the forward modelled equivalent water height values for the Lake Poyang in a magnitude of - 0.093 cm to 0.015 cm. In accordance to that, this magnitude can only be seen on a sub-millimetre scale. Despite of that, it has to be considered, that the Lake Poyang is the water body which indicates the largest surface area extent. Nonetheless, GRACE observes mass changes. Hence, it might be the case, that the difference between the consideration of a dynamic and a static water body shape is not driven by the size of a water body, but by its volume variation and thus in the last instance by its mass variation. Thus, GRACE might be more sensitive to volume variations than to surface area extents. Consequently, the following chapter 5.6 RESULT FOR THE LAKE SILING CO will focus on the water body Siling Co, which has the largest volume variation.

5.6 Result for the Lake Siling Co

To examine whether the consideration of a dynamic lake shape for a lake, which has a comparable large volume variation, will significantly influence the derived results, the forward modelled equivalent water height values, which were computed for the Lake Siling Co, will be investigated. In order to do so, the following Figure 27, was generated.

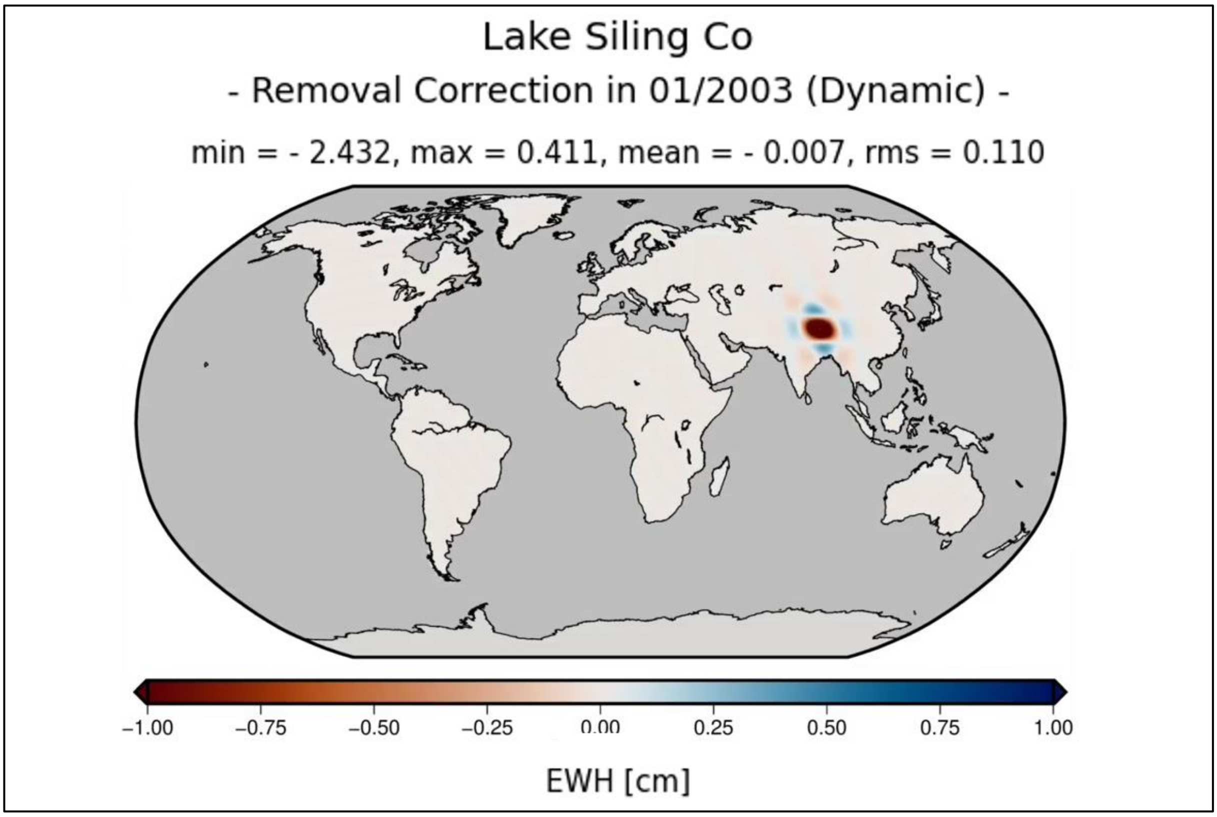

Figure 27: Removal correction in 01/2003 based on a dynamic lake shape for the Lake Siling Co

Source: Own representation in GROOPS and in Python

Similar to the Figure 17 and to the Figure 18, the Figure 27 also represents the first release of the monthly computed removal correction for 01/2003. The removal correction is expressed in terms of forward modelled equivalent water height values, which are indicated in the unit of centimetre. Consequently, the Figure 27 includes a dynamic lake shape for the Lake Siling Co. Hence, the forward modelled equivalent water height values range from - 2.432 cm to 0.411 cm. This results in an average equivalent water height value of - 0.007 cm. That means, that an average of - 0.007 cm equivalent water height has to be removed from the GRACE signal in order to withdraw the influence of the Lake Siling Co. The root mean square error equals 0.110 cm.

In comparison to the Figure 28, which is depicted below and which only contains equivalent water height values which were computed on the basis of a static water body shape, it can be seen that the statistical information deviates from the one provided in the Figure 27.

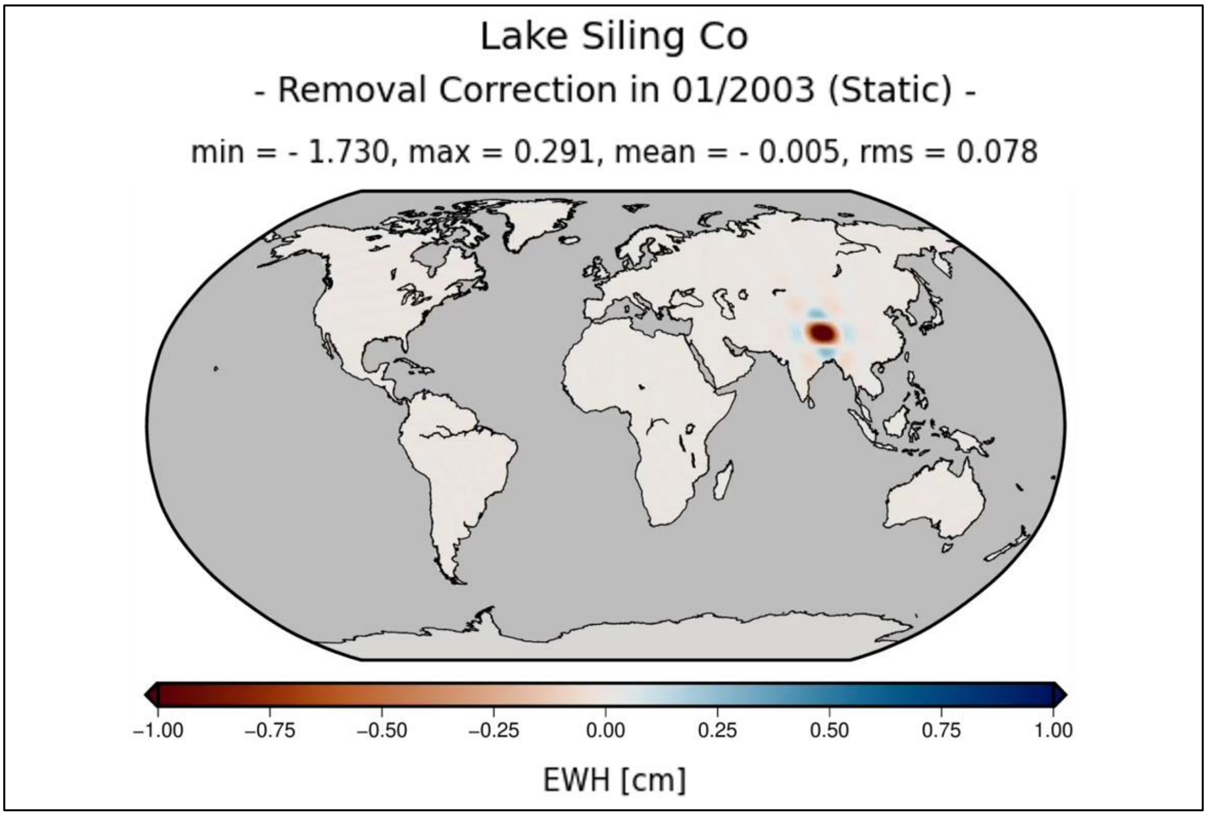

Figure 28: Removal correction in 01/2003 based on a static lake shape for the Lake Siling Co

Source: Own representation in GROOPS and in Python

This means, that the consideration of a dynamic water body shape for the Lake Siling Co has an influence. Based on the provided statistical information in the Figure 17, the Figure 18, the Figure 27 and the Figure 28, it can be seen that this influence is larger than the influence that a dynamic water body shape for the Lake Poyang causes. While the minimum and the maximum values from the Figure 17 cause a deviation from the underlying values in the Figure 18 from the first and second decimal place onwards, the values depicted the Figure 27 and the Figure 28 for Siling Co already deviate from the digit before the decimal point and the first decimal place onwards, respectively. Hence, the minimum value of the forward modelled equivalent water height values, which was computed on the basis of static water body shapes only, deviates from the respective value depicted in the Figure 27 by - 0.702 cm. Furthermore, also the maximum values of the forward modelled equivalent water height values deviate by 0.120 cm. Accordingly, the mean forward modelled equivalent water height values, which are provided in the Figure 27 and in the Figure 28, differ by - 0.002 cm. In comparison to the Figure 17, where the non-rounded mean forward modelled equivalent water height value only deviates by - 0.0003 cm to the one provided in the Figure 18, the influence that a water body with a large volume variation has, becomes evident. To further investigate this influence over time, the temporal variation of the forward modelled equivalent water height values was evaluated over a time frame reaching from 01/2003 to 12/2016. The result, which also includes the temporal variation of the GRACE signal and the temporal variation of the corrected GRACE signal, with the focus on the Lake Siling Co, is depicted in the Figure 29 below.

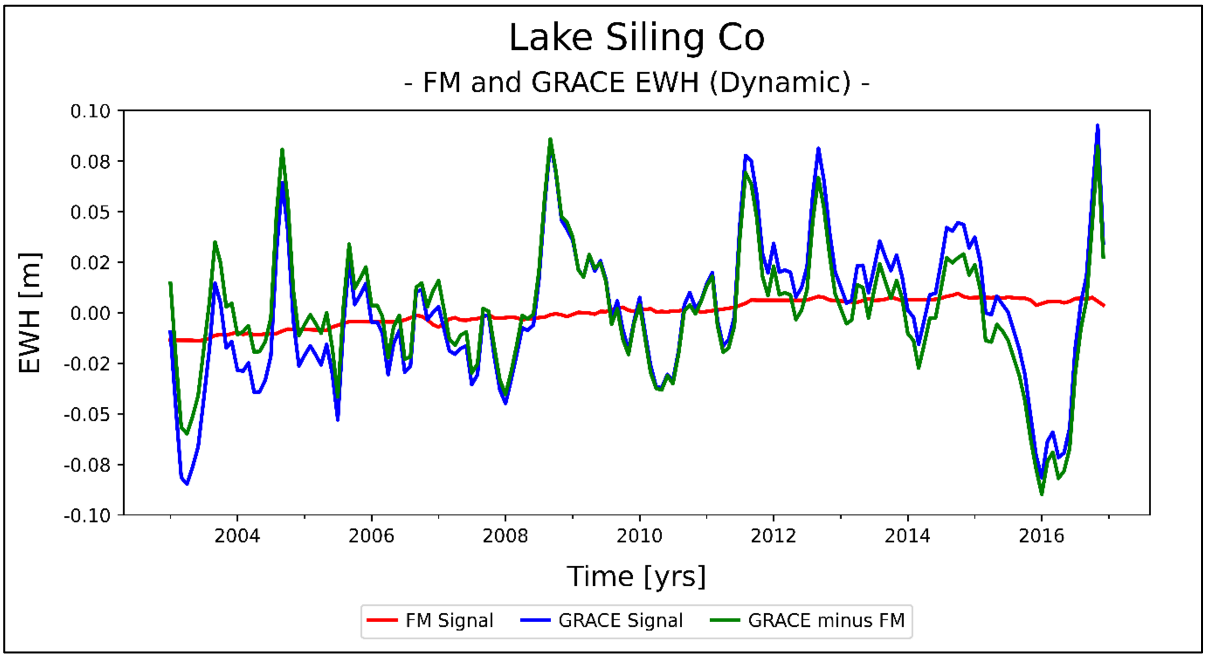

Figure 29: FM, GRACE and GRACE-FM EWH based on a dynamic water body shape for the Lake Siling Co

Source: Own representation in Python

Similar to the Figure 19 and the Figure 20, the Figure 29 illustrates three curves, whereas the red coloured curve represents the forward modelled equivalent water height values, the blue coloured curve visualizes the processed equivalent water height values, which were derived from GRACE observations, and the green coloured curve depicts the difference between the red coloured curve and the blue coloured curve. Hence, the forward modelled equivalent water height values of the red coloured curve, which refer to a dynamic lake shape of the Lake Siling Co, express the forward modelled gravity field and function as removal correction.

It can be seen, that the monthly forward modelled equivalent water height values fluctuate around 0.000 m, reaching their minimum value in 06/2003 where the forward modelled equivalent water height values reach - 0.014 m. In comparison to the Lake Poyang, it can be seen that the forward modelled equivalent water height values do not indicate a very strong annual and periodical behaviour. Nevertheless, very small peaks can be recognized towards the end of each year. Those small peaks are likely linked to the annual precipitation of the Plateau area, which mainly occurs from May to September (Liu & Chen, 2000), resulting in an average precipitation of 315 mm (Zhang et al., 2012). Furthermore, it is visible, that the forward modelled equivalent water height values slightly increase over the depicted time frame, reaching their maximum in 10/2014 with 0.010 m. This means, that also the water storage capacity of the Lake Siling Co increases. Such an increase was also observed by Tang et al., who stimulated the runoff process in the Siling Co basin from 2000 to 2016 in order to estimate the water storage changes of the Lake Siling Co. Their results showed, that the water storage capacity of the Lake Siling Co has increased by 1.2 billion m^3/year and that the lake area continues to expand (Tang et al., 2022). This increase is mainly linked to an incline of the water level and to a rapid expansion of the surface area from 2003 to 2013. Within this time frame, the surface area of the Lake Siling Co increased to 2318 km^2, which corresponds to a growth ratio of 14.6 % and an annual growth rate of 26.84 km^2 / year (Yi & Zhang, 2015). These results can also be confirmed when evaluating the surface area time series of the Lake Siling Co provided by the DAHITI database (Deutsches Geodätisches Forschungsinstitut, n.d.). By means of that, the Lake Siling Co gains volume and thus also mass. This mass gain from 2003 to 2013 is not only visible in the temporal variation of the forward modelled equivalent water height values, but also in the blue coloured curve, which represents the processed equivalent water height values which were derived from GRACE observations. Here, the processed equivalent water height values indicate a global minimum of - 0.085 m and a global maximum of 0.093 m. While the global minimum is reached in 01/2016, the global maximum occurs in 11/2016. Consequently, also the processed equivalent water height values, which were derived from GRACE observations, indicate a peak towards the end of each year, which is then followed by a steep decline. This decline persists until the beginning of the following year, where the processed equivalent water height values start to increase again. Since the processed equivalent water height values refer to the entire water column, meaning that the GRACE signal does not only contain the surface water body itself, but also other storage compartments such as groundwater or soil moisture, the magnitude of the signal and thus the magnitude of the annual peaks is much larger than the peaks of the forward modelled equivalent water height values. Finally, the green coloured curve illustrates the corrected GRACE signal. Hence, it refers to the subtraction of the red coloured curve from the blue coloured curve and thus expresses the temporal variation of the GRACE signal if the influence of the Lake Siling Co would be removed. Since the forward modelled equivalent water height values have a larger value span than those which were computed for the Lake Poyang, the temporal variation of the GRACE signal and the corrected GRACE signal also indicates a larger deviation. Since the Lake Siling Co is not influenced by a strong annual signal, those differences also do not only occur in the local minimum and maximum points, as they did for the Lake Poyang. The global minimum of the corrected equivalent water height values is - 0.090 m, which is reached in 01/2016. The highest corrected equivalent water height value is 0.086 m and appears in 09/2008. Therewith, the processed equivalent water height values, which were derived from GRACE observations and the corrected equivalent water height values, indicate their respective global minimum values in the same month and their global maximum values in different months.

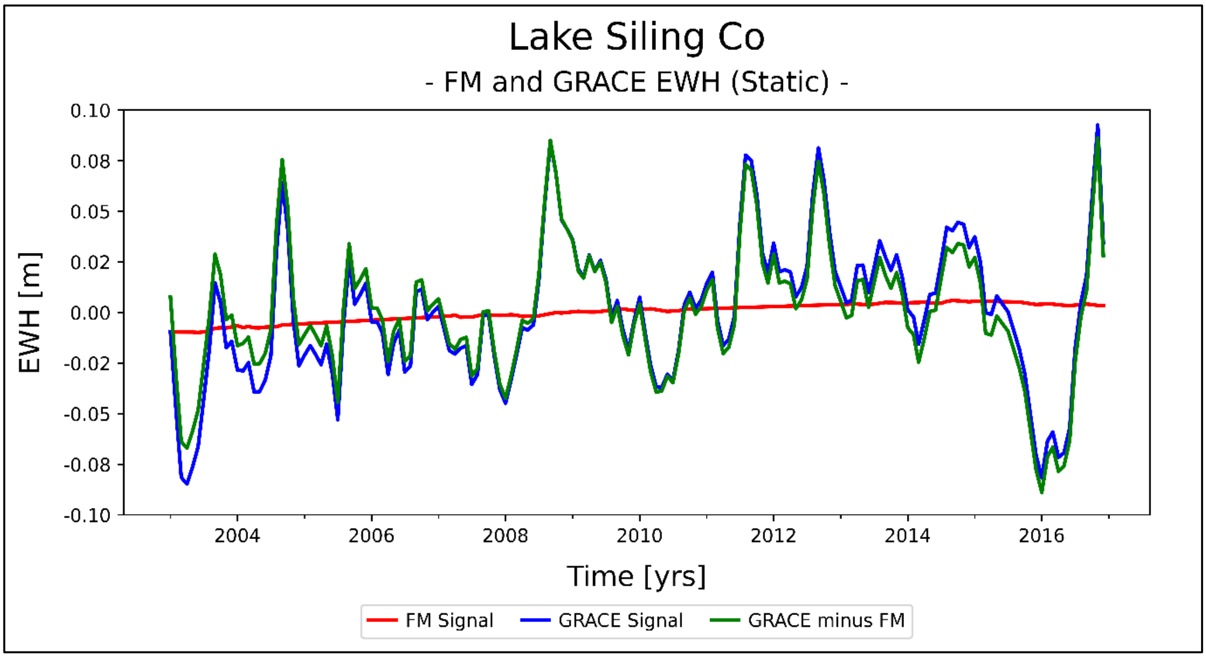

Figure 30: FM, GRACE and GRACE-FM EWH based on a static water body shape for the Lake Siling Co

Source: Own representation in Python

When comparing the temporal variation of the three curves between the Figure 29 and the Figure 30, which only differ in the aspect that a static shape was used in the Figure 30, it can be seen, that the overall temporal variation of all three curves is similar to the behaviour of the three curves depicted in the Figure 29. Nevertheless, the forward modelled equivalent water height values slightly differ. While they reach a minimum value of - 0.014 m in 06/2003 and a maximum value of 0.010 m in 10/2014 in the Figure 29, the minimum value now accounts - 0.010 m and occurs in 06/2003. In addition, the maximum value does not occur in 10/2014 anymore, but in 09/2014. Besides, it is also by 0.004 m smaller and equals 0.006 m. Since the processed equivalent water height values, which were derived from GRACE observations, remain the same, the corrected equivalent water height values, which function as removal correction, also slightly differ. By means of that, the corrected equivalent water height values range from - 0.090 m in 01/2016 to 0.086 m in 09/2008. Hence, the fact whether a dynamic or a static lake shape is used, slightly influences the temporal variation and the magnitude of removal correction and thus also the corrected GRACE signal.

To further quantify this difference, the forward modelled equivalent water height values were investigated to a greater extent. Hence, an additional figure, which does not only illustrate the forward modelled equivalent water height values which were computed on the basis of a dynamic and a static lake shape for the Lake Siling Co, but also the difference between those two forward modelled equivalent water height values, visualized on a smaller scale, was generated. The outcome is depicted in the Figure 31.

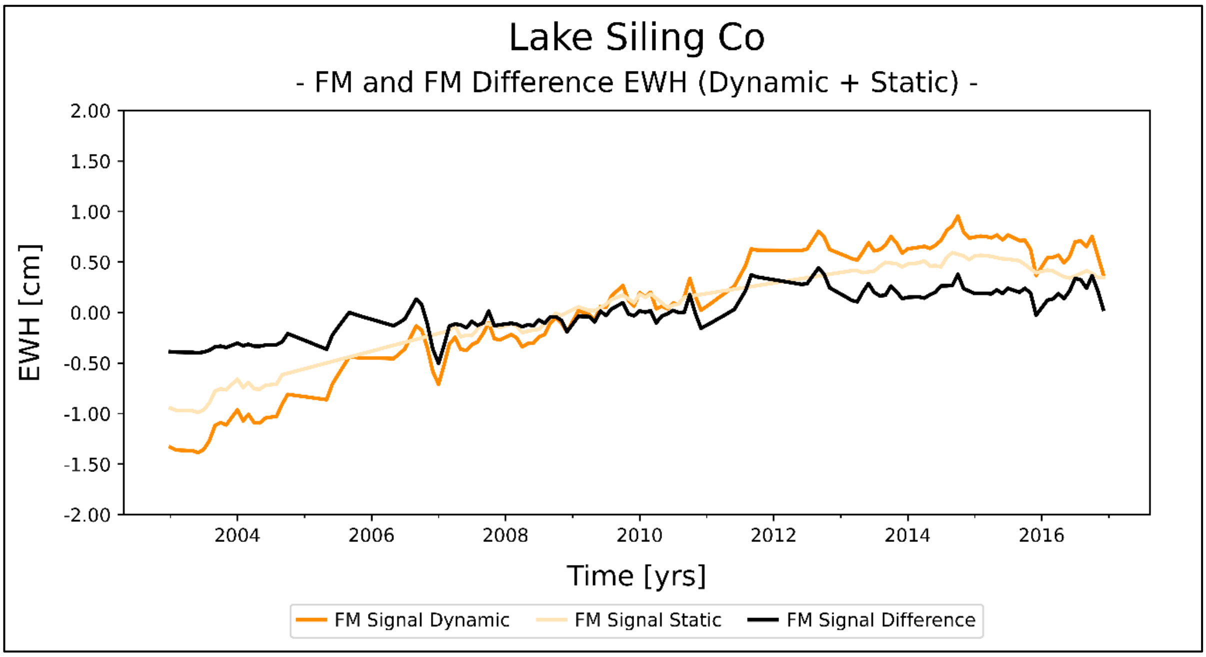

Figure 31: FM and FM difference EWH based on a dynamic and a static lake shape for the Lake Siling Co

Source: Own representation in Python

Hence, the Figure 31 illustrates the temporal variation of the forward modelled equivalent water height values, which were computed on the basis of a dynamic and a static lake shape respectively. While the forward modelled equivalent water height values, which were computed on the basis of a dynamic lake shape, are coloured in orange, the forward modelled equivalent water height values, which were computed under the consideration of the static lake shape, are coloured in yellow. By changing the unit of the y-axis from metre to centimetre, it becomes even clearer, that the equivalent water height values differ in the magnitude of millimetres.

The exact magnitude can be derived from the black coloured curve, which refers to the difference between the other two curves. Hence, the equivalent water height values, which refer to a static lake shape, are subtracted from those which refer to a dynamic water body shape. This difference faces a temporal variation. It has a global minimum value of - 0.503 cm, which occurs in 01/2007 and a global maximum value of 0.440 cm. This global maximum value is reached in 09/2012. The absolute mean value of the difference is 0.186 cm.

Comparing the difference between the forward modelled equivalent water height values derived from a dynamic water body shape and those derived from a static water body shape for the Lake Poyang and the Lake Siling Co, which is also depicted in the Figure 32, it can be seen that both differences range between - 0.600 cm and 0.600 cm. Despite of that, it can also be seen, that the computed difference for the Lake Siling Co, which is presented by the light grey coloured curve, deviates stronger from zero. This behaviour is also indicated by the mean value. While the mean value of the difference curve for the Lake Poyang is 0.107 cm, the average absolute deviation of the difference curve for the Lake Siling Co is 0.186 cm. Considering, that the Lake Poyang is the largest lake of the considered water bodies and that the Lake Siling Co is the lake which has the largest volume variation, the thesis, that the consideration of a dynamic lake shape is more important for water bodies, which face a large volume variation, is further supported.

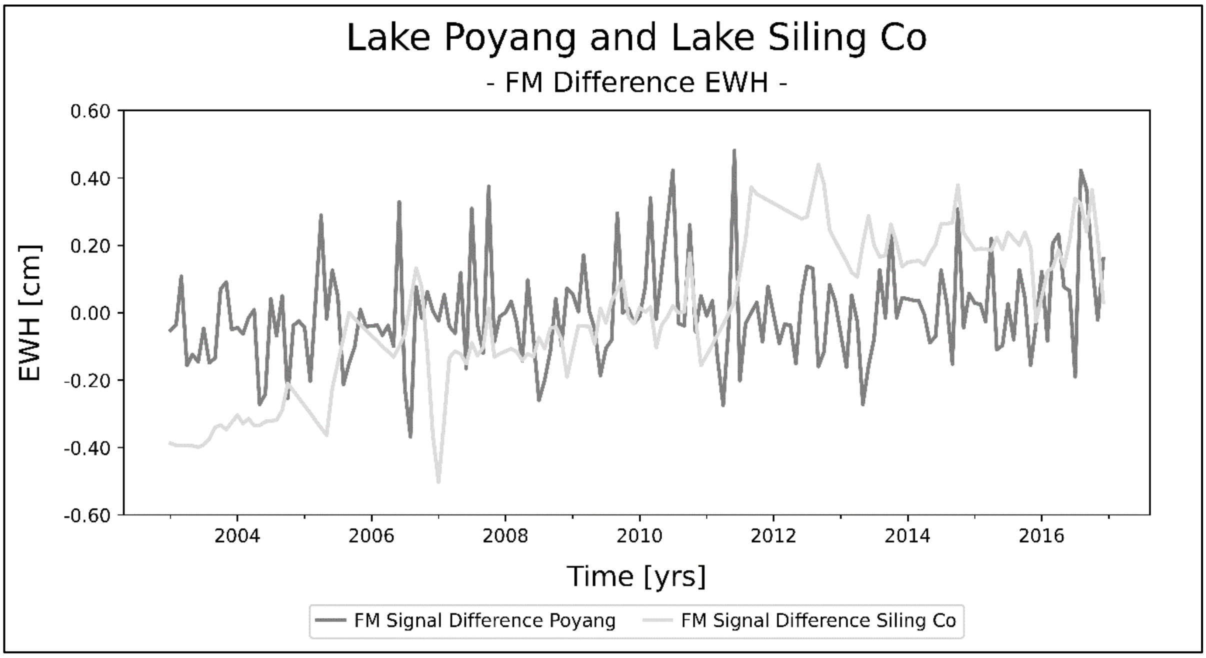

Figure 32: FM difference EWH for the Lake Poyang and the Lake Siling Co

Source: Own representation in Python

This can also be seen when comparing the temporal variation of the corrected equivalent water height values, which were computed under the consideration of a dynamic water body shape, with the temporal variation of corrected equivalent water height values, which were derived on the basis of a static water body shape for the Lake Siling Co. The difference between the respective dark blue coloured curve and the light blue coloured curve is illustrated by the black coloured curve. The equivalent water height values of this black coloured difference curve range from a minimum of - 0.008 m in 09/2012 to a maximum of 0.009 m in 01/2007, resulting in an absolute mean value and thus in an absolute mean deviation of 0.003 m. Consequently, the consideration of a dynamic or a static water body shape for the Lake Siling Co causes an average absolute deviation of the corrected equivalent water height values of 0.003 m.

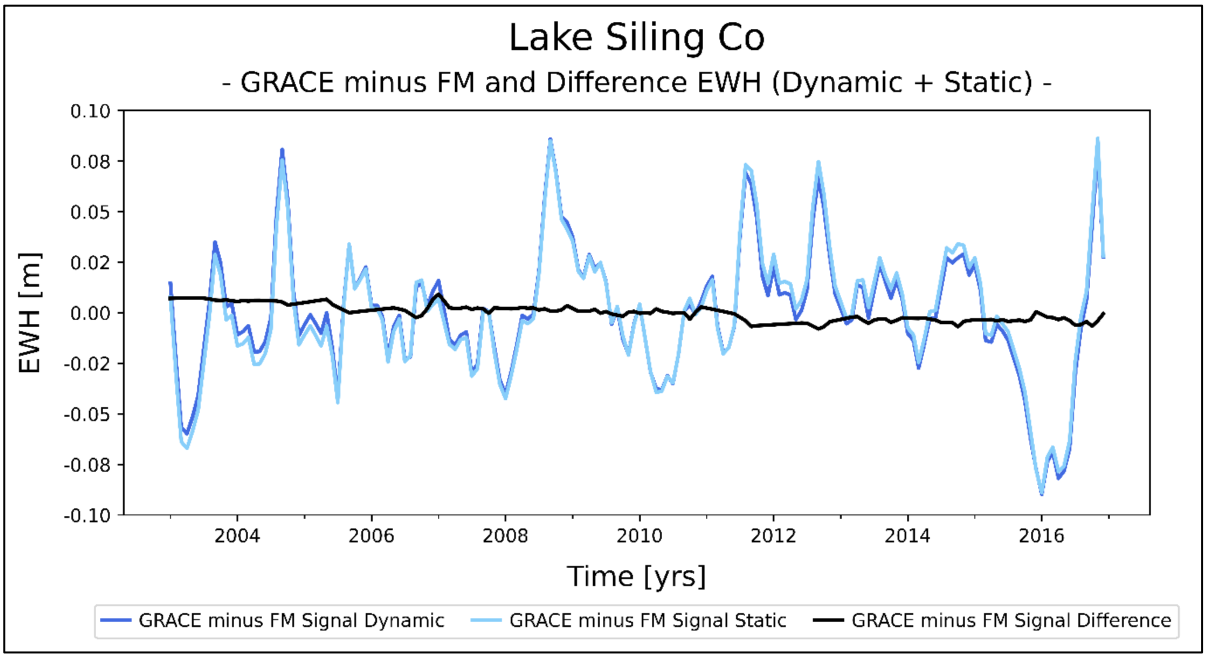

Figure 33: GRACE - FM and Difference EWH based on a dynamic and a static lake shape for the Lake Siling Co

Source: Own representation in Python

In comparison to the Figure 22, where the difference between the two blue curves is difficult to assess with the bare eye, the difference depicted in the Figure 33, which refers to the Lake Siling Co, is clearer. Hence, it is easier to distinguish between the dark blue coloured curve and the light blue coloured curve. Consequently, this absolute deviation of 0.003 m between the two corrected signals for the Lake Siling Co contrasts the computed average absolute deviation of 0.002 m for the Lake Poyang. A comparison of the two difference curves, each representing the difference of the corrected GRACE signal under the consideration of a dynamic and a static water body shape respectively, can be seen in the Figure 34. Hence, the Figure 34 shows, that the light grey coloured curve has a larger deviation from zero and hence, the consideration of a dynamic water body shape has also a larger influence on the Lake Siling Co. Consequently, the comparison between the Lake Poyang and the Lake Siling Co shows, that the consideration of an either dynamic or a static water body shape has a stronger impact on water bodies which have a strong volume variation rather than on water bodies which have a large surface area extent. Thus, the forward modelled equivalent water height values differ to a larger extent and thus also the removal correction has a larger influence on the GRACE signal. Based on these two investigated water bodies, it can be said, that the consideration of a dynamic water body shape is generally more crucial for water bodies which have a large volume variation.

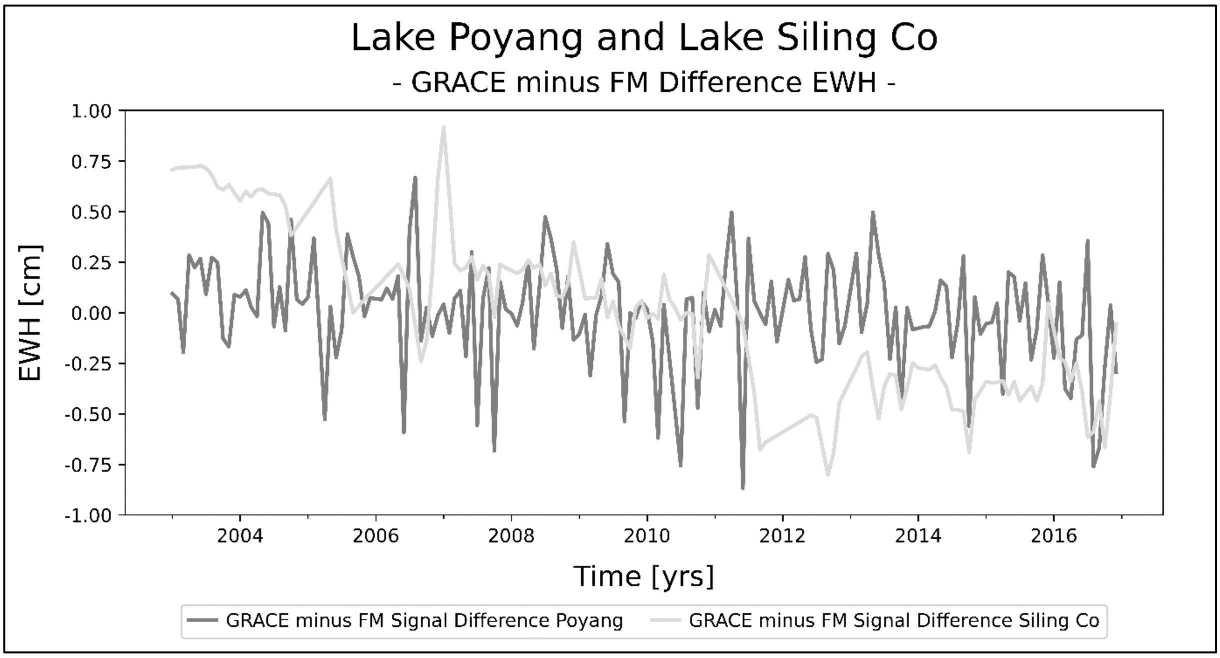

Figure 34: GRACE-FM difference EWH for the Lake Poyang and the Lake Siling Co

Source: Own representation in Python

Nevertheless, the question remains whether the resulting differences concerning the removal correction, can actually be detected by the satellite mission GRACE. Reviewing the corresponding Figure 35 for 01/2003 on the top of the following page, it can be seen, that the influence can already be detected on the initial scale, which reaches from - 1 EWH [cm] to 1 EWH [cm]. Hence, the scale of the colour bar does not have to be adjusted.

Despite of that, it has to be considered that the forward modelled equivalent water height values and thus also the removal correction, underly a temporal variation. This temporal variation is also illustrated by the fluctuations of the light grey coloured curve which is depicted in the Figure 32. In accordance to that, it was detected, that the monthly difference between the two computed removal corrections for the Lake Siling Co, is not visible on all generated figures in the selected time frame reaching from 01/2003 to 12/2016. An example for this would be 11/2009, which is depicted in the Figure 36 at the bottom of the following page.

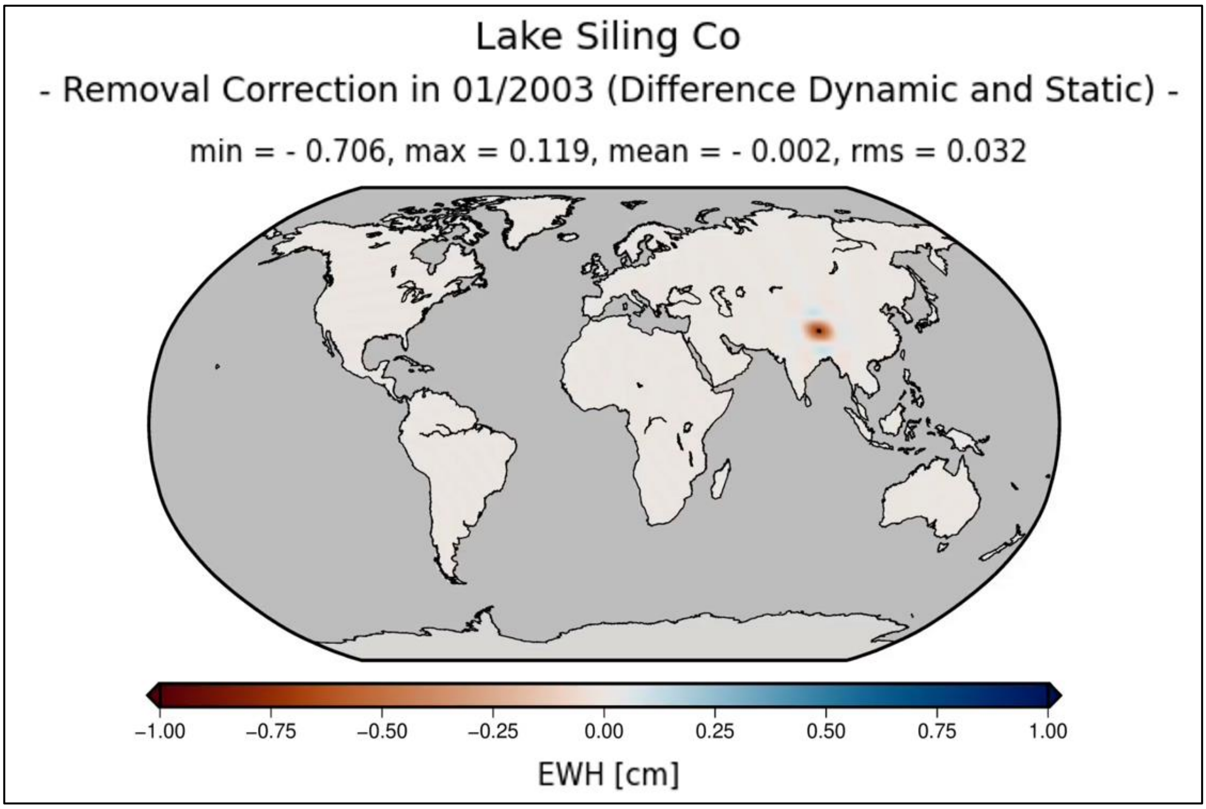

Figure 35: Removal correction difference in 01/2003 for the Lake Siling Co

Source: Own representation in GROOPS and in Python

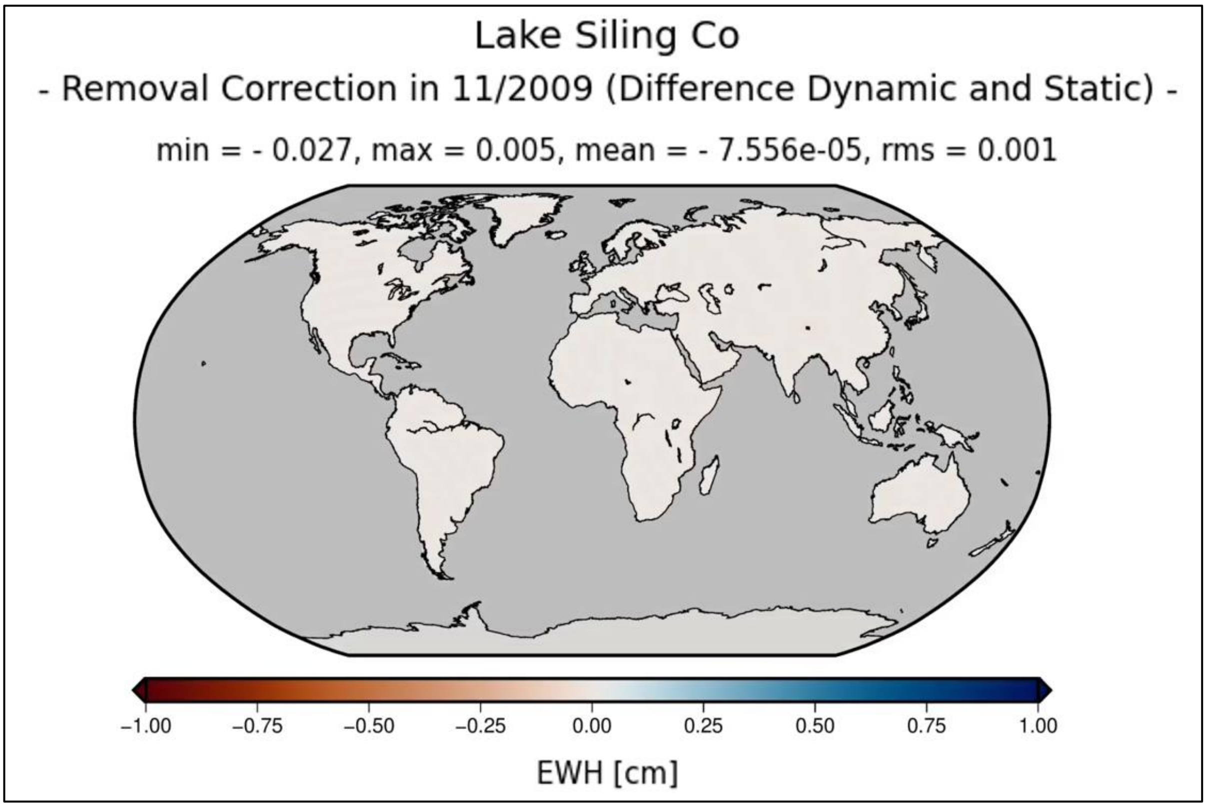

Figure 36: Removal correction difference in 11/2009 for the Lake Siling Co

Source: Own representation in GROOPS and in Python

In this case, the Figure 36 illustrates the difference between the removal correction that was computed under the consideration of a dynamic water body shape and the removal correction that was derived on the basis of a static water body shape in 11/2009. By evaluating the respective forward modelled equivalent water height values for the Lake Siling Co in the Figure 32 for this respective point in time, it can be seen, that the light grey curve reaches a to three digits rounded equivalent water height value of - 0.000 m. Consequently, the difference is not visible for GRACE and the scale of the colour bar has to be adjusted. The result can be seen in the Figure 37.

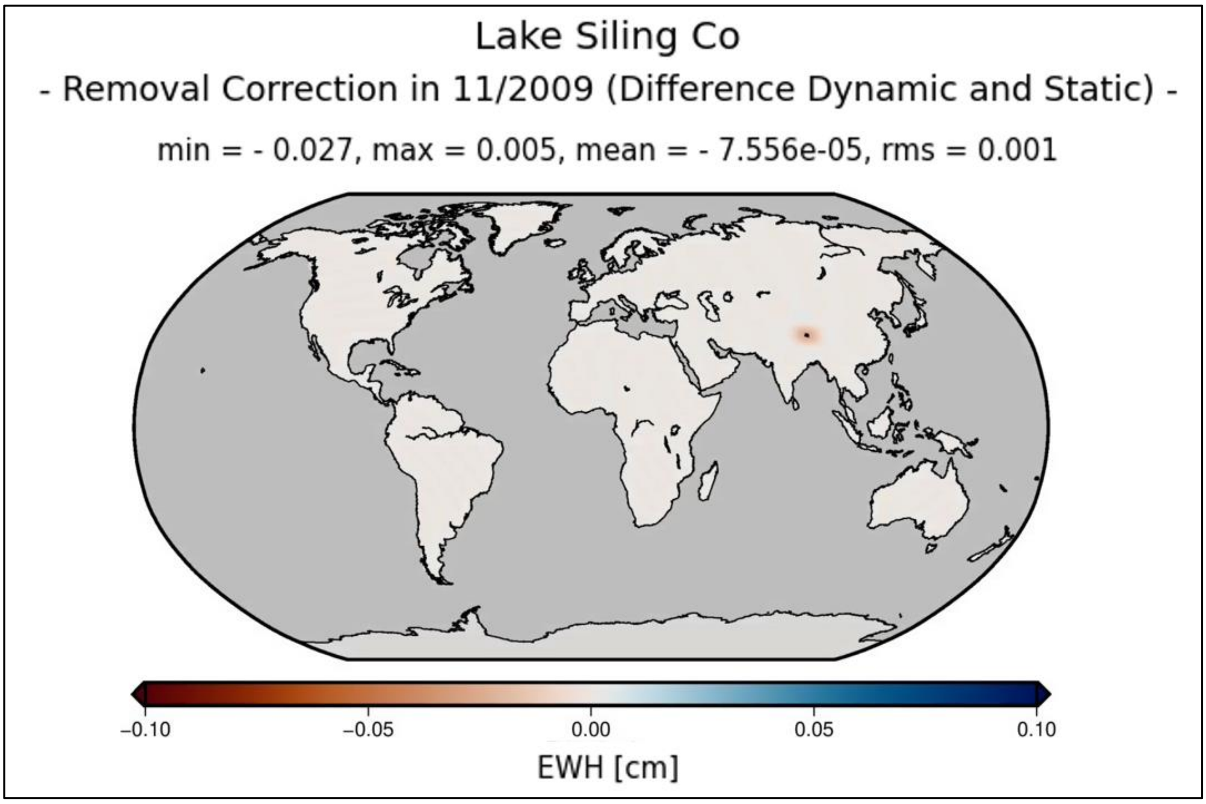

Figure 37: Removal correction difference in 11/2009 for the Lake Siling Co with an adjusted scale of the colour bar

Source: Own representation in GROOPS and in Python

Hence, the question whether the difference will be visible or not, depends on the magnitude of the forward modelled equivalent water height values.

5.7 Result for the Lake Tharthar

To assess whether the volume variation difference has a significant influence on the decision whether a dynamic or a static water body shape should be selected, an additional water body, being the Lake Tharthar, was investigated. For the purpose of that, the Figure 38 shows, that the difference between the forward modelled equivalent water height values, which were computed on the basis of a dynamic and a static water body shape for the Lake Tharthar respectively, varies between - 0.305 cm in 04/2011 and 0.262 cm in 05/2004, which results in an absolute mean deviation of 0.048 cm. This mean value refers to the absolute mean value of the black curve, which is also illustrated in the Figure 38.

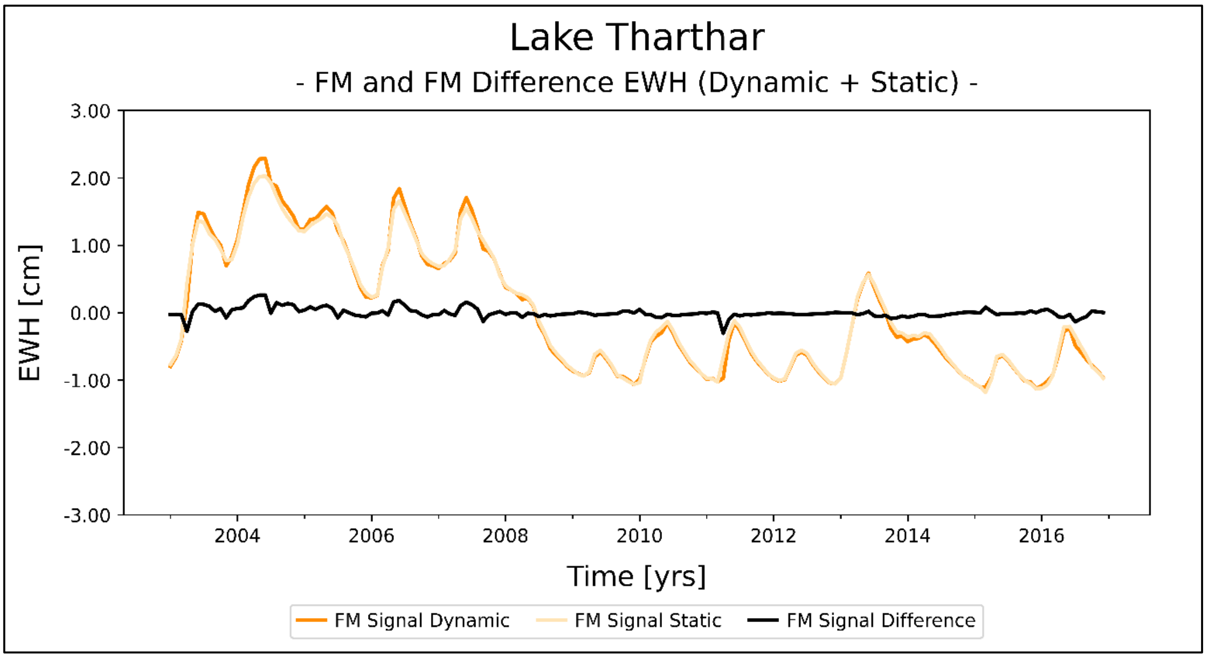

Figure 38: FM and FM difference EWH based on a dynamic and a static lake shape for the Lake Tharthar

Source: Own representation in Python

The influence that this difference has when subtracting the respective forward modelled equivalent water height values from the GRACE signal, is illustrated in the Figure 39 below.

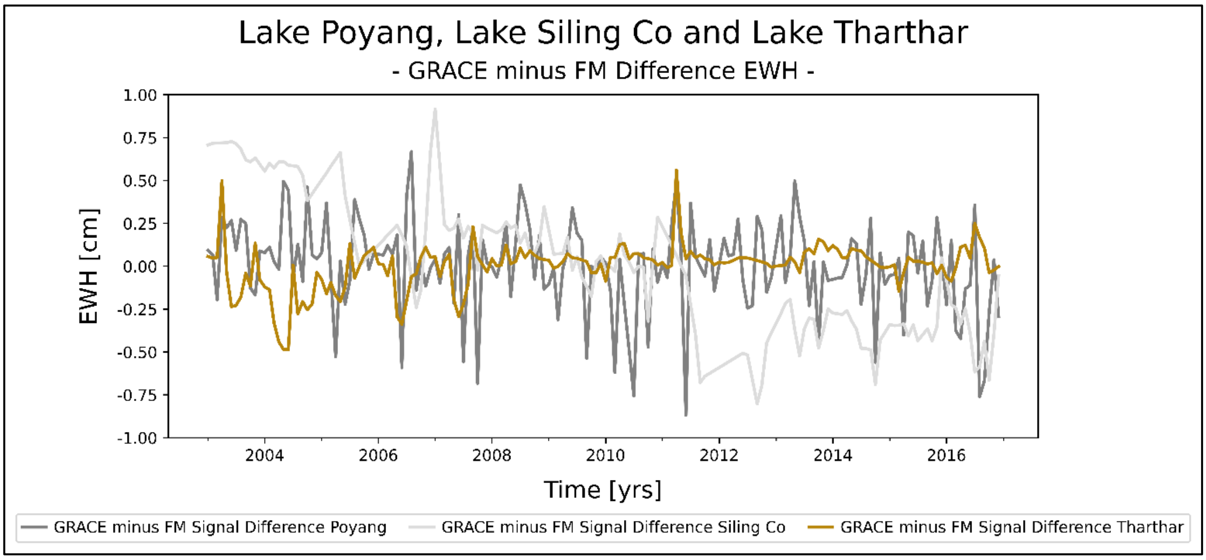

Figure 39: GRACE-FM difference EWH for the Lake Poyang, the Lake Siling Co and the Lake Tharthar

Source: Own representation in Python

In comparison to the two other investigated lakes the Lake Poyang and the Lake Siling Co, which are also depicted in the Figure 39, it can be seen, that the computed difference for the

Lake Tharthar is in the magnitude of the difference values which were also computed for the other two lakes. While the consideration of a dynamic or a static water body shape causes an average absolute deviation of the corrected equivalent water height values of 0.2 cm for the Lake Poyang and 0.3 cm for the Lake Siling Co, the average absolute deviation for the Lake Tharthar amounts 0.1 cm. Consequently, the Lake Tharthar, which has the largest volume variation difference, is least influenced. Since the difference between the consideration of a dynamic and a static water body shape is marginal, it can also not be seen from the satellite mission GRACE on the initial scale of the colour bar, reaching from - 1 EWH [cm] to 1 EWH [cm]. Similar to the result derived for the Lake Poyang, the scale of the colour bar has to be adjusted to - 0.1 EWH [cm] and 0.1 cm [EWH]. Only then, the difference between the consideration of a dynamic and a static water body shape for the Lake Tharthar, becomes visible. The result can also be seen in the Figure 40.

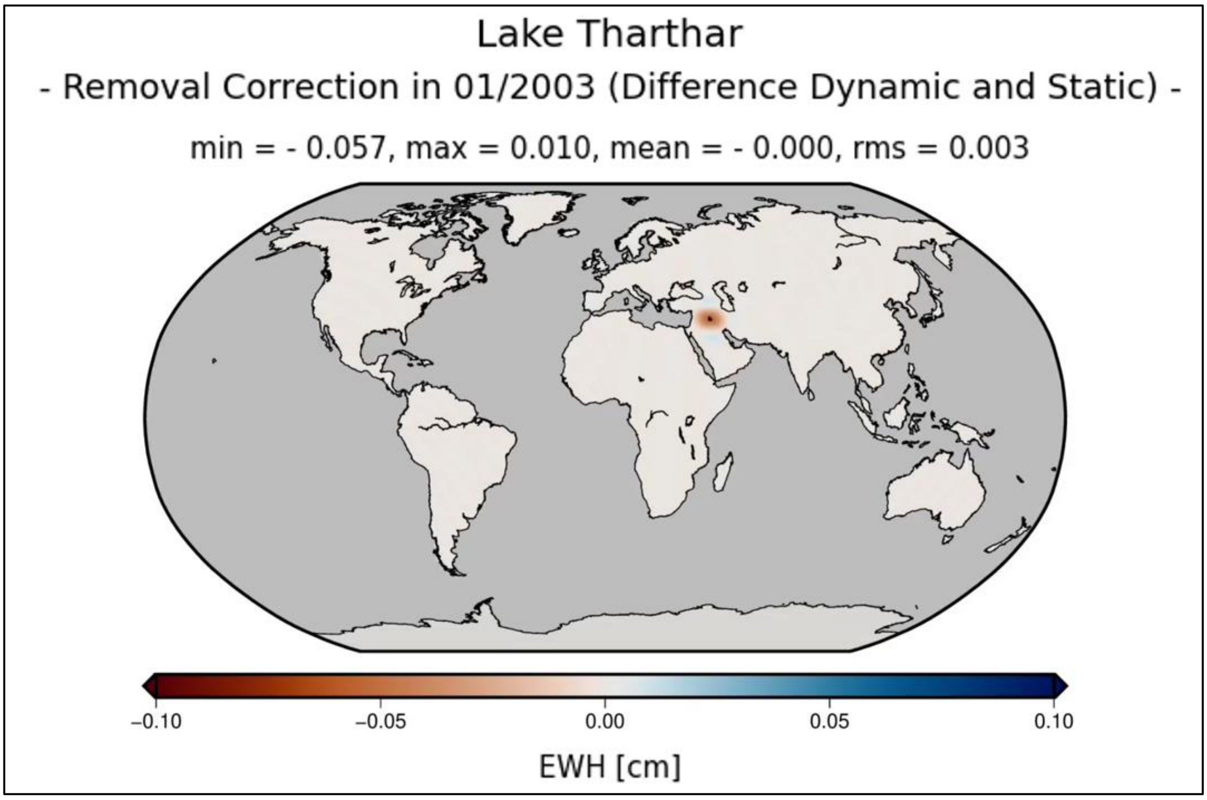

Figure 40: Removal correction difference in 01/2003 for the Lake Tharthar with an adjusted scale of the colour bar

Source: Own representation in GROOPS and in Python

Hence, the Figure 40 also indicates, that the difference of the two removal corrections, which were computed under the consideration of a dynamic and a static water body shape respectively, varies from a minimum value of - 0.057 cm to a maximum value of 0.010 cm in 01/2003.

5.8 Result for all Water Bodies

So far, the investigation has shown, that the consideration of an either dynamic or a static surface has an influence of the computed forward modelled equivalent water height values which then function as removal correction. Nevertheless, the investigation has also shown, that the influence of dynamic and static water body shapes varies from water body to water body. Since an extensive study of all 29 considered water bodies would exceed the scope of this study, the retrieved results are summarised in the following Figure 41 below. Hence, the Figure 41 illustrates the temporal variation of all forward modelled equivalent water height difference values. Those difference values refer to the difference between the forward modelled equivalent water height values, which were computed under the consideration of dynamic and static water body shapes respectively. Subsequently, the Figure 41 shows, that all forward modelled equivalent water height difference values indicate a temporal variation that fluctuates within a frame of - 0.529 cm to 0.588 cm. The boundary values for this frame are set by the green coloured curve, which refers to the equivalent water height difference values which were computed for the Lake Mead.

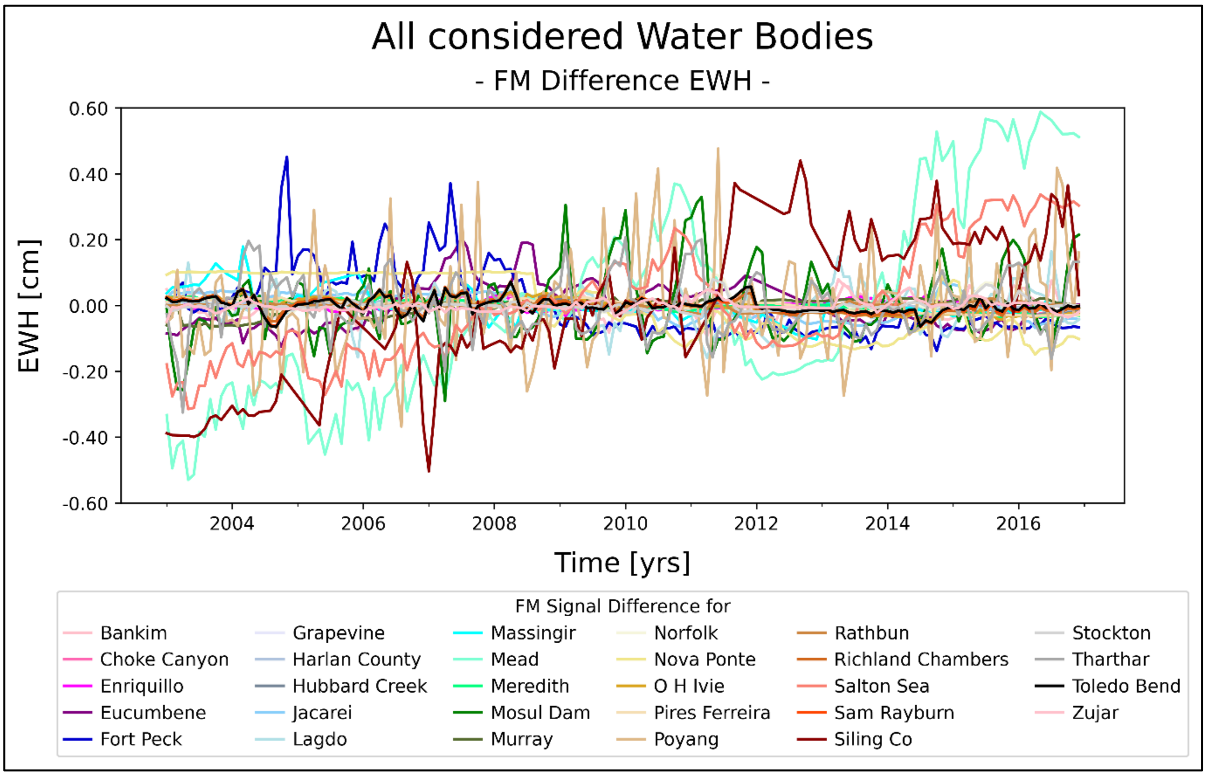

Figure 41: FM difference EWH based on a dynamic and a static lake shape for all considered water bodies

Source: Own representation in Python

Consequently, it can be assumed that the difference between the consideration of a dynamic and a static water body shape has the largest impact on the Lake Mead. To numerically quantify this assumption, the mean value of each curve depicted in the Figure 41 was computed. The result is visualized in the Figure 42. Subsequently, the Figure 42 illustrates, that the computed mean difference values vary between 0.006 cm for the Reservoir Rathbun to 0.243 cm for the Lake Mead. Consequently, the Figure 42 confirms, that the decision, whether a dynamic or a static water body shape should be considered throughout the forward modelling procedure, has the largest impact on the forward modelled equivalent water height values of the Lake Mead. The second largest difference occurs for the Lake Siling Co, which is followed by the Lake Salton Sea. The respective difference values equal 0.186 cm and 0.139 cm.

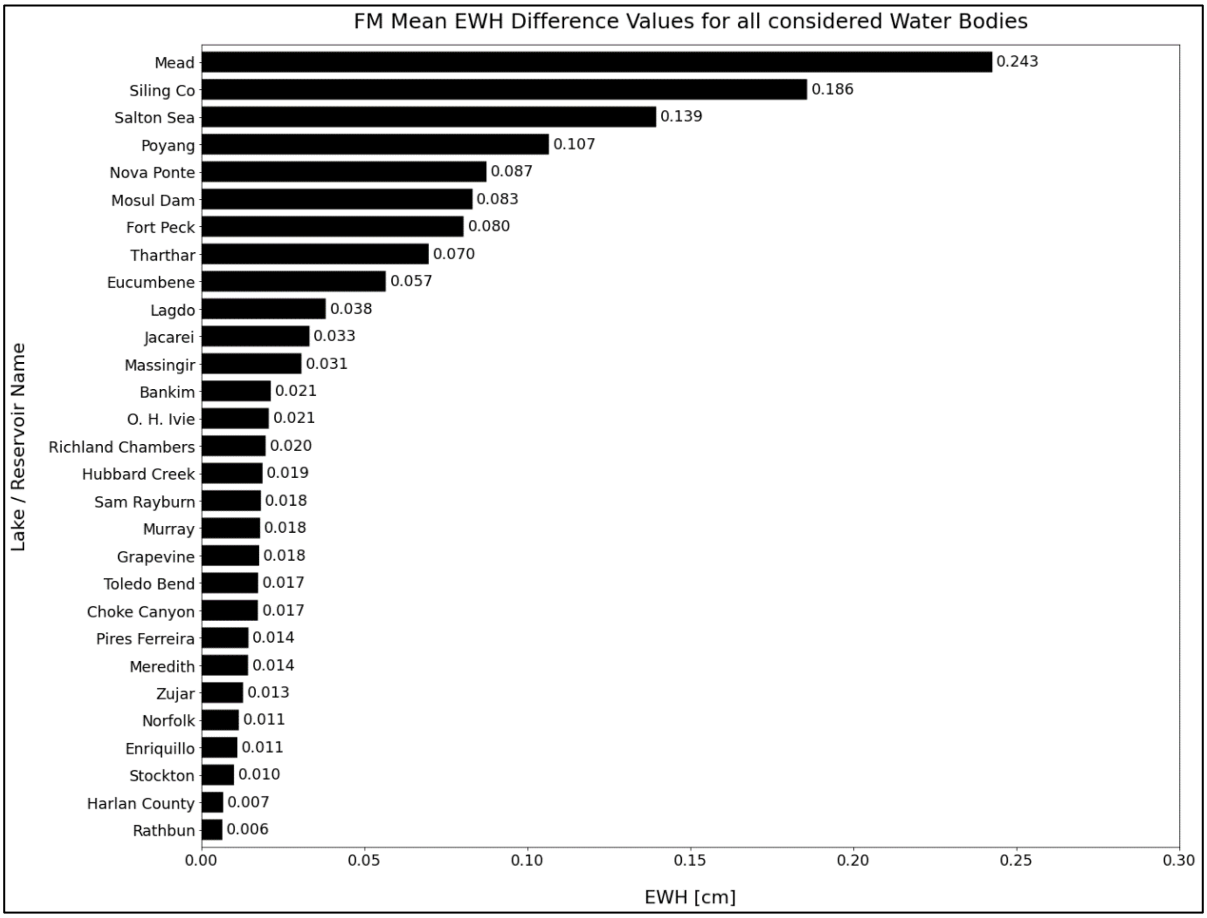

Figure 42: FM Mean EWH Difference values for all considered water bodies

Source: Own representation in Python

Despite of that, the Figure 43 shows, that only the computed difference values for the Lake Mead, which is located on the west coast of the United States of America and the Lake Siling Co, which is situated in the northern Tibetan Plateau of China, can clearly be seen from the satellite mission GRACE. The difference values of the remaining 27 water bodies, which are also depicted in the Figure 42, gather a higher visibility when the scale of the colour bar is adjusted. The outcome is depicted in the Figure 44, which is located on the bottom of the following page. Subsequently, the scale of the colour bar was adjusted from -1 EWH [cm] and 1 EWH [cm] to - 0.10 EWH [cm] and 0.10 EWH [cm].

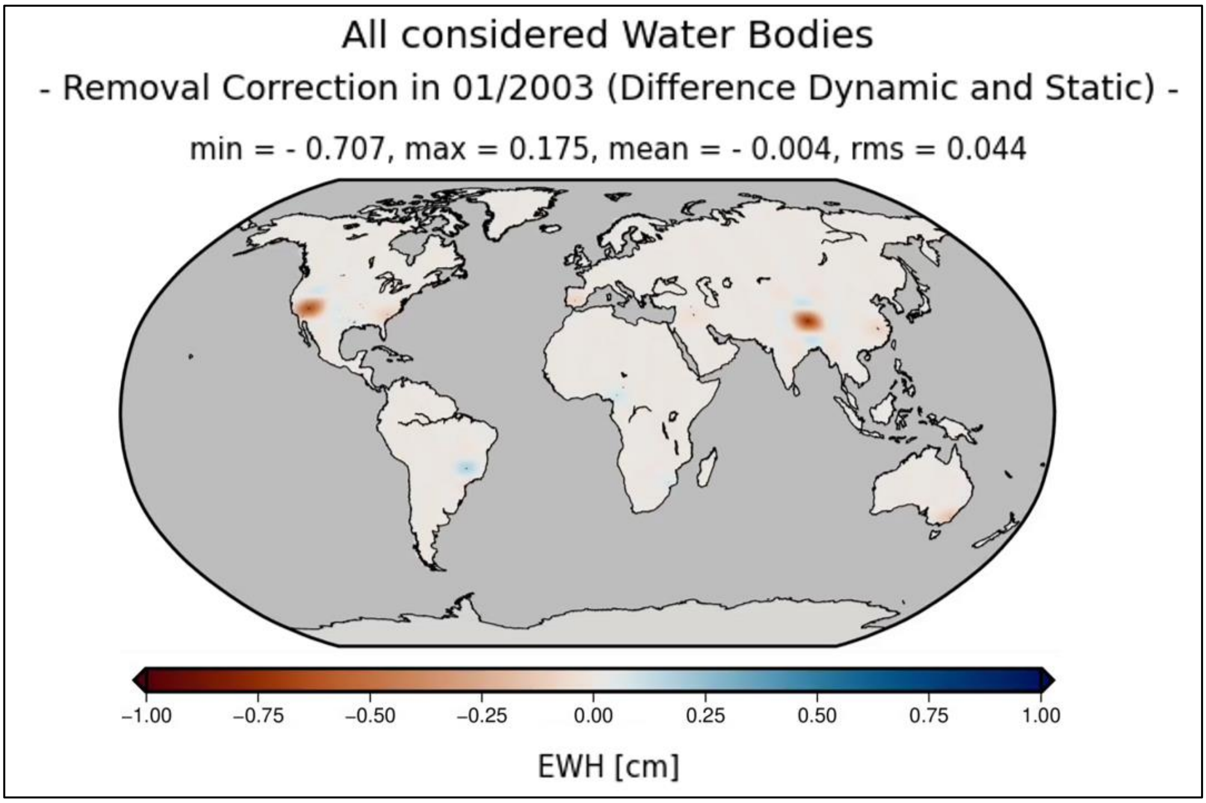

Figure 43: Removal correction difference in 01/2003 for all considered water bodies

Source: Own representation in GROOPS and in Python

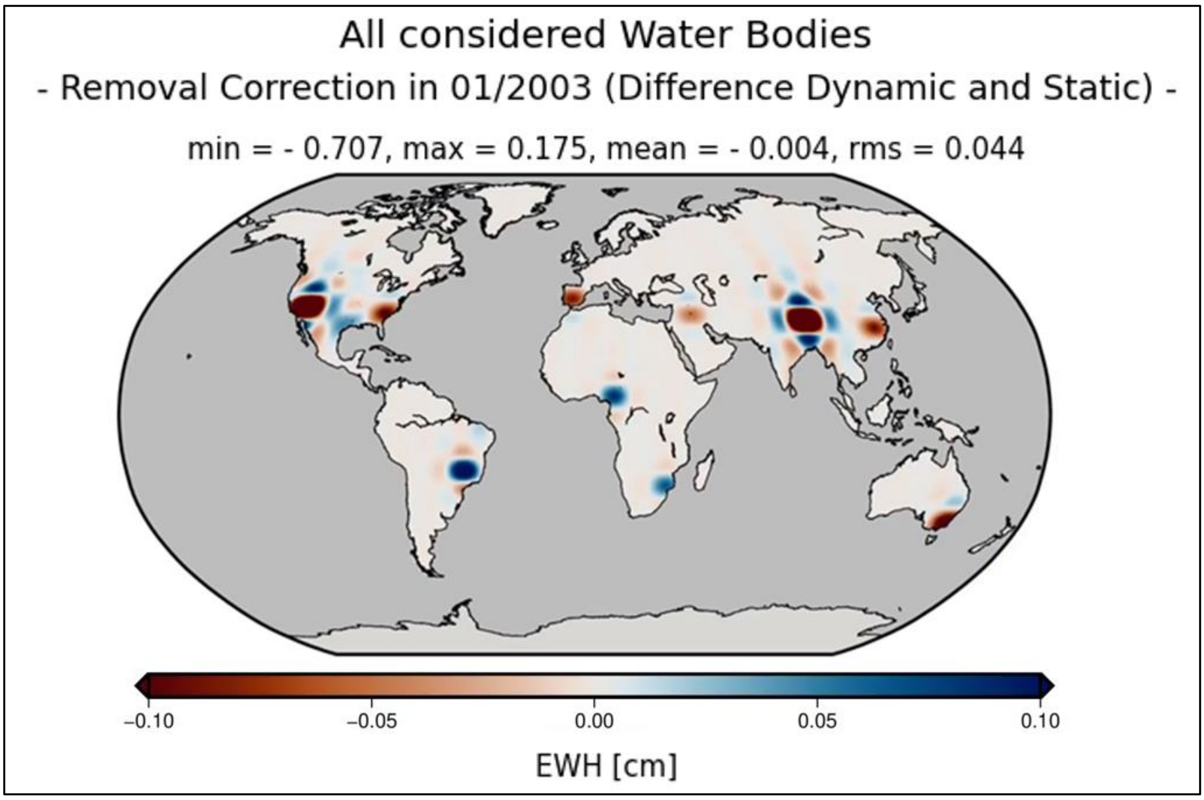

Figure 44: Removal correction difference in 01/2003 for all considered water bodies with an adjusted scale of the colour bar

Source: Own representation in GROOPS and in Python

In accordance to that, the Figure 44 clearly shows, that the Lake Mead and the Lake Siling Co experience severe negative differences. This means, that the forward modelled equivalent water height values, which were computed under the consideration of a dynamic water body shape were smaller than those computed on the basis of a static water body shape. This accounts at least for 01/2003, which is visualized in this respective figure. Following, also the Reservoir Zujar in Spain and the Reservoir Eucumbene in Australia, indicate a negative removal correction. Contrary to that, the Reservoir Nova Ponte in Brazil, the Lake Bankim and the Reservoir Lagdo, which are both located in west Africa, and for which the leakage effect causes the removal correction of the two water bodies to blend, and finally the Lake Massingir, which is located in South Africa, indicate a positive removal correction which is coloured in blue. For those cases, the consideration of dynamic water body shapes resulted in a slightly larger removal correction than the consideration of static water body shapes did.

To further assess the characteristics of the forward modelled equivalent water height difference time series and thus to gain a more comprehensive understanding concerning the effect that the consideration of an either dynamic or a static water body shape has, the trend as well as the amplitude of the two forward modelled equivalent water height signals were evaluated.

With respect to the trend, the long term trend of the forward modelled equivalent water height values, which were calculated on the basis of 29 dynamic as well as 29 static water body shapes over a time frame from 01/2003 to 12/2016, was computed. The results are depicted in the two following figures, the Figure 45 and the Figure 46. Hence, the statistical information, which is provided on top of both figures shows, that the consideration of an either dynamic or a static water body shape, changes the respective trend behaviour of the correction product. While the consideration of dynamic water body shapes causes a global trend of the forward modelled equivalent water height values, which reaches from - 0.345 cm to 0.276 cm, the consideration of static water body shapes causes the global trend of the forward modelled equivalent water height values to reach from - 0.342 cm to 0.229 cm. Hence, the respective minimum as well as the maximum value indicate a difference from the second decimal place onwards. Subsequently, also the computed mean value of the trend deviates by - 9.692e-5 cm. Nevertheless, those deviations are still in a range, for which, at least from a visual inspection, the gradient of the trend does not change. Consequently, the derived differences do not reverse the trend behaviour from for instance negative to positive. Thus, the forward modelled equivalent water height values of for example the Lake Mead, which is situated in Arizona and in Nevada, experience a decline, no matter whether a dynamic or a static water body shape is taken into consideration. Hence, the Lake Mead loses mass.

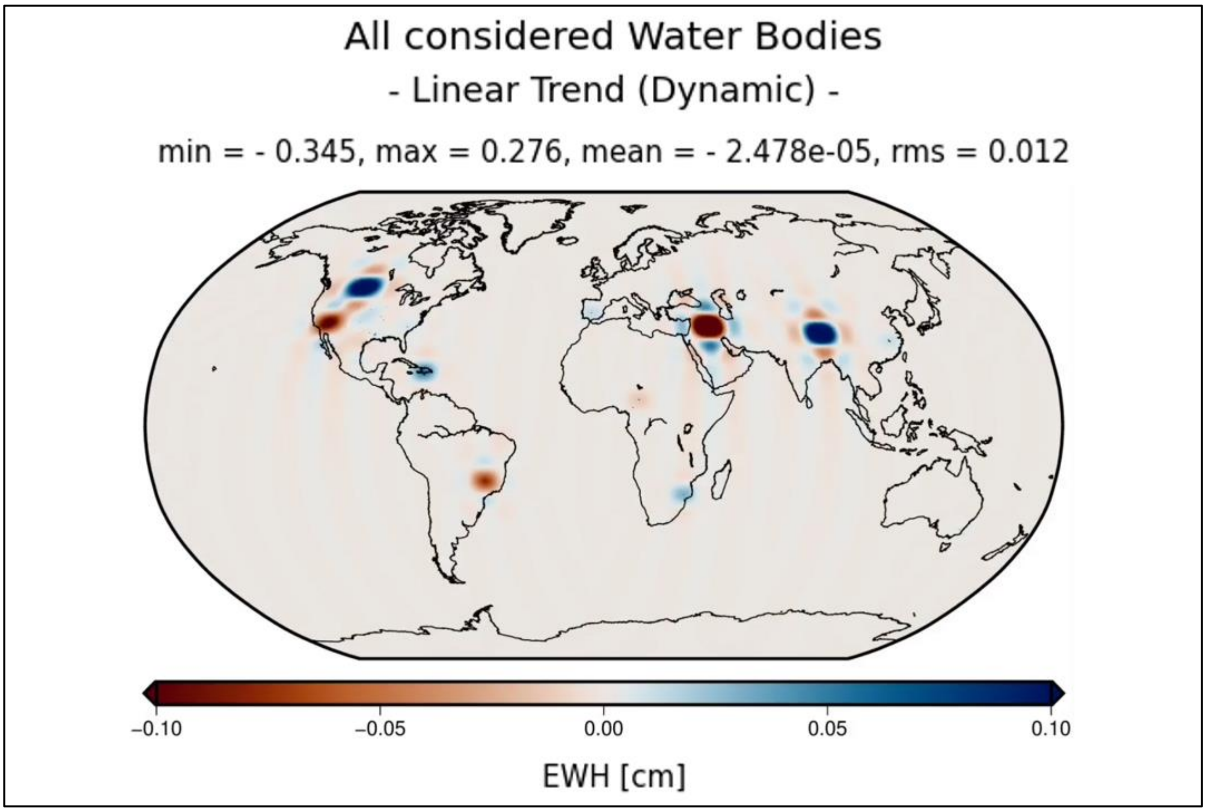

Figure 45: Linear trend based on a dynamic water body shape for all considered water bodies

Source: Own representation in GROOPS and in Python

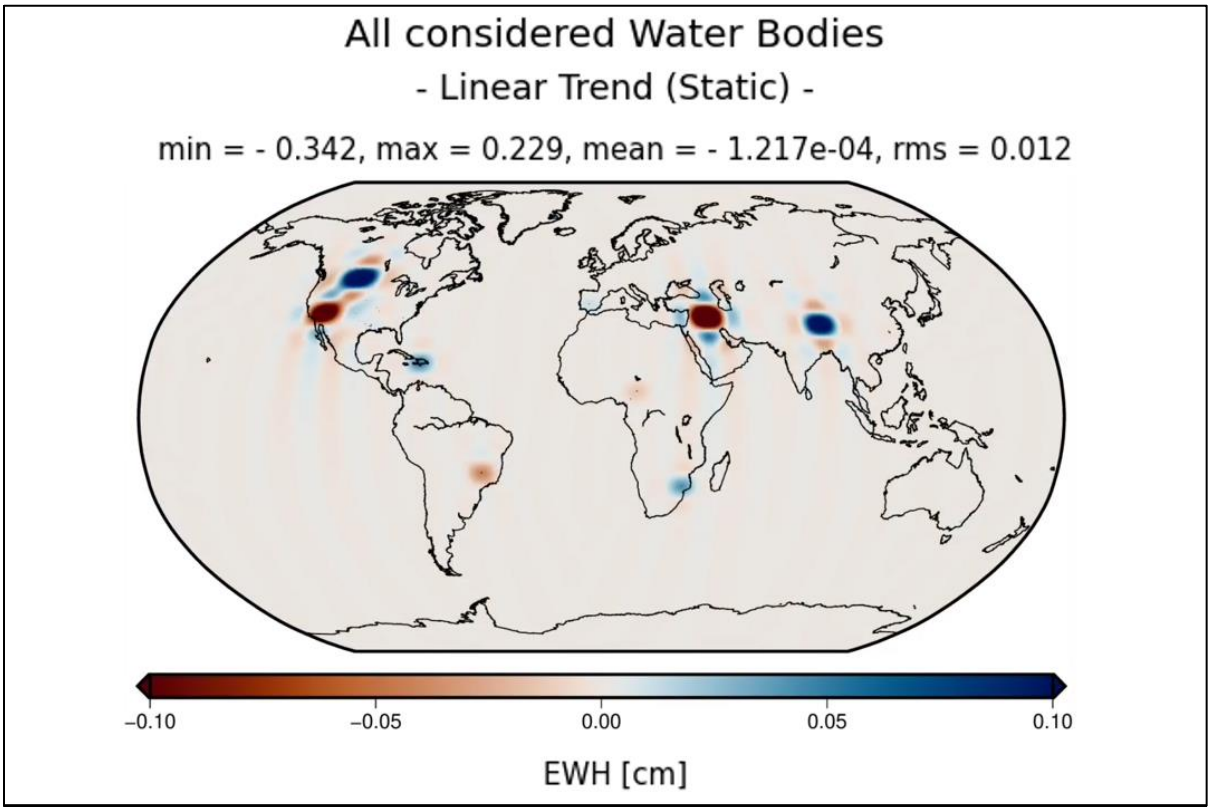

Figure 46: Linear trend based on a static water body shape for all considered water bodies

Source: Own representation in GROOPS and in Python

When evaluating the mean values of the Figure 45 and the Figure 46, which are both negative, it can further be said, that the water storage decrease overweights the water storage increase. This means that the majority of the 29 considered water bodies experience a loss of mass. This encounters at least for the evaluated time frame, reaching from 01/2003 to 12/2016. The reasons for a mass loss of a water body are usually attributed to climate change and the related rising temperatures. Nonetheless, the exact driving factors, which either lead to a mass loss or a mass gain of a water body, must always be analysed and evaluated for the respective water body itself.

With respect to the amplitudes of both forward modelled equivalent water height signals, the following two figures, the Figure 47 and the Figure 48 illustrate, that the minimum amplitudes for each grid cell vary between 6.067e-08 cm for the consideration of dynamic water body shapes and 3.208e-08 cm for the consideration of static water body shapes. Considering the maximum amplitude values, which amount to 1.036 cm and 1.056 cm respectively, it can be seen, that the mean values do not differ, at least for the first three digits, from each other.

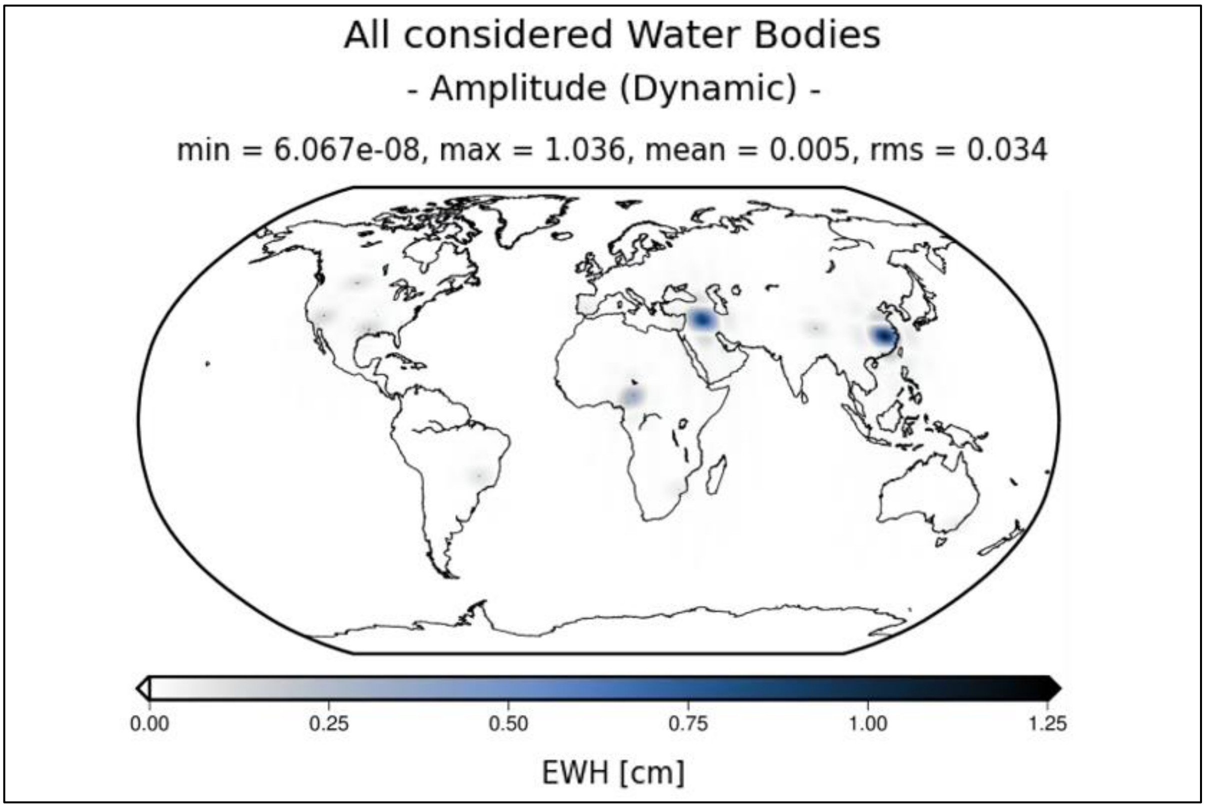

Figure 47: Amplitude based on a dynamic water body shape for all considered water bodies

Source: Own representation in GROOPS and in Python

Hence, the most prominent features within both figures are the Lake Poyang in east China as well as the Reservoir Mosul Dam and the Lake Tharthar, which are both located south - west of the Caspian Sea and for which both signal amplitudes blend into each other. Subsequently, all three water bodies indicate amplitudes of more than 1 cm. Most of the other lakes and reservoirs have mean correction amplitudes in the range of 0.25 cm.

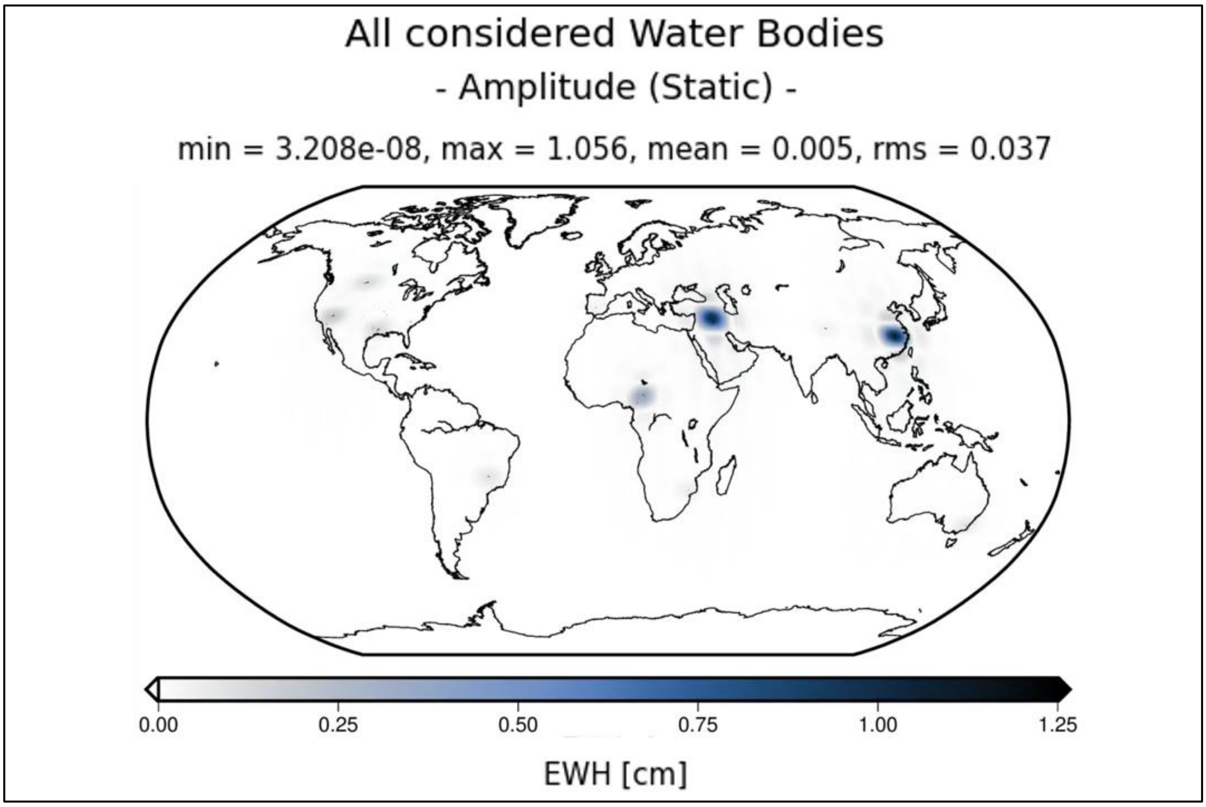

Figure 48: Amplitude based on a static water body shape for all considered water bodies

Source: Own representation in Python

When comparing the Figure 45 and the Figure 46, which illustrate the linear trend, with the Figure 47 and the Figure 48, which demonstrate the magnitude of the amplitudes, it becomes evident, that some surface water bodies can indicate a rather prominent trend signal without having a strong amplitude. An example for this would be the Lake Mead in Arizona / Nevada or the Reservoir Nova Ponte in Brazil. Contrary to that, there are also water bodies such as the Reservoir Toledo Bend, which is situated in south - east Texas, which exhibit a comparably strong amplitude, but which do not indicate any significant long term trend.

5.9 Investigation of the driving parameters

With the results depicted in the Figure 42, it becomes evident, that none of the three water bodies, which were further investigated throughout the chapters 5.5 RESULT FOR THE LAKE POYANG, 5.6 RESULT FOR THE LAKE SILING CO and 5.7 RESULT FOR THE LAKE THARTHAR, finally encountered the largest difference. Hence, the difference of the forward modelled equivalent water height values, which were computed under the consideration of a dynamic or a static water body shape respectively, is neither driven by the surface area extent, nor the volume variation and also not by the volume variation difference of the considered water body itself. To get a deeper insight by what the computed difference values from the Figure 42 may be driven, the input parameters of the forward modelling procedure, were further investigated. These input parameters comprise the surface area polygons and the water level values.

Although both forward modelling procedures were performed under the consideration of the same surface area polygons, the surface area time series from the DAHITI database are internally used to compute the volume variation time series (Schwatke et al., 2020), which were used in the course of this study to compute the new water level values for the dynamic case. Hence, it is worth to further investigate the difference between the surface area extent derived from the WaterPack product and the mean surface area extent which could be derived from the DAHITI database. The result is depicted in the Figure 49 below.

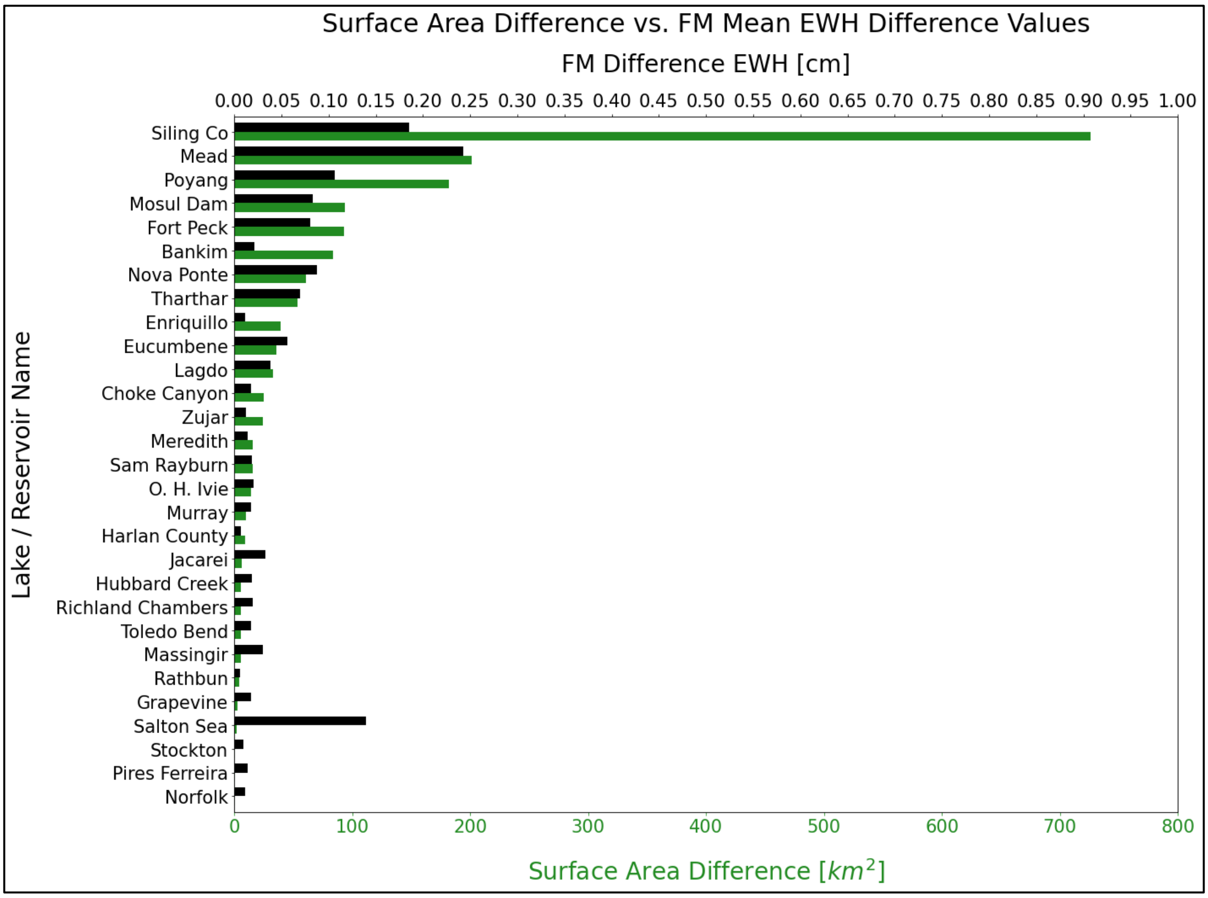

Figure 49: Relation between the surface area difference and the forward modelled mean EWH difference values for all considered water bodies

Source: Own representation in Python

Consequently, the green coloured bars from the Figure 49 show, that the Lake Siling Co faces the by far largest mean surface area extent difference which is followed by the Lake Mead. The exact numbers can be derived from the Figure 4. When comparing the magnitude of the green coloured bars with the magnitude of the black coloured bars, which illustrate the difference of the forward modelled equivalent water height values from the Figure 42, it can be seen, that the difference of the forward modelled equivalent water height values is not solely driven by the area size deviation of the underlying water body shapes. If the difference would only be driven by that aspect, not the Lake Mead, but the Lake Siling Co, which encounters the largest surface area extent difference, would also indicate the largest mean difference of the forward modelled equivalent water height values. As a result, a direct linear linkage between the difference of the surface area extents and the magnitude of the forward modelled equivalent water height difference values, can be precluded. Nevertheless, the Figure 42 still shows, that the majority of the short forward modelled equivalent water height difference bars occur in the lower half of the depicted bar chart. Since the bars are sorted according to the surface area difference values, there is a slight tendency, that an increasing surface area difference value is also accompanied by an increasing forward modelled equivalent water height difference value. Nevertheless, since there are a variety of water bodies such as for instance the already mentioned Lake Mead or the Lake Salton Sea, which counteract this tendency, this statement must be taken with caution.

Since the surface area values are directly used for the volume calculation, it can be assumed, that the surface area differences are also transferred to the volume variation differences. In order to verify this assumption, the area extent of the static polygons was multiplied with the water level time series derived from the DAHITI database. The retrieved product was then subtracted from the volume variation time series provided in the DAHITI database. This difference was then again visualized together with the retrieved forward modelled equivalent water height difference values. The result is depicted in the Figure 50. Hence, the bar chart indicates, that the Lake Mead is the water body which encounters the with 1.673 km^3 largest volume variation difference. The Lake Mead is followed by the Reservoir Nova Ponte and the Lake Siling Co, which indicate the second and third largest volume variation difference values respectively. At the same time, the Figure 50 outlines, that the Lake Mead also experiences the largest difference of the forward modelled equivalent water height values. Hence, the water body with the largest volume variation difference also encounters the largest forward modelled equivalent water height difference. Nevertheless, the second largest difference of the forward modelled equivalent water height values does not occur for the Reservoir Nova Ponte, but for the Lake Siling Co. Subsequently, the Figure 50 shows, that there is also no direct linear linkage between the parameter volume variation difference on one hand side and the parameter equivalent water height difference on the other hand side. Nevertheless, similar to the observations of the Figure 49, the Figure 50 gives still the impression, that an increasing volume variation difference is, at least on average, also accompanied by an increasing difference of the forward modelled equivalent water height values. Although this tendency is invalidated by for instance the Lake Salton Sea, which shows in relation to its volume variation difference a huge difference concerning the forward modelled equivalent water height values, and which is also further contradicted by for instance the Reservoir Nova Ponte, the Lake Tharthar or the Reservoir Jacarei, a certain tendency cannot be neglected.

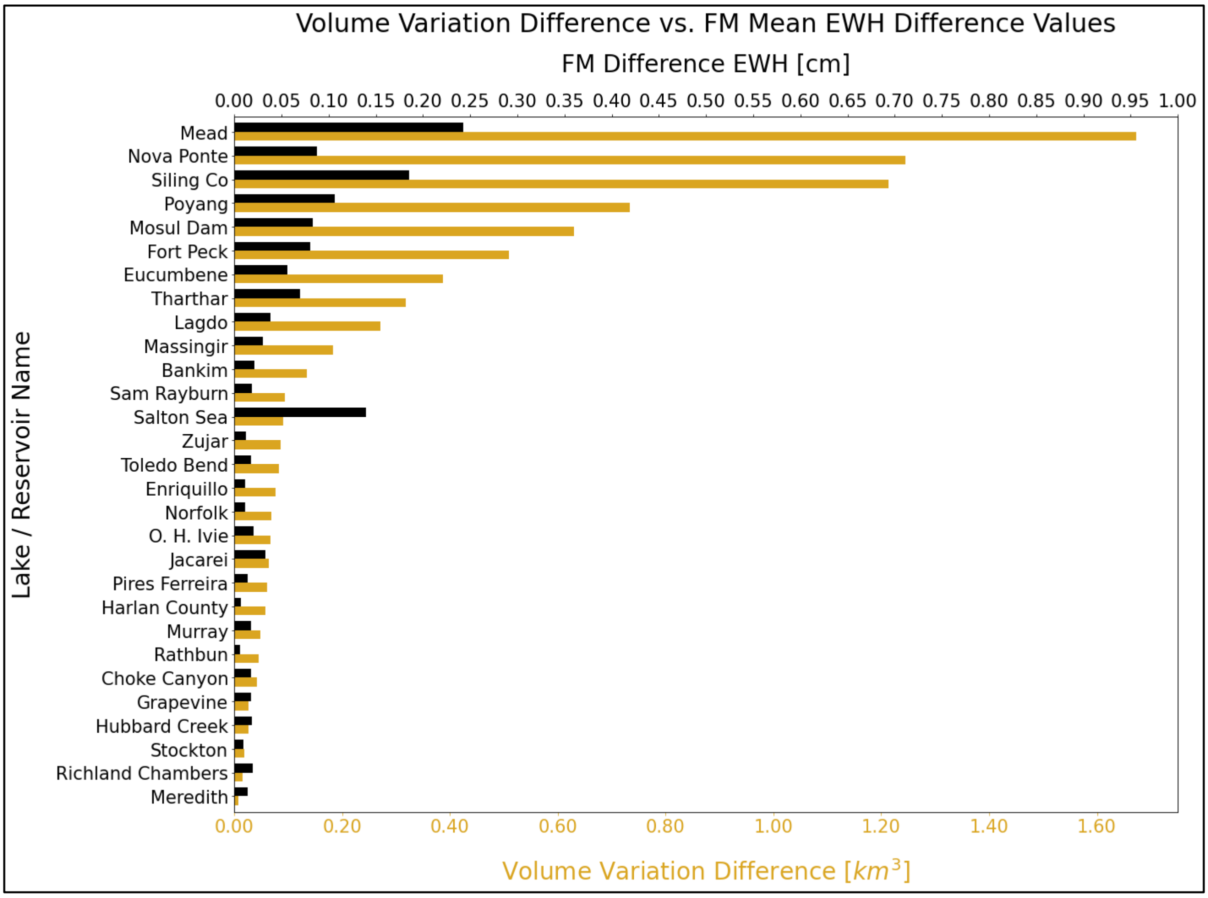

Figure 50: Relation between the surface area difference and the forward modelled mean EWH difference values for all considered water bodies

Source: Own representation in Python

Next to the surface area extent and the volume variation differences, it was also evaluated to which extent the varying water level input values could be considered as a driver for the forward modelled equivalent water level height difference values. As already mentioned in the chapter 5.1 PRE-PROCESSING, the inclusion of dynamic water body shapes was realized by dividing the volume variation time series from the DAHITI database through the surface area extent derived from the WaterPack polygons. Since the volume variation time series underly a varying surface area extent, the derived water level values are also based on a dynamic surface area extent. To assess to which extent the forward modelled equivalent water height difference values from the Figure 42 are driven by the varying water level values, the following Figure 51 was generated. Subsequently, the blue coloured bars of the Figure 51 illustrate the mean water level difference values in the unit of metre.

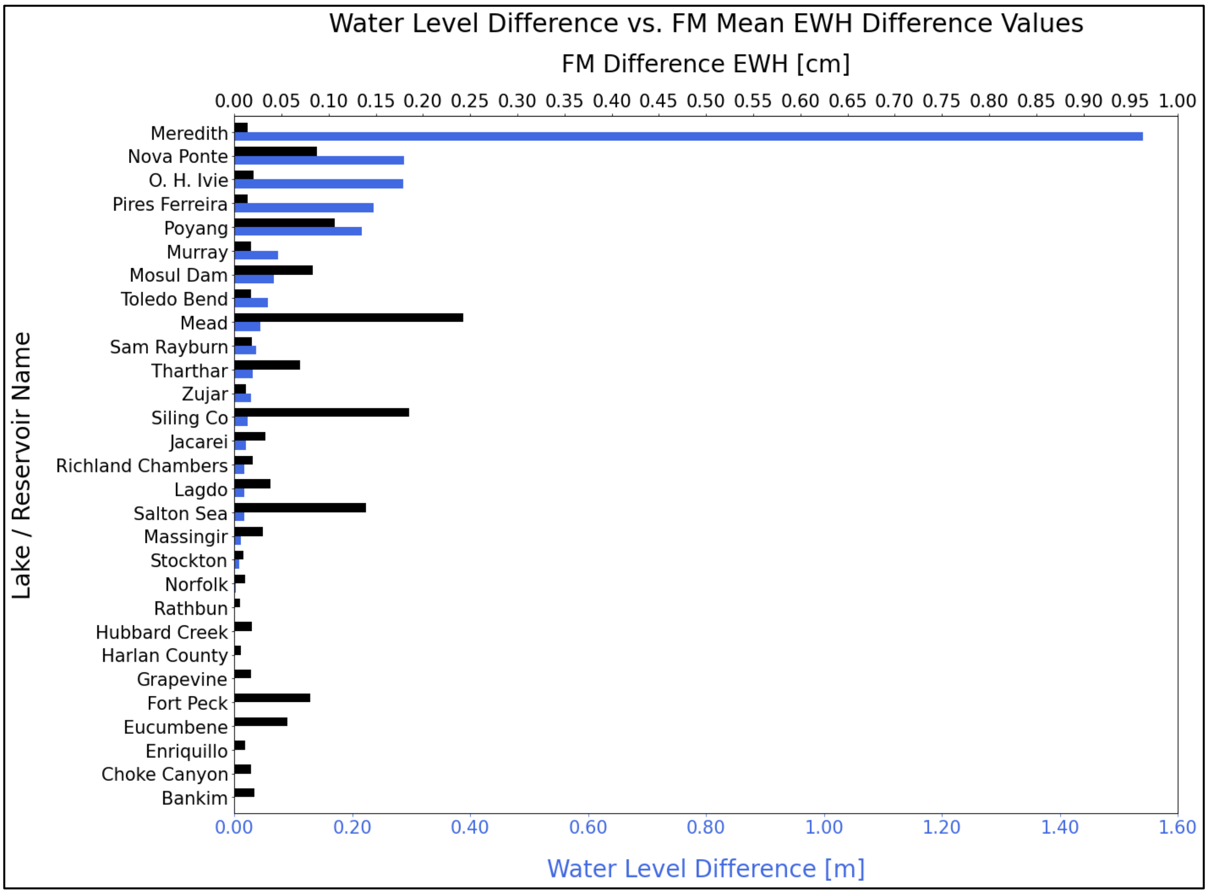

Figure 51: Relation between the water level difference and the forward modelled mean EWH difference values for all considered water bodies

Source: Own representation in Python

In accordance to that, the Figure 51 shows, that the mean water level difference values reach up to 1.541 m for the Reservoir Meredith. Nevertheless, since the DAHITI database only provides water level values for the Reservoir Meredith from the summer of 2016 onwards, as it was already shown in the Figure 14, meaning that the depicted difference value was computed on the basis of five monthly values, the result cannot be considered as representative. Consequently, the remaining 28 difference values provide a more reliable picture of the magnitude that those difference values can reach. On the contrary to that, the black coloured bars illustrate the magnitude of the computed forward modelled equivalent water height difference values. The exact magnitude can be derived from the Figure 42. Hence, it can be seen, that an increasing difference concerning the water level values, which were directly used for the forward modelling procedure, does not accompany with an increasing difference of the forward modelled equivalent water height values. Subsequently, the difference of the forward modelled equivalent water height values is also not directly linked to the deviation of the underlying water level values, which were used for the computation of the dynamic and the static case respectively. If there would be a direct linkage, the Lake Mead would not only indicate the largest difference concerning the forward modelled equivalent water height values, but also the largest difference concerning the underlying water level values.

Consequently, it seems that neither the single parameters of a water body, including its surface area extent, its volume variation and its volume variation difference, nor the difference between the input parameters, which were used for the computation of the respective forward modelled equivalent water height values, function as a key driver for the encountered differences of the forward modelled equivalent water height values.

6 Conclusion

To investigate the extent to which the consideration of dynamic and static water body shapes would influences the total water storage estimates derived from GRACE observations, adequate and suitable data was selected, processed and quantitatively evaluated. By generating time series, the selected data could be subjected to a detailed statistical analysis. This statistical analysis was carried out for all 29 considered globally distributed water bodies and the results were presented in a clear structure. Based on quantitatively calculated quality characteristics, namely size, volume variation and volume variation difference, focal points, which could then be further investigated throughout the subsequent research, became apparent. As a result, the Lake Poyang, the Lake Siling Co and the Lake Tharthar were subjected to an additional quantitative and qualitative investigation. This detailed investigation for all three selected lakes has shown, that neither the largest water body, nor the water body with the greatest volume variation, nor the water body with the greatest volume variation difference, ultimately showed the largest deviation. Against this background, the overall investigation has impressively demonstrated, that the differences of the forward modelled equivalent water height values, which were computed under the reciprocal inclusion of dynamic and static water body shapes, cannot be related to a single parameter.

Based on this outcome, it was then evaluated whether the differences are driven by the differences of the used input parameters. Therefore, not only the mean surface area extent values, but also the volume variation difference values and finally the used water level input values, were evaluated. Although there is a slight tendency, that an increasing surface area difference and thus also an increasing volume variation difference is also conducted with an increasing difference of the forward modelled equivalent water height values, there are still water bodies which counteract this tendency and thus no direct linear linkage between the respective parameters could be detected.

Based on these observations, it can be concluded, that the resulting differences of the forward modelled equivalent water height values are driven by reciprocally acting characteristics. Consequently, neither the features of the investigated water body itself, nor potential differences concerning the input parameters, but rather an interplay of all of these parameters caused the final results. Hence, the largest deviation could be attributed to the Lake Mead, which is situated in the United States of America. In accordance to that, the forward modelled equivalent water height values for the Lake Mead encountered a mean difference of 0.243 cm (Figure 42).

This result can be confirmed by a study that was conducted in 2019 (Semmelroth, 2019). Although Semmelroth used a regression analysis to establish a relationship between the surface area extent and the water level height value to derive time variable volume variation values, which he then compared to those volume variation values derived from a static computation model, he also outlined, that the Lake Mead indicates the largest deviation. Furthermore, he also found out, that the computation of a water volume variation, on the basis of a temporally variable surface area extent, does generally not cause a significant difference in relation to those volume variations, which were computed on the basis of a fixed mean surface area extent. Despite the fact that this conclusion was not derived by performing a forward modelling procedure, it can still be used as a rough validation of the results which were achieved in the course of this study.

Finally, it can be said, that the derived results, referring to the difference of the forward modelled equivalent water height values, which were computed under the consideration of dynamic and static water body shapes, have a consistently marginal and non-significant influence which cannot, except for the Lake Mead and the Lake Siling Co, be detected from GRACE on a non-adjusted scale of the colour bar. Nevertheless, this research also showed, that at least a difference in the range of sub-millimetres, could be computed for every single water body. Hence, the consideration of dynamic water bodies, does make a difference. This difference is also directly reflected in the corrected GRACE signal, which can then be used for calibration and assimilation purposes of hydrological models which do not explicitly contain a surface water compartment. Furthermore, the differences have a direct impact on the total water storage estimates. In combination with further uncertainty sources, such as those derived from groundwater or soil moisture estimates, those initially small and supposedly non-significant differences will add up and subtly increase. Finally, the extent to which those sources of uncertainty, including the differences which occur when either considering dynamic or static water body shapes, can be allowed, primarily depends on the requirements of the end product and in the last instance from the client and the user.

7 Discussion and Outlook

Against the background of the analysis and evaluation which was carried out, not only the used input data, but also the achieved results must be critically questioned. On top of that, it must be assessed how reliable the results of the investigation actually are.

Due to the fact that all processed data are the product of satellite observations, the quality of this data, which builds the fundament for the carried-out study, has to be examined. Although the existing methods to derive surface area extents and to develop time series of water level and volume variation fluctuations are well developed and sufficient to obtain data which is accurate enough to be further processed and analysed, the satellite measurements still contain errors and uncertainties. Hence, a further validation of this data in terms of ground measurements and an improvement of the underlying measurement techniques becomes necessary. Nevertheless, since care has been taken to ensure that the data was validated and since the applied validation procedure was further investigated and outlined, it can be said, that the data used has a reliable quality. Moreover, since the investigation concerning the consideration of dynamic and static water body shapes was not only executed on the basis of data which was retrieved from the same database, but also by applying the same processing procedure, a sufficient comparability of the results can be regarded as given.

Nevertheless, even if the data is of sufficient quality and even if it allows a comparability, the question, to which extent the investigation of highly inhomogeneous water bodies is actually meaningful, remains. Since the 29 water bodies were selected based on the intersection between the polygons, which were already available, and the volume variation time series, which were accessible from the DAHITI database, the choice of the considered water bodies was not driven by a thoughtful deliberation, but it was predefined by the available data. Considering that the volume variation time series from the DAHITI database are, due to the high processing effort, only available for small water bodies and considering, that volume change estimates particularly help to remove, or at least strongly reduce, the leakage effect in regions which are situated close to large water bodies or in regions which contain many small water bodies, the question arises how representative the results of the investigated lakes actually are. Against the background that GRACE has a spatial resolution of 300 km to 400 km and the consideration, that 21 out of the 29 investigated water bodies have a surface area extent, which is smaller than 500 km^2, the usage of the corrected GRACE data for the purpose of hydrological models is questionable and the resilience of the obtained results is further limited.

Furthermore, it has to be considered, that the prevailing study focusses on lakes and on reservoirs. Although this constraint was predetermined by the available polygons, it has to be taken into account, that there are also other forms of surface water bodies such as for instance rivers, whose mass variations effect the GRACE data and which are not covered by any correction, neither on the basis of dynamic or static water body shapes, yet. Since especially river deltas of large river basins such as the Amazonas basin or the Mississippi Basin are highly influenced by strong seasonal variations, a respective correction which could then be removed from the GRACE signal, would be of severe importance and interest for hydrological modelling (Deggim et al., 2021).

Subsequently, the achieved results should be considered as a first assessment which shows, that the introduction of dynamic water bodies actually causes a difference. In order to be able to estimate and to assess the ultimate maximum magnitude of these differences, further studies and the inclusion of larger water bodies, are essential. In addition, the presented study also offers the possibility to conduct further research on the inclusion of other water bodies such as rivers which would then help to perform more sophisticated data assimilation strategies. Consequently, such additional studies can also help to further improve the quality and thus also the credibility of hydrological models. In relation to the prevailing climate crisis and the growing water shortages, such models will gain an increasingly importance in the near future.

8 Bibliography

A, G., Wahr, J., & Zhong, S. (2013). Computations of the viscoelastic response of a 3-D compressible Earth to surface loading: an application to Glacial Isostatic Adjustment in Antarctica and Canada. Geophysical Journal International: Volume 192, Issue 2, pp. 557-572. Retrieved from https://doi.org/10.1093/gji/ggs030, last accessed on 13.08.2023.

Alfieri, L., Avanzi, F., Delogu, F., Gabellani, S., Bruno, G., Campo, L., Libertino, A., Massari, C., Tarpanelli, A., Rains, D., Miralles, D. G., Quast, R., Vreugdenhil, M., Wu, H., Brocca, L. (2022). High-resolution satellite products improve hydrological modelling in northern Italy. Hydrology and Earth System Sciences: Volume 26, pp. 3921-3939. Retrieved from https://doi.org/10.5194/hess-26-3921-2022, last accessed on 13.08.2023.

Bechtel, B. (2015). A New Global Climatology of Annual Land Surface Temperature. Remote Sensing: Volume 7, Issue 3, pp. 2850-2870. Retrieved from https://doi.org/10.3390/rs70302850, last accessed on 13.08.2023.

Blank, D., Eicker, A., Jensen, L., Güntner, A. (2023). A global analysis of water storage variations from remotely sensed soil moisture and daily satellite gravimetry. Hydrology and Earth System Science: Volume 27, Issue 13, pp. 2413-2435. Retrieved from https://doi.org/10.5194/hess-27-2413-2023, last accessed on 13.08.2023.

Boak, E. H., & Turner, I. L. (2005). Shoreline Definition and Detection: A Review. Journal of Coastal Research: Volume 214, pp. 688-703. Retrieved from https://doi.org/10.2112/03-0071.1, last accessed on 13.08.2023.

Braga, F., Tosi, L., Prati, C., Alberotanza, L. (2023). Shoreline detection: capability of COSMO-SkyMed. European Journal of Remote Sensing: Volume 46, Issue 1, pp. 837-853. Retrieved from https://doi.org/10.5721/EuJRS20134650, last accessed on 13.08.2023.

Copernicus. (2018). Sea level daily gridded data from satellite observations for the Mediterranean Sea from 1993 to 2020. Climate Change Service. Retrieved from https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-level-mediterranean?tab=overview, last accessed on 13.08.2023.

Deggim, S., Eicker, A., Schawohl, L., Gerdener, H., Schulze, K., Engels, O., Kusche, J., Saraswati, A. T., van Dam, T., Ellenbeck, L., Dettmering, D., Schwatke, C., Mayr, S., Klein, I., Longuevergne, L. (2021). RECOG RL01: correcting GRACE total water storage estimates for global lakes/reservoirs and earthquakes. Earth System Science Data: Volume 13, Issue 5, pp. 2227-2244. Retrieved from https://doi.org/10.5194/essd-13-2227-2021, last accessed on 13.08.2023.

Dembélé, M., Ceperley, N., Zwart, S., Salvadore, E., Mariethoz, G., Schaefli, B. (2020). Potential of satellite and reanalysis evaporation datasets for hydrological modelling under various model calibration strategies. Advances in Water Resources: Volume 143. Retrieved from https://doi.org/10.1016/j.advwatres.2020.103667, last accessed on 13.08.2023.

Deutsches Geodätisches Forschungsinstitut. (n.d.). Database for Hydrological Time Series of Inland Waters (DAHITI). Water Level Time Series from Satellite Altimetry. Retrieved from https://dahiti.dgfi.tum.de/en/products/water-level-altimetry/, last accessed on 13.08.2023.

Deutsches Geodätisches Forschungsinstitut. (n.d.). Database for Hydrological Time Series of Inland Waters (DAHITI). Time Series of Surface Areas. Retrieved from https://dahiti.dgfi.tum.de/en/233/surface-area/, last accessed on 13.08.2023.

Döll, P., Kaspar, F., Lehner, B. (2003). A global hydrological model for deriving water availability indicators: model tuning and validation. Journal of Hydrology: Volume 270, Issues 1-2, pp. 105-134. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0022169402002834?via%3Dihub, last accessed on 13.08.2023.

Erkin, N., (2013). Water: Hydrological cycle. Retrieved from http://www.cawater-info.net/all_about_water/en/?p=2612, last accessed on 13.08.2023.

Forootan, E., & Kusche, J. (2011). Separation of global time-variable gravity signals into maximally independent components. Journal of Geodesy: Volume 86, pp. 477-497. Retrieved from https://doi.org/10.1007/s00190-011-0532-5, last accessed on 13.08.2023.

Frappart, F., Papa, F., Santos da Silva, J., Ramillien, G., Prigent, C., Seyler, F., Calmant, S. (2012). Surface freshwater storage and dynamics in the Amazon basin during the 2005 exceptional drought. Environmental Research Letters. Retrieved from https://doi.org/10.1088/1748-9326/7/4/044010, last accessed on 13.08.2023.

German Aerospace Center. (n.d.). Global WaterPack (GWP). DLR Earth Observation Center. Retrieved from https://www.dlr.de/eoc/en/desktopdefault.aspx/tabid-11882/20871_read-74101/, last accessed on 13.08.2023.

Hauk, M., & Pail, R. (2018). Treatment of ocean tide aliasing in the context of a next generation gravity field mission. Geophysical Journal International: Volume 214, Issue 1, pp. 345-365. Retrieved from https://doi.org/10.1093/gji/ggy145, last accessed on 13.08.2023.

Hinds, E. (n.d.). What is the difference between hydrographic and bathymetric surveys? Landform Surveys. Retrieved from https://www.landform-surveys.co.uk/news/general-updates/difference-between-hydrographic-and-bathymetric-surveys/, last accessed on 13.08.2023.

Holst, C. (2017). Das Kalmanfilter zur Zustandsschätzung ebener Fahrzeugtrajektorien. Memos der Geodäsie - 3 / 2017.

Jet Propulsion Laboratory. (n.d.). What is 'Equivalent Water Thickness'? GRACE Tellus. Retrieved from https://grace.jpl.nasa.gov/data/monthly-mass-grids/, last accessed on 13.08.2023.

Jet Propulsion Laboratory. (n.d.). GRACE-FO. Retrieved from https://grace.jpl.nasa.gov/mission/grace-fo/ , last accessed on 13.08.2023.

Klein, I., Gessner, U., Dietz, A., Kuenzer, C. (2017). Global WaterPack – A 250 m resolution dataset revealing the daily dynamics of global inland water bodies. Retrieved from https://doi.org/10.1016/j.rse.2017.06.045, last accessed on 13.08.2023.

Kusche, J. (2007). Approximate decorrelation and non-isotropic smoothing of time-variable GRACE-type gravity field models. Journal of Geodesy: Volume 81, pp. 733-749. Retrieved from https://doi.org/10.1007/s00190-007-0143-3, last accessed on 13.08.2023.

Kusche, J., Schmidt, R., Petrovic, S., Rietbroek, R. (2009). Decorrelated GRACE time-variable gravity solutions by GFZ, and their validation using a hydrological model. Journal of Geodesy, pp. 903-913. Retrieved from https://doi.org/10.1007/s00190-009-0308-3, last accessed on 13.08.2023.

Liu, X., & Chen, B. (2000). Climatic warming in the Tibetan Plateau during recent decades. International Journal of Climatology: Volume 20, Issue 14, pp. 1729-1742. Retrieved from https://doi.org/10.1002/1097-0088(20001130)20:14<1729::AID-JOC556>3.0.CO;2-Y, last accessed on 13.08.2023.

Mayer-Gürr, T., Behzadpour, S., Eicker, A., Ellmer, M., Koch, B., Krauss, S., Pock, C., Rieser, D., Strasser, S., Süsser-Rechberger, B., Zehentner, N., Kvas, A. (2021). Computers and Geosciences. GROOPS: A software toolkit for gravity field recovery and GNSS processing. Retrieved from https://doi.org/10.1016/j.cageo.2021.104864, last accessed on 13.08.2023.

Mohr, K. (2023). Gravity Recovery and Climate Experiment (GRACE). NASA Earth Sciences. Retrieved from https://earth.gsfc.nasa.gov/geo/missions/grace, last accessed on 13.08.2023.

Nasa Science. (n.d.). Water Cycle. Retrieved from https://science.nasa.gov/earth-science/oceanography/ocean-earth-system/ocean-water-cycle, last accessed on 13.08.2023.

Neema, A. (2022). Spatiotemporal Data Augmentation of MODIS-LANDSAT Water Bodies using Generative Adversarial Networks. Utah State University: Master Thesis, pp. 1-41. Retrieved from https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=9728&context=etd, last accessed on 13.08.2023.

Ogilvie, A., Belaud, G., Massuel, S., Mulligan, M., Goulven, P., Malaterre, P.-O., Calvez, R. (2018). Combining Landsat observations with hydrological modelling for improved surface water monitoring of small lakes. Journal of Hydrology: Volume 566, pp. 109-121. Retrieved from https://doi.org/10.1016/j.jhydrol.2018.08.076, last accessed on 13.08.2023.

Ramillien, G., Seoane, L., Darrozes, J. (2022). An Innovative Slepian Approach to Invert GRACE KBRR for Localized Hydrological Information at the Sub-Basin Scale. Remote Sensing: Volume 14, Issue 13, pp. 1824 - 1840. Retrieved from https://doi.org/10.3390/rs13091824, last accessed on 13.08.2023.

Ruhr Universität Bochum. (n.d.). WaterGAP3. Retrieved from https://www.hydrology.ruhr-uni-bochum.de/hydro/forschung/watergap.html.en, last accessed on 13.08.2023.

Sánchez, L., Pearlman, M., Heki, K. (2023). Global Geodetic Observing System. Retrieved from Satellite Altimetry: https://ggos.org/item/satellite-altimetry/, last accessed on 13.08.2023.

Scanlon, B. R., Zhang, Z., Save, H., Sun, A., Müller Schmied, H., van Beek, L., Wiese, D. N., Wada, Y., Long, D., Reeds, R. C., Longeuvergne, L., Döll, P., Bierkens, M. (2018). Global models underestimate large decadal declining and rising water storage trends relative to GRACE satellite data. Proceedings of the National Academy of Sciences: Volume 115, Issue 6, pp. 1080-1089. Retrieved from https://doi.org/10.1073/pnas.1704665115, last accessed on 13.08.2023.

Schwatke, C., Dettmering, D., Seitz, F. (2020). Volume Variations of Small Inland Water Bodies from a Combination of Satellite Altimetry and Optical Imagery. Remote Sensing. Retrieved from https://doi.org/10.3390/rs12101606, last accessed on 13.08.2023.

Schwatke, C., Dettmering, D., Bosch, W., Seitz, F. (2015). DAHITI - an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. Hydrology and Earth System Sciences, 19, pp. 4345-4364. Retrieved from https://doi.org/10.5194/hess-19-4345-2015, last accessed on 13.08.2023.

Semmelroth, C. (2019). Einfluss der zeitlich variablen Ausdehnung von Oberflächengewässern auf mit Hilfe von Satellitenaltimetrie abgeleitete Wasservolumen. HafenCity Universität Hamburg: Master Thesis, pp. 1-60.

Shum, C., Kuo, C., Mitrovica, J. (2002). Glacial Isostatic Adjustment in the Great Lakes Region Inferred by Tide Gauges and Satellite Altimetry. American Geophysical Union, Spring Meeting. Retrieved from https://ui.adsabs.harvard.edu/abs/2002AGUSM.U42A..14S/abstract, last accessed on 13.08.2023.

Skyora. (2021). WHAT IS SATELLITE REMOTE SENSING? Retrieved from https://www.skyrora.com/remote-sensing/, last accessed on 13.08.2023.

Soltani, S. S., Ataie-Ashitiani, B., Simmons, C. T. (2021). Review of assimilating GRACE terrestrial water storage data into hydrological models: Advances, challenges and opportunities. Earth-Science Reviews: Volume 213. Retrieved from https://doi.org/10.1016/j.earscirev.2020.103487, last accessed on 13.08.2023.

Spatialpost. (2023). Exploring the Pros and Cons: Advantages and Disadvantages of Remote Sensing. Retrieved from https://www.spatialpost.com/advantages-and-disadvantages-of-remote-sensing/, last accessed on 13.08.2023.

Swenson, S., Chambers, D., Wahr, J. (2008). Estimating geocenter variations from a combination of GRACE and ocean model output. Journal of Geophysical Research: Volume 113, Issue B8, pp. 1-12. Retrieved from https://doi.org/10.1029/2007JB005338, last accessed on 13.08.2023.

Swenson, S. (2023). GRACE: Gravity Recovery and Climate Experiment: Surface mass, total water storage, and derived variables. NCAR | Climate Data Guide. Retrieved from https://climatedataguide.ucar.edu/climate-data/grace-gravity-recovery-and-climate-experiment-surface-mass-total-water-storage-and, last accessed on 13.08.2023.

Tang, Y., Huo, J., Zhu, D., Yuan, Z. (2022). Simulation of the Water Storage Capacity of Siling Co Lake on the Tibetan Plateau and Its Hydrological Response to Climate Change. Water: Volume 14, Issue 19, p. 3175. Retrieved from https://doi.org/10.3390/w14193175, last accessed on 13.08.2023.

Vath, M. (2021). Kommunen Digital Gestalten. Handreichung Lokale Pegel. https://infoportal.fliwas3.de/site/Fliwas3/get/documents_E1423371115/fliwas3/Daten_FLIWAS3/Dokumente/Handreichung%20Lokale%20Pegel%20-%20Komm.ONE.pdf, last accessed on 13.08.2023.

Vuglinskiy, V. (2009). Assessment of the status of the development of the standards for the Terrestrial Essential Climate Variables. WATER LEVEL - Water level in lakes and reservoirs, water storage. Retrieved from https://www.fao.org/3/i1280e/i1280e.pdf, last accessed on 13.08.2023.

Wang, S., Zhang, L., Zhang, H., Han, X., Zhang, L. (2020). Spatial-Temporal Wetland Landcover Changes of Poyang Lake Derived from Landsat and HJ-1A/B Data in the Dry Season from 1973–2019. Remote Sensing: Volume 12, Issue 10, pp. 1-22. Retrieved from https://doi.org/10.3390/rs12101595, last accessed on 13.08.2023.

Werth, S., & Güntner, A. (2010). Calibration of a Global Hydrological Model with GRACE Data. System Earth via Geodetic-Geophysical Space Techniques, pp. 417-426. Retrieved from https://doi.org/10.1007/978-3-642-10228-8_36, last accessed on 13.08.2023.

Witte, B., & Sparla, P. (2015). Vermessungskunde und Grundlagen der Statistik für das Bauwesen, 8. neu bearbeitete und erweiterte Auflage. Berlin: Wichmann.

Yi, G., & Zhang, T. (2015). Delayed Response of Lake Area Change to Climate Change in Siling Co Lake, Tibetan Plateau, from 2003 to 2013. International Journal of Environmental Research and Public Health, pp. 13886-13900. Retrieved from https://doi.org/10.3390/ijerph121113886, last accessed on 13.08.2023.

Zhang, J. (2019). Climate Change's Effect on Poyang Lake. Retrieved from http://www.aksik.org/node/3587, last accessed on 13.08.2023.

Zhang, Y., Yao, T., Ma, Y. (2012). Climatic changes have led to significant expansion of endorheic lakes in Xizang (Tibet) since 1995. Sciences in Cold and Arid Areas, pp. 0463-0467. Retrieved from https://www.researchgate.net/publication/258615764, last accessed on 13.08.2023.

Zhu, S., Liu, B., Wan, W., Xie, H., Fang, Y., Chen, X., Li, H., Fang, W., Zhang, G., Tao, M., Hong, Y. (2019). A New Digital Lake Bathymetry Model Using the Step-Wise Water Recession Method to Generate 3D Lake Bathymetric Maps Based on DEMs. Water: Volume 11, p. 1151. Retrieved from https://doi.org/10.3390/w11061151, last accessed on 13.08.2023.

9 Appendix

Appendix A: List of lakes and reservoirs which were used in the course of this study.

Number	**Name**	**Country (Continent)**	**Target Type**	**Surface Area Extent [km^2]**
1	Bankim	Cameroon (Africa)	Lake	163.151
2	Choke Canyon	United States of America (North America)	Reservoir	55.002
3	Enriquillo	Dominican Republic (North America)	Lake	258.712
4	Eucumbene	Australia (Australia)	Reservoir	121.453
5	Fort Peck	United States of America (North America)	Lake	816.522
6	Grapevine	United States of America (North America)	Lake	21.204
7	Harlan County	United States of America (North America)	Reservoir	50.042
8	Hubbard Creek	United States of America (North America)	Reservoir	43.101
9	Jacarei	Brazil (South America)	Reservoir	38.818
10	Lagdo	Cameroon (Africa)	Reservoir	619.991
11	Massingir	Mozambique (Africa)	Lake	118.582

12	Mead	United States of America (North America)	Lake	581.122
13	Meredith	United States of America (North America)	Reservoir	34.962
14	Mosul Dam	Iraq (Asia)	Reservoir	347.024
15	Murray	United States of America (North America)	Lake	180.775
16	Norfolk	United States of America (North America)	Reservoir	79.430
17	Nova Ponte	Brazil (South America)	Reservoir	236.628
18	O. H. Ivie	United States of America (North America)	Reservoir	47.026
19	Pires Ferreira	Brazil (South America)	Reservoir	44.816
20	Poyang	China (Asia)	Lake	2105.407
21	Rathbun	United States of America (North America)	Reservoir	50.631
22	Richland Cham-bers	United States of America (North America)	Reservoir	156.410
23	Salton Sea	United States of America (North America)	Lake	928.590
24	Sam Rayburn	United States of America (North America)	Reservoir	379.806
25	Siling Co	China (Asia)	Lake	1639.646

26	Stockton	United States of America (North America)	Reservoir	96.465
27	Tharthar	Iraq (Asia)	Lake	1698.304
28	Toledo Bend	United States of America (North America)	Reservoir	599.111
29	Zujar	Spain (Europe)	Reservoir	93.218

Appendix B: Reference manual for the new version of the GROOPS Script.

Notes:

The following descriptions refer to the script "230527_GlobalCDA_Version_neues_Groops_EWH_bearb.xml", which is located in the folder /home/annika/groops/scenario/230527_GlobalCDA_Version_neues_Groops/2019_03_GlobalCDA/. Subsequently, also the input data and the generated files and plots are stored in the depicted subfolders of this path.

Functions of the script, which are commented out, are not part of the following descriptions and will not be further elaborated.

Unless stated, the explanations of individual parameters have been taken from the documentation of the GROOPS software. A .pdf version of the respective documentation can be derived from /home/annika/groops/docs/documentation.pdf.

Table of Contents for the reference manual

List of Equations for the reference manual

0 Global

The global settings within GROOPS allow to define variables, which can then be directly accessed from the script. Hence, all global elements automatically appear in the dropdown value list of the config elements of the same type. Whenever a global element is selected from the dropdown list, the respective config element is linked to the global element. In case a global element is removed, all linked values of the respective elements will be replaced by the value of the deleted global element. An overview of the global variables and a respective explanation can be found below.

Θ listName: 191029_Global
→ listName defines the name of the list. It must be of type string.

Θ folderName
folderName: FileAsciiTable → folderName defines an AsciiTable which contains a list of strings. inputfile: Projects/{listName}_mergedList.txt → inputfile defines the path and the filename of the multi column ASCII file. Each column is separated by a whitespace. startLine: 0 → startLine defines that the loop should start at the first line, which has an index of 0. countLines: --- → countLines defines that the number of read count lines should not be further specified. Hence, all lines are read. variableLoopString: timeseriesFile → variableLoopString defines that the variable name of the 1. column should be "timeseriesFile". variableLoopString: borderFile → variableLoopString defines that the variable name of the 2. column should be "borderFile". variableLoopString: folderName → variableLoopString defines that the variable name of the 3. column should be "folderName". variableLoopString: globalcda_poly_id

→ variableLoopString defines that the variable name of the 4. column should be "glob-alcda_poly_id".
variableLoopIndex: ---
→ variableLoopIndex defines that the variable with the index of the current iteration should not be further specified.
variableLoopCount: ---
→ variableLoopCount defines that the total number of iterations should not be counted.

Θ gridSizeCoarse: 0.5
→ gridSizeCoarse defines that the resolution of the coarse grid should be 0.5. Hence, each grid cell should have a size of 0.5 ° x 0.5 °.

Θ gridSizeFM: 0.025
→ gridSizeFM defines that the resolution of the forward modelled grid should be 0.025. Hence, each grid cell should have a size of 0.025 ° x 0.025 °.

Θ minDegree: 0
→ minDegree defines that the minimum degree of the expansion should be 0 °.

Θ maxDegree: 96
→ maxDegree defines that the maximum degree of the expansion should be 96 °.

Θ timeFrame
timeFrame: monthly
→ timeFrame defines a monthly time series.
monthStart: 01 [= 1]
→ monthStart defines that the start month of the time frame should be January.
yearStart: 2003
→ yearStart defines that the start year of the time frame should be 2003.
monthEnd: 11
→ monthEnd defines that the end month of the time frame should be November.

yearEnd: 2016

→ yearEnd defines that the end year of the time frame should be 2016.

useMonthMiddle: no

→ useMonthMiddle defines that the time point should not be generated at the mid of each month. Hence, they are given at the first of each month and a time point behind the last month.

Θ timeFramePC2BMTS

timeFramePC2BMTS: monthly

→ timeFramePC2BMTS defines a monthly time series.

monthStart: 01 [= 1]

→ monthStart defines that the start month of the time frame should be January.

yearStart: 2003

→ yearStart defines that the start year of the time frame should be 2003.

monthEnd: 12

→ monthEnd defines that the end month of the time frame should be December.

yearEnd: 2016

→ yearEnd defines that the end year of the time frame should be 2016.

useMonthMiddle: no

→ useMonthMiddle defines that the time point should not be generated at the mid of each month. Hence, they are given at the first of each month and a time point behind the last month.

Θ LocationPC2BMTS

timeFramePC2BMTS: commandOutput

→ timeFramePC2BMTS defines that a loop over the command output should be performed.

command: cd data/PotentialCoefficients/ForwardModelled/{listName}; ls

→ command defines the path and the filename of the file from which each output line should become a loop iteration.

silently: no

→ silently defines that the output should be shown.

variableLoopString: InputPC2BMTS

→ variableLoopString defines that the variable InputPC2BMTS should be replaced.

variableLoopIndex: ---

→ variableLoopIndex defines that the variable with the index of the current iteration should not be further specified. variableLoopCount: --- → variableLoopCount defines that the total number of iterations should not be counted.

Θ loopTime
loopTime: timeSeries → loopTime loops over a sequence of variables. In respect of a timeSeries, loopTime loops over points in time. timeSeries: Θ timeFrame [= monthly] → timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016. variableLoopTime: loopTime → variableLoopTime defines that loopTime should be the variable which contains the time of each epoch. variableLoopIndex: --- → variableLoopIndex defines that the variable with the index of the current iteration should not be further specified. variableLoopCount: --- → variableLoopCount defines that the total number of iterations should not be counted.

Θ timeStart: 52640 [= 2003-01-01]
→ timeStart defines that the time frame should start on 01/01/2003.

Θ timeEnd: 57753 [= 2016-12-31]
→ timeEnd defines that the time frame should end on 31/12/2016.

Θ referenceTime: 55197 + 12/24 [= 2010-01-01 12:00:00 (55197.5)]
→ reference time defines that the referenceTime should be the 01/01/2010 at 12:00:00. Thus, the reference time is in the middle of the selected time frame. If the reference time would be outside the selected time frame, the estimation would become more inaccurate.

Θ timeSeries: Θ timeSeriesMonthly [= everyMonth]
→ timeSeries defines that a time series with a monthly sampling should be generated.

Θ timeSeriesMonthly:
Θ timeSeriesMonthly: everyMonth → timeSeries defines that a time series with a monthly sampling should be generated. timeStart: timeStart [= 2003-01-01 (52640)) → timeStart defines that the first point in time should be the 01/01/2003. timeEnd: timeEnd [= 2016-12-31 (57752)) → timeEnd defines that the last pint in time should be the 31/12/2016.

Θ gridCoarse
gridCoarse: geograph → the gridCoarse generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. deltaPhi: {gridSizeCoarse} [= 0.5] → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. height: 0.0 [= 0] → height defines that the distance of the points above the ellipsoid should be 0 m. R: 6378137.0 [= 6378137] → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. inverseFlattening: 298.2572221010 [= 298.2572221] → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 1: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 2: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

<u>border: ---</u>

→ border defines that a no regional subset of points should be extracted from the global grid.

Θ gridBorder
<u>gridBorder: rectangle</u> → gridBorder defines a region on the surface of the Earth. In respect of a rectangle, the region is defined along the lines of geographical coordinates. <u>minLambda: - 180</u> → minLambda defines that the minimum degree of longitude should be - 180 °. <u>minLambda: 180</u> → maxLambda defines that the maximum degree of longitude should be 180 °. <u>minPhi: - 90</u> → minPhi defines that the minimum degree of latitude should be - 90 °. <u>maxPhi: 90</u> → maxPhi defines that the maximum degree of latitude should be 90 °. <u>exclude: no</u>

→ exclude defines that no points within the rectangular area should be dismissed.

Θ LocationRemoved2NetCDF
<u>LocationRemoved2NetCDF: commandOutput</u> → LocationRemoved2NetCDF defines that a loop over the command output should be performed. <u>command: cd data/Grids/RemovedNetCDF/{listName}_txt/; ls</u> → command defines the path and the filename of the file from which each output line should become a loop iteration. <u>silently: no</u> → silently defines that the output should be shown. <u>variableLoopString: InputRemoved2NetCDF</u> → variableLoopString defines that the variable InputRemoved2NetCDF should be replaced. <u>variableLoopIndex: ---</u> → variableLoopIndex defines that the variable with the index of the current iteration should not be further specified. <u>variableLoopCount: ---</u> → variableLoopCount defines that the total number of iterations should not be counted.

Θ LocationRestored2NetCDF
<u>LocationRestored2NetCDF: commandOutput</u> → LocationRestored2NetCDF defines that a loop over the command output should be performed. <u>command: cd data/Grids/RemovedNetCDF/{listName}_txt/; ls</u> → command defines the path and the filename of the file from which each output line should become a loop iteration. <u>silently: no</u> → silently defines that the output should be shown. <u>variableLoopString: InputRestored2NetCDF</u> → variableLoopString defines that the variable InputRestored2NetCDF should be replaced. <u>variableLoopIndex: ---</u> → variableLoopIndex defines that the variable with the index of the current iteration should

not be further specified. variableLoopCount: --- → variableLoopCount defines that the total number of iterations should not be counted.

Θ inputTimeSpline: data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc
→ inputTimeSpline defines the path and the filename of the forward modelled time spline input file.

Θ inputTimeSplineGrace2016200212201706: /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2016/itsg-grace2016_MD90_deg1c20repl_no1502_GIA-reduced_mean-red_DDK3_interp_200212-201706.dat
→ inputTimeSplineGrace2016200212201706 defines the path and the filename of a time spline. This time spline stores potential coefficients which describe the monthly gravity field in a time frame from 12/2002 to 06/2017 as it was observed by GRACE. The resulting gravity field is already pre-processed.

Θ inputTimeSplineGrace2018200204201706: /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2018/timeSplines/old_monthly/timeSpline_ITSG-Grace2018_monthly_n96_deg1_c20_replaced_noGIA_noMean_2002-04_2017-06_interp_ddk3.dat
→ inputTimeSplineGrace2018200204201706 defines the path and the filename of a time spline. This time spline stores potential coefficients which describe the monthly gravity field in a time frame from 04/2002 to 06/2017 as it was observed by GRACE. The resulting gravity field is already pre-processed.

Θ inputTimeSplineGrace2018200204201608: /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2018/timeSplines/old_monthly/timeSpline_ITSG-Grace2018_monthly_n96_deg1_c20_replaced_noGIA_noMean_2002-04_2016-08_interp_ddk3.dat
→ inputTimeSplineGrace2018200204201706 defines the path and the filename of a time spline. This time spline stores potential coefficients which describe the monthly gravity field in a time frame from 04/2002 to 08/2016 as it was observed by GRACE. The resulting gravity field is already pre-processed.

Θ kernel
<u>kernel: waterHeight</u> → kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 3: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n. <u>density: 1025</u> → density defines that the density of the water should be 1025 $\frac{kg}{m^3}$. <u>inputfileLoadingLoveNumber: data/loadLoveNumbers_Gegout97.txt</u> → inputfileLoadingLoveNumber defines the path and the filename of the loading love number input file. Hence, the load love numbers describe the elastic reaction of the crust and the mantle of the Earth to the loading mass on the surface.

Θ mjdExists
<u>mjdExists: fileExist</u> → mjdExists is the name of a variable which can be used to check if a file or directory exists.

<u>file: data/Grids/GriddedWaterLevel/{folderName}/{mjd}.txt</u> → file defines the path and the filename of the file whose existence should be checked.

1 RunCommand

Goal:

The goal is to execute system commands.

Parameters:

command: /home/annika/groops/scenario/230527_GlobalCDA_Version_neues_Groops/ 2019_03_GlobalCDA/pythonPrograms/GlobalCDA.py
→ command defines that the python script "GlobalDCA.py" should be executed.

silently: no
→ silently defines that the output should be shown.

continueAfterError: no
→ continueAfterError defines that the program should not continue with the next iteration when an error occurs.

executeParallel: no
→ executeParallel defines that several commands should not be executed in parallel.

Result:

The function RunCommand generates four different .txt files, which are named "{listName}_borderList.txt", "{listName}_infoList.txt", "{listName}_mergedList.txt" and "{listName}_timeseriesList.txt". The .txt file "{listName}_borderList.txt" contains a list of dictionaries. Each dictionary contains several variables, such as for instance the type of the water body. Meanwhile, the .txt file with the name "{listName}_infoList.txt" contains the name of the water body, the name of the country in which the water body is located and the area in km^2. The .txt file "{listName}_mergedList.txt" contains the filename of the monthly water level time series for each water body, the filename of the respective border polygon and an internal id. Furthermore, the .txt file "{listName}_timeseriesList.txt" contains a list of dictionaries. Each dictionary contains several variables such as for instance the last update of the surface area, the continent or the latitude.

2 LoopPrograms

Goal:

The goal is to repeat the programs which are defined inside the loop.

Parameters:

loop
loop: fileAsciiTable → loop loops over a list of strings from files. inputfile: Projects/{listName}_mergedList.txt → inputfile defines the path and the filename of the file with the necessary strings. The strings have to be separated by a whitespace. startLine: 0 → startLine defines the line from which the loop should start. In this case the loop should start from the first line, which has the index 0. countLines: --- → countLines defines that the number of read count lines should not be further specified. Hence, all lines are read. variableLoopString: timeseriesFile → variableLoopString defines that the variable name for the 1. column should be "timeseriesFile". variableLoopString: borderFile → variableLoopString defines that the variable name for the 2. column should be "border-File". variableLoopString: folderName → variableLoopString defines that the variable name for the 3. column should be "folder-Name". variableLoopString: globalcda_poly_id → variableLoopString defines that the variable name for the 4. column should be "glob-alcda_poly_id". variableLoopIndex: lake → variableLoopIndex defines that the variable with the index of the current iteration should be "lake". variableLoopCount: ---

→ variableLoopCount defines that the total number of iterations should not be counted.

continueAfterError: no
→ continueAfterError defines that the program should not continue with the next iteration when an error occurs.

processCountPerIteration: 0
→ processCountPerIteration defines that all processes should be used within each iteration.

parallelLog: yes
→ parallelLog defines that all processing nodes should be executed in parallelized loops.

2.1 LoopPrograms

Goal:

The goal is to repeat the programs which are defined inside the loop.

Parameters:

loop
<u>loop: timeSeries</u> → loop loops over points in time and generates a series in ascending order. <u>timeSeries: Θ timeFrame [= monthly]</u> → timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016. <u>variableLoopTime: mjd</u> → variableLoopTime defines that monthly iterations should be performed. <u>variableLoopIndex: ---</u> → variableLoopIndex defines that the variable with the index of the current iteration should not be further specified. <u>variableLoopCount: ---</u> → variableLoopCount defines that the total number of iterations should not be counted.

continueAfterError: no
→ continueAfterError defines that the program should not continue with the next iteration when an error occurs.

processCountPerIteration: 0
→ processCountPerIteration defines that all processes should be used within each iteration.

parallelLog: yes
→ parallelLog defines that all processing nodes should be executed in parallelized loops.

2.1.1 IfPrograms

Goal:

The goal is to run a list of programs when a certain condition is met. Otherwise, if it is defined, an elseProgram should be executed.

Parameters:

condition
<u>condition: fileExist</u> → condition defines that the program should check whether a directory or a file exists. <u>file: data/Grids/GriddedWaterLevel/{folderName}/0_shape.txt</u> → file defines the path and the filename of the file whose status should be checked.

2.1.1.1 File Remove

Goal:

The goal is to remove a file if the condition of the previous program IfPrograms evaluates to true.

Parameters:

files: data/Grids/GriddedWaterLevel/{folderName}/0_shape.txt
→ files defines the path and the filename of the files that should be removed if the condition evaluates to true.

elseProgram: ---
→ elseProgram defines that no program should be executed if the condition evaluates to false.

Result:

The function IfPrograms checks if the denoted file exists or not. If it exists, then it will be removed. This can be traced back to the fact, that the respective file was then computed throughout an earlier run of the program.

2.1.2 IfPrograms

Goal:

The goal is to run a list of programs when a certain condition is met. Otherwise, if it is defined, an elseProgram should be executed.

Parameters:

condition
condition: fileExist → condition defines that the program should check whether a directory or a file exists. file: data/Grids/GriddedWaterLevel/{folderName}/{mjd}.txt → file defines the path and the filename of the files whose status should be checked.

2.1.2.1 File Remove

Goal:

The goal is to remove a file if the condition of the previous program IfPrograms evaluates to true.

Parameters:

files: data/Grids/GriddedWaterLevel/{folderName}/{mjd}.txt
→ files defines the path and the filename of the files that should be removed if the condition evaluates to true.

elseProgram: ---
→ elseProgram defines that no program should be executed if the condition evaluates to false.

Result:

The function IfPrograms checks if the denoted file exists or not. If it exists, then it will be removed. This can be traced back to the fact, that the respective file was computed throughout an earlier run of the program.

2.2 GriddedDataCreate

Goal:

The goal is to create a set of water level grid points and to write them into an output grid.

Parameters:

outputfileGrid: data/Grids/GriddedWaterLevel/{folderName}/0_shape.txt
→ outputfileGrid defines the path and the filename of the new grid output files.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.025] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.025 °. deltaPhi: {gridSizeCoarse} [= 0.025] → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.025 °. height: 0.0 [= 0] → height defines that the distance of the points above the ellipsoid should be 0 m. R: 6378137.0 [= 6378137] → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. inverseFlattening: 298.2572221010 [= 298.2572221] → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 4: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 5: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137 \text{ m} - 6356752.3141 \text{ m})}{6378137 \text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: polygon

→ border defines that a regional subset of points should be extracted from the global grid.

inputfilePolygon: data/Borders/{borderFile}

→ inputfilePolygon defines the path and the filename of the polygon that should be extracted from the global grid.

buffer: 0

→ buffer defines that a barrier of 0 metre should be established around the polygon.

exclude: no

→ exclude defines that no points within the polygon should be dismissed.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the

inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 6: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by $\bar{f} = \frac{1}{f}$. Equation 7: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

value: 1.0 [= 1]
→value defines that the data0 column should be initialized with 1.0 values.

Result:

The function GriddedDataCreate generates one .txt file with gridded data for each considered water body. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.025 ° x 0.025 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column is initialized with values of 1.0.

2.3 LoopPrograms

Goal:

The goal is to repeat the programs which are defined inside the loop.

Parameters:

loop
<u>loop: fileAsciiTable</u> → loop loops over a list of strings from files. <u>inputfile: data/TimeSeries/WaterLevelMonthly/{timeseriesFile}</u> → inputfile defines the path and the filename of the files with the necessary strings. The strings have to be separated by a whitespace. <u>startLine: 0</u> → startLine defines the line from which the loop should start. In this case the loop should start from the first line, which has the index 0. <u>variableLoopString: mjd</u> → variableLoopString defines that the variable name for the 1. column should be "mjd". <u>variableLoopString: waterLevel</u> → variableLoopString defines that the variable name for the 2. column should be "waterLevel". <u>variableLoopIndex: ---</u> → variableLoopIndex defines that the variable with the index of the current iteration should not be further specified. <u>variableLoopCount: ---</u> → variableLoopCount defines that the total number of iterations should not be counted.

continueAfterError: no
→ continueAfterError defines that the program should not continue with the next iteration when an error occurs.

processCountPerIteration: 0
→ processCountPerIteration defines that all processes should be used within each iteration.

parallelLog: yes
→ parallelLog defines that all processing nodes should be executed in parallelized loops.

2.3.1 GriddedDataCalculate

Goal:

The goal is to manipulate the water level grid files.

Parameters:

outputfileGriddedData: data/Grids/GriddedWaterLevel/{folderName}/{mjd}.txt
→ outputfileGriddedData defines the path and the filename of the monthly grid output files.

inputfileGriddedData: data/Grids/GriddedWaterLevel/{folderName}/0_shape.txt
→ inputfileGriddedData defines the path and the filename of the gridded water level input files.

constant: ---
→ constant defines that no further constant is defined.

parameter: ---
→ parameter defines that no additional parameter is defined.

leastSquares: ---
→ leastSquares defines that the expression should not be minimized by adjusting the parameters.

removalCriteria: ---
→ removalCriteria defines that points should not be removed if one criterion evaluates true.

longitude: longitude
→ longitude is described by the expression longitude.

latitude: latitude
→ latitude is described by the expression latitude.

height: height
→ height is described by the expression height.

area: area
→ area is described by the expression area.

value: data0*{waterLevel}
→ value defines that the initialized values of the data0 column should be replaced by the actual water level. Therefore, the initialized values of 1.0 are multiplied with the water level.

computeArea: no
→ computeArea defines that no automatic area computation of rectangular grids, which will overwrite the area information, should be performed.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 8: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}$.

Equation 9: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\ m\ -\ 6356752.3141\ m)}{6378137\ m}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

statistics: <none>
→ statistics defines that no statistic columns should be computed.

Result:

The function GriddedDataCalculate generates monthly .txt files with gridded data for each considered water body. How many monthly .txt files will be computed depends on the length of the water level time series for each considered water body. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.025 ° x 0.025 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents water level in the unit of metres.

2.3.2 RunCommand

Goal:

The goal is to execute system commands.

Parameters:

command: awk 'NR==2 && $5==0 {system("rm data/Grids/GriddedWaterLevel/{folder-Name}/{mjd}.txt")}' data/Grids/GriddedWaterLevel/{folderName}/0_shape.txt
→ command defines that the gridded water level file should be removed if the respective file is empty. To check whether the file is empty, the number of grid cells, which is denoted in the header of each .txt file, is evaluated.

silently: no
→ silently defines that the output should be shown.

continueAfterError: no
→ continueAfterError defines that the program should not continue with the next iteration when an error occurs.

executeParallel: no
→ executeParallel defines that several commands should not be executed in parallel.

Result:

The function RunCommand removes each empty monthly gridded water level file. This step is necessary to concatenate the files which belong to one month in a later step.

3 LoopPrograms

Goal:

The goal is to repeat the programs which are defined inside the loop.

Parameters:

loop
loop: timeSeries → loop loops over points in time and generates a series in ascending order. timeSeries: Θ timeFrame [= monthly] → timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016. variableLoopTime: mjd → variableLoopTime defines that monthly iterations should be performed. variableLoopIndex: --- → variableLoopIndex defines that the variable with the index of the current iteration should not be further specified. variableLoopCount: --- → variableLoopCount defines that the total number of iterations should not be counted.

continueAfterError: no
→ continueAfterError defines that the program should not continue with the next iteration when an error occurs.

processCountPerIteration: 0
→ processCountPerIteration defines that all processes should be used within each iteration.

parallelLog: yes
→ parallelLog defines that all processing nodes should be executed in parallelized loops.

3.1 IfPrograms

Goal:

The goal is to run a list of programs when a certain condition is met. Otherwise, if it is defined, an elseProgram should be executed.

Parameters:

condition
condition: fileExist → condition defines that the program should check whether a directory or a file exists. file: data/Grids/GriddedWaterLevelCombinedFine/{listName}/{listName}_LGFine_{mjd}.txt → file defines the path and the filename of the files whose status should be checked.

3.1.1 File Remove

Goal:

The goal is to remove a file if the condition of the previous program IfPrograms evaluates to true.

Parameters:

files: data/Grids/GriddedWaterLevelCombinedFine/{listName}/{listName}_LGFine_{mjd}.txt
→ files defines the path and the filename of the files that should be removed if the condition evaluates to true.

elseProgram: ---
→ elseProgram defines that no program should be executed if the condition evaluates to false.

Result:

The function IfPrograms checks if the denoted file exists or not. If it exists, then it will be removed. This can be traced back to the fact, that the respective file was computed throughout an earlier run of the program.

3.2 GriddedDataConcatenate

Goal:

The goal is to concatenate the gridded water level files to monthly solutions and to write them to a new grid.

Parameters:

outputfileGriddedData: data/Grids/GriddedWaterLevelCombinedFine/{listName}/{listName}_LGFine_{mjd}.txt
→ outputfileGriddedData defines the path and the filename of the monthly concatenated water level fine grid output files.

inputfileGriddedData [loop= folderName][condition= mjdExists]: data/Grids/GriddedWaterLevel/{folderName}/{mjd}.txt
→ inputfileGriddedData defines the path and the filename of the monthly gridded water level input files over which should be looped. In order to do so, it is checked whether the path and the filename exist.

border: ---
→ border defines that no regional subset of points should be extracted from the global grid.

sortPoints: no
→ defines that the points should not be sorted from north / west to south / east.

removeDuplicates: <none>
→ removeDuplicates defines that duplicate points should not be removed.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 10: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$ Equation 11: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $\mathrm{f} = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$ $\mathrm{f} = 0.003352810681$ and thus, the inverseFlattening is $\bar{\mathrm{f}} = \frac{1}{0.003352810681}$ $\bar{\mathrm{f}} = 298.2572221.$

Result:

The function GriddedDataConcatenate generates 168 .txt file with combined gridded data from each considered water body for each month. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.025 ° x 0.025 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the water level value in the unit metre.

3.3 IfPrograms

Goal:

The goal is to run a list of programs when a certain condition is met. Otherwise, if it is defined, an elseProgram should be executed.

Parameters:

condition
<u>condition: fileExist</u> → condition defines that the program should check whether a directory or a file exists. <u>file: data/PotentialCoefficients/ForwardModelled/{listName}/{mjd}.txt</u> → file defines the path and the filename of the files whose status should be checked.

3.3.1 File Remove

Goal:

The goal is to remove a file if the condition of the previous program IfPrograms evaluates to true.

Parameters:

files: data/PotentialCoefficients/ForwardModelled/{listName}/{mjd}.txt
→ files defines the path and the filename of the files that should be removed if the condition evaluates to true.

elseProgram: ---
→ elseProgram defines that no program should be executed if the condition evaluates to false.

Result:

The function IfPrograms checks if the denoted file exists or not. If it exists, then it will be removed. This can be traced back to the fact, that the respective file was computed throughout an earlier run of the program.

3.4 GriddedData2PotentialCoefficients

Goal:

The goal is to use the gravity field functionals from the inputfileGriddedData and to estimate potential coefficients.

Parameters:

outputfilePotentialCoefficients: data/PotentialCoefficients/ForwardModelled/{listName}/{mjd}.txt
→ outputfileGriddedData defines the path and the filename of the monthly forward modelled potential coefficient output files.

inputfileGriddedData: data/Grids/GriddedWaterLevelCombinedFine/{listName}/{list-Name}_LGFine_{mjd}.txt
→ inputfileGriddedData defines the path and the filename of the monthly fine gridded water level input files.

value: data0
→ value defines the water level values should be used to compute the potential coefficients.

weight: area
→ weight defines that the cells and thus also the water level values should be weighted according to the size of the respective cell.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 12: Coefficients of the Kernel   Source: Mayer-Gürr et al., n.d.

includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]
→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

leastSquares: no
→ leastSquares defines that the potential coefficients should not be computed with a least squares approach, but with a quadrature Equation.

3.5 GriddedData2GriddedDataStatistics

Goal:

The goal is to assign gridded data to grid points and thus to change the resolution of the grid from 0.025 ° x 0.025 ° to 0.5 ° x 0.5 °.

Parameters:

outputfileGriddedData: data/Grids/GriddedWaterLevelCombinedCoarse/{listName}/{list-Name}_LGCoarse_{mjd}.txt
→ outputfileGriddedData defines the path and the filename of the monthly coarse grid output files.

inputfileGriddedData: data/Grids/GriddedWaterLevelCombinedFine/{listName}/{listName}_LGFine_{mjd}.txt
→ inputfileGriddedData defines the path and the filename of the monthly fine gridded water level input files.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. deltaPhi: {gridSizeCoarse} [= 0.5] → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. height: 0.0 [= 0] → height defines that the distance of the points above the ellipsoid should be 0 m. R: 6378137.0 [= 6378137] → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. inverseFlattening: 298.2572221010 [= 298.2572221] → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 13: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$ Equation 14: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: ---

→ border defines that no regional subset of points should be extracted from the global grid.

cellsPerNewCell: ({gridSizeCoarse}/{gridSizeFM}) [= 20]
→ cellsPerNewCell defines that 20 new points should be assigned to the same node.

statistic: fmean

→ statistics defines that fmean should be used as a statistical tool if multiple values fall on the same cell. It is computed by applying the following EquationEquation 15

$$\text{fmean} = \frac{\text{sum}}{\text{cellsPerNewCell}}.$$

Equation 15: Computation of fmean

Source: Mayer-Gürr et al., n.d.

emptyValue: 0
→ emptyValue defines that nodes which do not have any data should indicate a value of 0.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the

inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 16: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 17: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

Result:

The function GriddedData2GriddedDataStatistics generates one .txt file with gridded data for each month. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the water level. Each water level value refers to the fmean value of all water height values which fall onto that respective grid cell. Here, only those point coordinates, which are situated within one of the global inland water bodies, indicate a value. The remaining values are set to 0.

3.6 GriddedData2GriddedDataStatistics

Goal:

The goal is to assign gridded data to grid points and to thus change the resolution of the grid from 0.025 ° x 0.025 ° to 0.5 ° x 0.5 °. The output grid should be saved to another location than the grid which was processed throughout the previous computation.

Parameters:

outputfileGriddedData: data/Grids/RestoredNetCDF/{listName}_txt/{listName}_LGCoarse_{mjd}.txt
→ outputfileGriddedData defines the path and the filename of the monthly coarse grid output files.

inputfileGriddedData: data/Grids/GriddedWaterLevelCombinedFine/{listName}/{listName}_LGFine_{mjd}.txt
→ inputfileGriddedData defines the path and the filename of the monthly fine gridded water level input files.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. deltaPhi: {gridSizeCoarse} [= 0.5] → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. height: 0.0 [= 0] → height defines that the distance of the points above the ellipsoid should be 0 m. R: 6378137.0 [= 6378137] → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 18: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$ Equation 19: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $\mathrm{f} = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$ $\mathrm{f} = 0.003352810681$ and thus, the inverseFlattening is $\bar{\mathrm{f}} = \frac{1}{0.003352810681}$ $\bar{\mathrm{f}} = 298.2572221.$ border: --- → border defines that no regional subset of points should be extracted from the global grid.

cellsPerNewCell: ({gridSizeCoarse}/{gridSizeFM}) [= 20]
→ cellsPerNewCell defines that 20 new points should be assigned to the same node.

statistic: fmean
→ statistics defines that fmean should be used as statistical tool if multiple values fall on the same cell. It is computed by applying the following Equation $\text{fmean} = \frac{\text{sum}}{\text{cellsPerNewCell}}.$ Equation 20: Computation of fmean Source: Mayer-Gürr et al., n.d.

emptyValue: 0
→ emptyValue defines that nodes which do not have any data should indicate a value of 0.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$\mathrm{f} = \frac{(\text{Semimajor axis } - \text{ semiminor axis})}{\text{semimajor axis}}$$

Equation 21: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by

$$\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$$

Equation 22: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$\mathrm{f} = \frac{(6378137\text{ m } - \text{ } 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$\mathrm{f} = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{\mathrm{f}} = \frac{1}{0.003352810681}$$

$$\bar{\mathrm{f}} = 298.2572221.$$

Result:

The function GriddedData2GriddedDataStatistics generates one .txt file with gridded data for each month. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the water level. Each water level value refers to the fmean value of all water height values which fall onto that respective grid cell. Here, only those point coordinates, which are situated within one of the global inland water bodies, indicate a value. The remaining values are set to 0.

3.7 GridRectangular2NetCdf

Goal:

The goal is to convert a sequence of GridRectangular files, in this case the coarse grid files which have a resolution of 0.5 ° x 0.5 °, to a NetCdf file.

Parameters:

outputfileNetCdf: data/Grids/RestoredNetCDF/{listName}_nc/{listName}_Restored_ {mjd}.nc
→ outputfileNetCdf defines the path and the filename of the monthly NetCdf output files.

inputfileGridRectangular: data/Grids/GriddedWaterLevelCombinedCoarse/{listName}/ {listName}_LGCoarse_{mjd}.txt
→ inputfileGridRectangular defines the path and the filename of the monthly coarse gridded water level input files.

times
times: uniformSampling → times defines that a series of points along a time axis should be created in ascending order. In respect of a uniform sampling, a time series with a uniform sampling is generated. timeStart: {mjd} [= 00:00:00] → timeStart defines that the first point in time should be the first available modified julian date. timeEnd: {mjd} [= 00:00:00] → timeEnd defines that the last point in time should be the last available modified julian date. sampling: 1 [= 1 d]

→ sampling defines that the time step between the generated points in time should be 1.

dataVariable
dataVariable: --- → dataVariable defines that the metadata for the data variables should be set. selectDataField: 0 → selectDataField defines that the first data field, which refers to data0 and which contains the water level values, should be selected. name: EWH → name defines that the variable within the NetCdf file should be named "EWH". datatype: float → datatype defines that the EWH values should be of type float. attribute: --- → attribute defines that no further attributes should be written into the NetCdf file.

globalAttribute: --- → globalAttribute defines that no further meta data should be written into the NetCdf file.

Result:

The function GridRectangular2NetCdf generates one NetCdf file for each month. Each NetCdf file contains the respective modified julian date, the longitudes and the latitudes for each 0.5 ° and a matrix which contains the water level values for each grid cell.

3.8 NetCdfInfo

Goal:

The goal is to retrieve information of the generated NetCdf files.

Parameters:

inputfileNetCdf: data/Grids/RestoredNetCDF/{listName}_nc/{listName}_Restored_{mjd}.nc
→ inputfileNetCdf defines the path and the filename of the monthly NetCdf input files from which information such as dimensions and variables should be derived.

Result:

The function NetCdfInfo displays the information of each NetCdf file in the console. This information includes the variables time, latitude, longitude, value as well as the dimension of each file and, if available, global attributes.

4 PotentialCoefficients2BlockMeanTimeSplines

Goal:

The goal is to write the monthly potential coefficients into one time spline file.

Parameters:

outputfileTimeSplines: data/PotentialCoefficients/TimeSplines/{listName}_ForModTime-Splines.gfc
→ outputfileTimeSplines defines the path and the filename of the forward modelled time spline output file.

outputfileTimeSplinesCovariance: ---
→ outputfileTimeSplinesCovariance defines that the variances should not be saved.

inputfilePotentialCoefficients [loop= LocationPC2BMTS]: data/PotentialCoefficients/For-wardModelled/{listName}/{InputPC2BMTS}
→ inputfilePotentialCoefficients defines the path and the filename of the monthly forward modelled potential coefficient files over which should be looped and which are necessary to compute the time spline.

filter
filter: filterDdk → filter allows to filter the spherical harmonic expansion. filterDdk performs an orderwise filtering with the DDK filter developed by Kusche. et al., in 2009. Hereby, DDK is an abbreviation for denoising and decorrelation kernel. In comparison to the original Kusche filter from 2007, the new, simplified approach allows to realize a higher resolution whereas far less coefficients have to be stored (Kusche et al., 2009). level: 3 → level defines that the DDK filter level should be three. The higher the level, the weaker is the filter. inputfileNormalEquation: /data1/sphericalHarmonicsFilter/DDK/normalsKuscheGfzBlock_n2-120_orderwiseNonAlternating.dat.gz → inputfileNormalEquation defines the path and the filename of the DDK filter input file.

minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]
→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

removeMean: yes
→ removeMean removes the temporal mean of the series before the spline is estimated. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

interpolate: no
→ interpolate defines that missing files should not be interpolated.

splineTimeSeries: Θ timeFramePC2BMTS [= monthly]
→ splineTimeSeries defines that the potential coefficients are valid in a time frame reaching from 01/2003 to 12/2016. Since the time interval is monthly, it is defined between adjacent points in time. For a degree of 0, one more point in time is needed than the number of potential coefficient files.

splineDegree: 0
→ splineDegree defines that the degree of the spline should be 0. A spline degree of 0 refers to a temporal block means. Hence, the spline function is a piece wise constant function. Consequently, it is also denoted as step function (House, 2014).

Result:

The function PotentialCoefficients2BlockMeanTimeSplines uses all forward modelled coefficients, filters them and writes them into one time spline file. Hence, the time spline file contains the monthly dates expressed as modified julian date and 168 triangular matrices which store the filtered spherical harmonic coefficients up to a degree of 96 for each month.

5 LoopPrograms

Goal:

The goal is to repeat the programs which are defined inside the loop.

Parameters:

loop
loop: timeSeries → loop loops over points in time and generates a series in ascending order. timeSeries: Θ timeFrame [= monthly] → timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016. variableLoopTime: mjd → variableLoopTime defines that monthly iterations should be performed. variableLoopIndex: --- → variableLoopIndex defines that the variable with the index of the current iteration should not be further specified. variableLoopCount: --- → variableLoopCount defines that the total number of iterations should not be counted.

continueAfterError: no
→ continueAfterError defines that the program should not continue with the next iteration when an error occurs.

processCountPerIteration: 0
→ processCountPerIteration defines that all processes should be used within each iteration.

parallelLog: yes
→ parallelLog defines that all processing nodes should be executed in parallelized loops.

5.1 Gravityfield2GriddedData

Goal:

The goal is to compute gravity field values on a given grid.

Parameters:

outputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_FM_{mjd}.txt
→ outputfileGriddedData defines the path and the filename of the monthly forward modelled gravity field grid output files.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. deltaPhi: {gridSizeCoarse} [= 0.5] → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. height: 0.0 [= 0] → height defines that the distance of the points above the ellipsoid should be 0 m. R: 6378137.0 [= 6378137] → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. inverseFlattening: 298.2572221010 [= 298.2572221] → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 23: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 24: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: Θ gridBorder [= rectangle]

→ border allows to extract a regional subset of points from the global grid. In this case the rectangle defines a global grid.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $$k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$$ Equation 25: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc] → inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

time: {mjd} [= 00:00:00]
→ time defines that the gravity field should be evaluated once a month.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 26: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$ Equation 27: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $\mathrm{f} = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$ $\mathrm{f} = 0.003352810681$ and thus, the inverseFlattening is $\bar{\mathrm{f}} = \frac{1}{0.003352810681}$ $\bar{\mathrm{f}} = 298.2572221.$

Result:

The function Gravityfield2GriddedData generates one .txt file with gridded data for each month. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gravity field in terms of equivalent water height values in the unit of metres.

5.2 GriddedDataConcatenate

Goal:

The goal is to concatenate several monthly gravity field grid inputs and to write them to a new grid.

Parameters:

outputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_FM_{mjd}_masked.txt
→ outputfileGriddedData defines the path and the filename of the monthly concatenated forward modelled gravity field grid output files.

inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_FM_{mjd}.txt
→ inputfileGriddedData defines the path and the filename of the monthly forward modelled gridded gravity field input files.

border
border: polygon → border allows to select a polygon region on the surface of the Earth by defining the longitude and the latitude of the polygon coordinates. inputfilePolygon: /data2/backup_poessneck_2023_01_23/groopsData/border/continents.xml → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates. buffer: 0 → buffer defines that a barrier of 0 metre should be established around the polygon. exclude: no → exclude defines that no points within the polygon should be dismissed. Hence, all continents are selected.

border
<u>border: polygon</u> → border allows to select a polygon region on the surface of the Earth by defining the longitude and the latitude of the polygon coordinates. <u>inputfilePolygon: /data2/backup_poessneck_2023_01_23/groopsData/border/antarctica.xml</u> → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for Antarctica. <u>buffer: 0</u> → buffer defines that a barrier of 0 metre should be established around the polygon. <u>exclude: yes</u> → exclude defines that the points within the polygon should be dismissed. Hence, Antarctica should be dismissed. This can be traced back to the fact, that Antarctica is covered by snow and ice and thus, the processing of the observed data deviates from the processing of conventional vegetation zones.

sortPoints: no
→ defines that the points should not be sorted from north / west to south / east.

removeDuplicates: <none>
→ removeDuplicates defines that duplicate points should not be removed.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 28: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by $\bar{f} = \frac{1}{f}.$ Equation 29: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

Result:

The function GriddedDataConcatenate generates one .txt file with gridded data for each month. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the forward modelled gravity field in terms of equivalent water height values on all continents except Antarctica.

5.3 PlotMap

Goal:

The goal is to generate a global map which visualizes the removal correction for each considered water body and for every month in a time frame from 01/2003 to 12/2016.

Parameters:

outputfile: data/Maps/{listName}/{listName}_FM_{mjd}.png
→ outputfile defines the path and the filename of the generated output map.

title: RECOG-LR RL01 (removal correction) {mjd:%y-%m}
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid. width: 0.5 → width defines that the width of the coastlines should be 0.5 points. color: black → color defines that the colour of the coastlines should be black. landColor: rgb → landColor defines that the land area should be filled with rgb values. red: 218 → red defines that the intensity of the red colour should be 218. green: 214 → green defines that the intensity of the green colour should be 214. blue: 211 → blue defines that the intensity of the blue colour should be 211. oceanColor: gray → oceanColor defines that the ocean area should be filled with a gray colour. minArea: 10000 → minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

layer
layer: griddedData → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_FM_{mjd}_masked.txt → inputfileGriddedData defines the path and the filename of the monthly concatenated forward modelled gridded gravity field input files. value: data0*100 → value defines that data0, which contains the forward modelled equivalent water height values that define the gravity field, should be multiplied with 100 to change the unit from metre to centimetre. increment: 0.5 → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid. illuminate: no → illuminate defines that the grid should not be brightened. resample: <none> → resample defines that the concatenated gravity field grid input values should not be resampled. gridlineRegistered: no → gridlineRegistered defines that the input should not be treated as point values but as cell means.

layer
layer: polygon → layer defines the content of the map. Hence, a polygon around the Black Sea should be drawn. inputfilePolygon: /data2/backup_poessneck_2023_01_23/groopsData/border/specialBorders/blackSea_poly.txt → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the Black Sea. line: solid → line defines that the line style of the polygon should be solid.

width: 0

→ width defines that the width of the coastlines should be 0 points. Since the layer coast is activated, the polygon can be seen anyways.

color: black

→ color defines that the colour of the polygon should be black.

fillColor: gray

→ fillColor defines that the polygon should be filled with a gray colour.

value: 175

→ value defines that the fillColor should have the value 175. Hence, the fill colour is computed from a colour bar.

drawLineAsGreatCircle: yes

→ drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

layer

layer: coast

→ layer defines the content of the map. Hence, coastlines should be plotted.

resolution: medium

→ resolution defines that the resolution of the coastlines should be medium.

line: solid

→ line defines that the line style of the coastlines should be solid.

width: 0.5

→ width defines that the width of the coastlines should be 0.5 points.

color: black

→ color defines that the colour of the coastlines should be black.

landColor: <none>

→ landColor defines that there is no specific colour with which the land area should be filled.

oceanColor: <none>

→ oceanColor defines that the ocean area should be filled with a gray colour.

minArea: 10000

→ minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 30: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 31: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 0
→ majorTickSpacing defines that the boundary annotation should be set every 0 °. Hence, no annotation is given at all.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 0
→ gridLineSpacing defines that the spacing of the grid lines should be set every 0 °. Hence, no grid lines are drawn at all.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: - 30 → min defines that the minimum value of the colour bar should be set to - 30. max: 30 → max defines that the maximum value of the colour bar should be set to 30. annotation: --- → annotation defines that no boundary annotation should be drawn. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [cm]

→ label defines that the axis description and hence the description of the colour bar should be set to "EWH [cm]". logarithmic: no → logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. triangleRight: yes → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. illuminate: no → illuminate defines that the grid should not be brightened. vertical: no → vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. length: 100 → length defines that the length of the colour bar should be 100 %. margin: 0.4 → margin defines that the space between the colour bar and the figure should be 0.4 cm. colorTable: vik → colorTable defines that the colour bar with the name "vik" should be used. This colour bar ranges from dark blue to dark brown. reverse: yes → reverse defines that the colour bar should be reversed. Hence, the colour bar ranges from dark brown to dark blue. showColorbar: yes → showColorbar defines that the colour bar should be plotted.

projection
projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other

meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions.

centralMeridian: 0

→ centralMeridian defines that the central meridian should be set at 0 °.

options
width: 16 → width defines that the width of the plot should be 16 cm. height: --- → height defines that the height of the plot given in centimetre should not be further specified. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. options: FONT_ANNOT_PRIMARY=10p → options defines that the font which is used for primary annotations should be 10 pixels. options: MAP_ANNOT_OFFSET_PRIMARY=0.1c → options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm. options: FONT_LABEL=10p → options defines that the font, which is used to plot the labels below the annotation, should be 10 points. options: MAP_LABEL_OFFSET=0.1c → options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm. options: FONT_ANNOT_SECONDARY=10p → options defines that the font for a secondary time axis should be 10 points. transparent: no

→ transparent defines that the background of the plot should not be transparent. dpi = 300 → dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch. removeFiles: yes → removeFiles defines that the .gmt and script files should be removed after the computation. viewPlot: no → viewPlot defines that the plot should not be automatically shown after the computation.

Result:

The function PlotMap generates 168 monthly global maps within a time frame of 01/2003 to 12/2016. Each map represents the first release of the monthly computed removal correction. The removal correction is expressed in terms of equivalent water height values, which are indicated in the unit of centimetre. Hence, each map visualizes the size of the forward modelled equivalent water height values that has to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact, that the prevailing water body has on the processed equivalent water height values, which were derived from GRACE observations, can be removed. Hence, the GRACE signal can be corrected. Consequently, each map functions as an indicator which shows how strong each water body actually influences the mass change observed by GRACE. This information is extremely helpful to make the estimates of GRACE more consistent with the output from hydrological models.

5.4 GriddedData2GriddedDataStatistics

Goal:

The goal is to assign gridded data to grid points. In comparison to the computation performed under 3.5 GRIDDEDDATA2GRIDDEDDATASTATISTICS, not the statistical operation fmean, but mean is used. This means that in case multiple values fall on the same cell, the mean value of those values is assigned to the cell. The final grid should have a resolution of 0.5 ° x 0.5 °.

Parameters:

outputfileGriddedData: data/Grids/RemovedNetCDF/{listName}_txt/{listName}LGCoarse _{mjd}.txt
→ outputfileGriddedData defines the path and the filename of the monthly coarse grid output files.

inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_FM_{mjd}.txt
→ inputfileGriddedData defines the path and the filename of the monthly concatenated forward modelled gridded equivalent water height value input files.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. deltaPhi: {gridSizeCoarse} [= 0.5] → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. height: 0.0 [= 0] → height defines that the distance of the points above the ellipsoid should be 0 m. R: 6378137.0 [= 6378137] → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. inverseFlattening: 298.2572221010 [= 298.2572221] → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 32: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$ Equation 33: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\ \mathrm{m}\ -\ 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$ <u>border: ---</u> → border defines that no regional subset of points should be extracted from the global grid.

cellsPerNewCell: 1
→ cellsPerNewCell defines that 1 new point should be assigned to the same node.

statistic: mean
→ statistics defines that mean should be used as statistical tool if multiple values fall on the same cell.

emptyValue: 0
→ emptyValue defines that nodes which do not have any data should indicate a value of 0.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis}\ -\ \text{semiminor axis})}{\text{semimajor axis}}$

Equation 34: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 35: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

Result:

The function GriddedData2GriddedDataStatistics generates one .txt file with gridded data for each month. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gravity field in terms of equivalent water height values. The equivalent water height value of each grid cell refers to the mean value of all water height values that fall onto the respective grid cell.

5.5 GridRectangular2NetCdf

Goal:

The goal is to convert a sequence of GridRectangular files, in this case the monthly coarse grid files with a resolution of 0.5 ° x 0.5 °, to a NetCdf file.

Parameters:

outputfileNetCdf: data/Grids/RemovedNetCDF/{listName}_nc/listName}_Restored_{mjd}.nc
→ outputfileNetCdf defines the path and the filename of the monthly NetCdf output files.

inputfileGridRectangular: data/Grids/RemovedNetCDF/{listName}_txt/listName}_LGCoarse_{mjd}.txt
→ inputfileGridRectangular defines the path and the filename of the monthly forward modelled coarse gridded gravity field input files.

times
times: uniformSampling → times defines that a series of points along a time axis should be created in ascending order. In respect of a uniform sampling, a time series with a uniform sampling is generated. timeStart: {mjd} [= 00:00:00] → timeStart defines that the first point in time should be the first available modified julian date. timeEnd: {mjd} [= 00:00:00] → timeEnd defines that the last point in time should be the last available modified julian date. sampling: 1 [= 1 d] → sampling defines that the time step between the generated points in time should be 1.

dataVariable
dataVariable: --- → dataVariable defines that the metadata for the data variables should be set. selectDataField: 0 → selectDataField defines that the first data field, which refers to data0 and which contains the processed equivalent water height values, which were derived from GRACE observations, should be selected. name: EWH → name defines that the variable within the NetCdf file should be named "EWH".

datatype: float
→ datatype defines that the EWH values should be of type float.
attribute: ---
→ attribute defines that no further attributes should be written into the NetCdf file.

globalAttribute: ---
→ globalAttribute defines that no further meta data should be written into the NetCdf file.

Result:

The function GridRectangular2NetCdf generates one NetCdf file for each month. Each NetCdf file contains the respective modified julian date, the longitudes and the latitudes for each 0.5 ° and a matrix which contains the processed equivalent water height values, which were derived from GRACE observations, for each grid cell.

5.6 NetCdfInfo

Goal:

The goal is to retrieve information of the generated NetCdf files.

Parameters:

inputfileNetCdf: data/Grids/RemovedNetCDF/{listName}_nc/listName}_Restored_{mjd}.nc
→ inputfileNetCdf defines the path and the filename of the monthly NetCdf output files from which information such as dimensions and variables should to be derived.

Result:

The function NetCdfInfo displays the information of each NetCdf file in the console. This information includes the variables time, latitude, longitude, value as well as the dimension of each file and, if available, global attributes.

6 GroupPrograms

Goal:

The goal is to run the individually defined programs in a group.

Parameters:

outputfileLog: ---
→ outpufileLog defines that no additional log file should be created.

silently: no
→ silently defines that the output should be shown.

6.1 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean forward modelled equivalent water height values which express the time variable gravity field over the Mississippi Basin.

Parameters:

outputfileTimeSeries: data/TimeSeries/FMtestMississippi.txt
→ outputfileTimeSeries defines the path and the filename of the mean forward modelled equivalent water height value time series output file for the Mississippi Basin.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. deltaPhi: {gridSizeCoarse} [= 0.5] → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °.

height: 0.0 [= 0]

→ height defines that the distance of the points above the ellipsoid should be 0 m.

R: 6378137.0 [= 6378137]

→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 36: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 37: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: polygon

→ border defines that a subset of points should be extracted from the global grid.

inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin.txt

→ inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the Mississippi Basin.

buffer: 0

→ buffer defines that a barrier of 0 metre should be established around the polygon.

exclude: no

→ exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

<table>
<tr><td>kernel</td></tr>
<tr><td>
<u>kernel: filterGauss</u>
→ kernel defines harmonic isotropic integral kernels K. Each kernel can be smoothed by a gauss filter which is defined by
$$F(\cos\psi) = \frac{b \cdot e^{-b(1-\cos\psi)}}{1 - e^{-2b}}$$
Equation 38: Gauss filter
Source: Mayer-Gürr et al., n.d.
and where
$$b = \frac{\ln(2)}{1 - \cos\left(\frac{r}{R}\right)}$$
Equation 39: Strength of the Gaussian Filtering
Source: Mayer-Gürr et al., n.d. and (Rexer, 2012)
While ψ indicates the angle between x and y, r refers to the filter radius in kilometre and R implies the radius of the Earth also indicated in kilometre.
<u>kernel: Θ kernel [= waterHeight]</u>
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n
$$k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$$
Equation 40: Coefficients of the Kernel
Source: Mayer-Gürr et al., n.d.
includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.
<u>radius: 300</u>
</td></tr>
</table>

→ radius defines the filter radius in kilometres.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc] → inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the Mississippi Basin. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the gravity field is expressed in terms of an averaged, filtered and forward modelled equivalent water height value. The unit of this equivalent water height value is metre.

6.2 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean equivalent water height values which express the time variable gravity field and which were derived from GRACE observations over the Mississippi Basin.

Parameters:

outputfileTimeSeries: data/TimeSeries/GRACEtestMississippi.txt
→ outputfileTimeSeries defines the path and the filename of the mean equivalent water height value time series output file for the Mississippi Basin.

grid
<u>grid: geograph</u> → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. <u>deltaLambda: {gridSizeCoarse} [= 0.5]</u> → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. <u>deltaPhi: {gridSizeCoarse} [= 0.5]</u> → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. <u>height: 0.0 [= 0]</u> → height defines that the distance of the points above the ellipsoid should be 0 m. <u>R: 6378137.0 [= 6378137]</u> → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. <u>inverseFlattening: 298.2572221010 [= 298.2572221]</u> → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 41: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by $\bar{f} = \frac{1}{f}.$ Equation 42: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$ $f = 0.003352810681$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: polygon

→ border defines that a subset of points should be extracted from the global grid.

inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin.txt

→ inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the Mississippi Basin.

buffer: 0

→ buffer defines that a barrier of 0 metre should be established around the polygon.

exclude: no

→ exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel

kernel: Θ kernel [= waterHeight]

→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n

$$k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$$

Equation 43: Coefficients of the Kernel

Source: Mayer-Gürr et al., n.d.

includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
<u>gravityfield: timeSplines</u> → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. <u>inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2016200212201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2016/itsg-grace2016_MD90_deg1c20repl_no1502_GIAreduced_mean-red_DDK3_interp_200212-201706.dat]</u> → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. <u>inputfileTimeSplinesCovariance: ---</u> → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. <u>minDegree: {minDegree} [= 0]</u> → minDegree defines that the minimum degree of the expansion should be 0 °. <u>maxDegree: 60</u> → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. <u>factor: 1.0 [= 1]</u> → factor defines that the result should be multiplied by 1. This factor is defined by default.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the Mississippi Basin. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the gravity field is expressed in terms of an equivalent water height value. The unit of this equivalent water height value is metre. In this case, the processed equivalent water height values are not forward modelled, but directly derived from the GRACE observations. These observations are already pre-processed. Hence, the data is already interpolated and the effect of the glacial isostatic adjustment is also removed.

6.3 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean equivalent water height values which express the corrected time variable gravity field over the Mississippi Basin.

Parameters:

outputfileTimeSeries: data/TimeSeries/GRACE-FMtestMississippi.txt
→ outputfileTimeSeries defines the path and the filename of the corrected mean equivalent water height value time series output file for the Mississippi Basin.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude.

deltaLambda: {gridSizeCoarse} [= 0.5]

→ deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °.

deltaPhi: {gridSizeCoarse} [= 0.5]

→ deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °.

height: 0.0 [= 0]

→ height defines that the distance of the points above the ellipsoid should be 0 m.

R: 6378137.0 [= 6378137]

→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 44: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 45: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: polygon

→ border defines that a subset of points should be extracted from the global grid.

<u>inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin.txt</u> → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the Mississippi Basin. <u>buffer: 0</u> → buffer defines that a barrier of 0 metre should be established around the polygon. <u>exclude: no</u> → exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel
<u>kernel: Θ kernel [= waterHeight]</u> → kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 46: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
<u>gravityfield: timeSplines</u> → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. <u>inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2016200212201706 [= /data2/ backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2016/itsg-grace2016_</u>

MD90_deg1c20repl_no1502_GIAreduced_mean-red_DDK3_interp_200212-201706.dat] → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: data/PotentialCoefficients/TimeSplines/testList_ForModTimeSplinesDDK3.gfc] → inputfileTimeSplinesGravityfield defines the path and the filename of a test forward modelled time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: - 1

→ factor defines that the forward modelled equivalent water height values, which represent the gravity field, should be subtracted from the processed equivalent water height values which were derived from GRACE observations.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the Mississippi Basin. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the corrected time variable gravity field is expressed in terms of an averaged equivalent water height value. The unit of the averaged equivalent water height value is metre. Hence, the corrected equivalent water height values refer to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations.

6.4 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean forward modelled equivalent water height values which express the time variable gravity field over the first unit of the Mississippi Basin.

Parameters:

outputfileTimeSeries: data/TimeSeries/FM_Mississippi_u1.txt
→ outputfileTimeSeries defines the path and the filename of the mean forward modelled equivalent water height value time series output file for the unit 1 of the Mississippi Basin.

grid
<u>grid: geograph</u> → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. <u>deltaLambda: {gridSizeCoarse} [= 0.5]</u> → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. <u>deltaPhi: {gridSizeCoarse} [= 0.5]</u> → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. <u>height: 0.0 [= 0]</u> → height defines that the distance of the points above the ellipsoid should be 0 m. <u>R: 6378137.0 [= 6378137]</u> → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. <u>inverseFlattening: 298.2572221010 [= 298.2572221]</u> → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis } - \text{ semiminor axis})}{\text{semimajor axis}}$ Equation 47: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by $\bar{f} = \frac{1}{f}.$ Equation 48: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\ m\ -\ 6356752.3141\ m)}{6378137\ m}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$ <u>border: polygon</u> → border defines that a subset of points should be extracted from the global grid. <u>inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit1_Hermann.txt</u> → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Hermann of the Mississippi Basin. <u>buffer: 0</u> → buffer defines that a barrier of 0 metre should be established around the polygon. <u>exclude: no</u> → exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel
<u>kernel: filterGauss</u> → kernel defines harmonic isotropic integral kernels K. Each kernel can be smoothed by a gauss filter which is defined by

$$F(\cos\psi) = \frac{b \cdot e^{-b(1-\cos\psi)}}{1 - e^{-2b}}$$ Equation 49: Gauss filter Source: Mayer-Gürr et al., n.d. and where $$b = \frac{\ln(2)}{1 - \cos\left(\frac{r}{R}\right)}$$ Equation 50: Strength of the Gaussian Filtering Source: Mayer-Gürr et al., n.d. and (Rexer, 2012) While ψ indicates the angle between x and y, r refers to the filter radius in kilometre and R implies the radius of the Earth also indicated in kilometre. kernel: Θ kernel [= waterHeight] → kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $$k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$$ Equation 51: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n. radius: 300 → radius defines the filter radius in kilometres.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc] → inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file.

inputfileTimeSplinesCovariance: ---
→ inputfileTimeSplinesCovariance defines that no covariance time spline should be used.
minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.
maxDegree: 60
→ maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time.
factor: 1.0 [= 1]
→ factor defines that the result should be multiplied by 1. This factor is defined by default.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the unit Hermann of the Mississippi Basin. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the gravity field is expressed in terms of an averaged, filtered and forward modelled equivalent water height value. The unit of this equivalent water height value is metre.

6.5 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean forward modelled equivalent water height values which express the time variable gravity field over the second unit of the Mississippi Basin.

Parameters:

outputfileTimeSeries: data/TimeSeries/FM_Mississippi_u2.txt
→ outputfileTimeSeries defines the path and the filename of the mean forward modelled equivalent water height value time series output file for the unit 2 of the Mississippi Basin.

grid
<u>grid: geograph</u> → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. <u>deltaLambda: {gridSizeCoarse} [= 0.5]</u> → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. <u>deltaPhi: {gridSizeCoarse} [= 0.5]</u> → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. <u>height: 0.0 [= 0]</u> → height defines that the distance of the points above the ellipsoid should be 0 m. <u>R: 6378137.0 [= 6378137]</u> → R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 52: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 53: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: polygon

→ border defines that a subset of points should be extracted from the global grid.

inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit2_Alton.txt

→ inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Alton of the Mississippi Basin.

buffer: 0

→ buffer defines that a barrier of 0 metre should be established around the polygon.

exclude: no

→ exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel
<u>kernel: filterGauss</u> → kernel defines harmonic isotropic integral kernels K. Each kernel can be smoothed by a gauss filter which is defined by $F(\cos\psi) = \frac{b \cdot e^{-b(1-\cos\psi)}}{1 - e^{-2b}}$ Equation 54: Gauss filter Source: Mayer-Gürr et al., n.d. and where $b = \frac{\ln(2)}{1 - \cos\left(\frac{r}{R}\right)}$ Equation 55: Strength of the Gaussian Filtering Source: Mayer-Gürr et al., n.d. and (Rexer, 2012) While ψ indicates the angle between x and y, r refers to the filter radius in kilometre and R implies the radius of the Earth also indicated in kilometre. <u>kernel: Θ kernel [= waterHeight]</u> → kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 56: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n. <u>radius: 300</u> → radius defines the filter radius in kilometres.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc] → inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the unit Alton of the Mississippi Basin. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the gravity field is expressed in terms of an averaged, filtered and forward modelled equivalent water height value. The unit of this equivalent water height value is metre.

6.6 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean forward modelled equivalent water height values which express the time variable gravity field over the third unit of the Mississippi Basin.

Parameters:

outputfileTimeSeries: data/TimeSeries/FM_Mississippi_u3.txt
→ outputfileTimeSeries defines the path and the filename of the mean forward modelled equivalent water height value time series output file for the unit 3 of the Mississippi Basin.

grid
<u>grid: geograph</u> → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. <u>deltaLambda: {gridSizeCoarse} [= 0.5]</u> → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °.

deltaPhi: {gridSizeCoarse} [= 0.5]

→ deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °.

height: 0.0 [= 0]

→ height defines that the distance of the points above the ellipsoid should be 0 m.

R: 6378137.0 [= 6378137]

→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 57: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 58: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: polygon

→ border defines that a subset of points should be extracted from the global grid.

inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit3_Metropolis.txt

→ inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Metropolis of the Mississippi Basin.

<u>buffer: 0</u>

→ buffer defines that a barrier of 0 metre should be established around the polygon.

→ exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel

<u>kernel: filterGauss</u>

→ kernel defines harmonic isotropic integral kernels K. Each kernel can be smoothed by a gauss filter which is defined by

$$F(\cos\psi) = \frac{b \cdot e^{-b(1-\cos\psi)}}{1 - e^{-2b}}$$

Equation 59: Gauss filter

Source: Mayer-Gürr et al., n.d.

and where

$$b = \frac{\ln(2)}{1 - \cos\left(\frac{r}{R}\right)}$$

Equation 60: Strength of the Gaussian Filtering

Source: Mayer-Gürr et al., n.d. and (Rexer, 2012)

While ψ indicates the angle between x and y, r refers to the filter radius in kilometre and R implies the radius of the Earth also indicated in kilometre.

<u>kernel: Θ kernel [= waterHeight]</u>

→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n

$$k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$$

Equation 61: Coefficients of the Kernel

Source: Mayer-Gürr et al., n.d.
includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n. radius: 300 → radius defines the filter radius in kilometres.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc] → inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the unit Metropolis of the Mississippi Basin. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the gravity field is expressed in terms of an averaged, filtered and forward modelled equivalent water height value. The unit of this equivalent water height value is metre.

6.7 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean forward modelled equivalent water height values which express the time variable gravity field over the fourth unit of the Mississippi Basin.

Parameters:

outputfileTimeSeries: data/TimeSeries/FM_Mississippi_u4.txt
→ outputfileTimeSeries defines the path and the filename of the mean forward modelled equivalent water height value time series output file for the unit 4 of the Mississippi Basin.

grid
<u>grid: geograph</u> → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. <u>deltaLambda: {gridSizeCoarse} [= 0.5]</u> → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. <u>deltaPhi: {gridSizeCoarse} [= 0.5]</u> → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. <u>height: 0.0 [= 0]</u> → height defines that the distance of the points above the ellipsoid should be 0 m. <u>R: 6378137.0 [= 6378137]</u> → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. <u>inverseFlattening: 298.2572221010 [= 298.2572221]</u> → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} \; - \; \text{semiminor axis})}{\text{semimajor axis}}$ Equation 62: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$ Equation 63: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $\mathrm{f} = \frac{(6378137 \text{ m} \; - \; 6356752.3141 \text{ m})}{6378137 \text{ m}}$ $\mathrm{f} = 0.003352810681$

and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$ <u>border: polygon</u> → border defines that a subset of points should be extracted from the global grid. <u>inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit4_Vicksburg.txt</u> → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Vicksburg of the Mississippi Basin. <u>buffer: 0</u> → buffer defines that a barrier of 0 metre should be established around the polygon. <u>exclude: no</u> → exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel
<u>kernel: filterGauss</u> → kernel defines harmonic isotropic integral kernels K. Each kernel can be smoothed by a gauss filter which is defined by $F(\cos\psi) = \frac{b \cdot e^{-b(1-\cos\psi)}}{1 - e^{-2b}}$ Equation 64: Gauss filter Source: Mayer-Gürr et al., n.d. and where $b = \frac{\ln(2)}{1 - \cos\left(\frac{r}{R}\right)}$ Equation 65: Strength of the Gaussian Filtering Source: Mayer-Gürr et al., n.d. and (Rexer, 2012) While ψ indicates the angle between x and y, r refers to the filter radius in kilometre and R implies the radius of the Earth also indicated in kilometre.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $$k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$$ Equation 66: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.
radius: 300
→ radius defines the filter radius in kilometres.

gravityfield
gravityfield: timeSplines
→ gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain.
inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc]
→ inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file.
inputfileTimeSplinesCovariance: ---
→ inputfileTimeSplinesCovariance defines that no covariance time spline should be used.
minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.
maxDegree: 60
→ maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time.
factor: 1.0 [= 1]
→ factor defines that the result should be multiplied by 1. This factor is defined by default.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the unit Vicksburg of the Mississippi Basin. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the gravity field is expressed in terms of an averaged, filtered and forward modelled equivalent water height value. The unit of this equivalent water height value is metre.

6.8 PlotGraph

Goal:

The goal is to generate a two-dimensional plot which visualizes the temporal variation of total water height values over the Mississippi Basin for every month from 01/2003 to 12/2016. Hence, the graph should not only illustrate the forward modelled equivalent water height values, but also the processed equivalent water height values which were derived from GRACE observations. Finally, the graph should also visualize the corrected GRACE signal. Hence, the corrected GRACE signal refers to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations. Furthermore, the plot should also illustrate the forward modelled equivalent water height values for the four units of the Mississippi Basin, namely Hermann, Alton, Metropolis and Vicksburg. These forward modelled equivalent water height values express the gravity field and function as removal correction.

Parameters:

outputfile: data/Graphs/{listName}/Grace-FM_Mississippi.png
→ outputfile defines the path and the filename of the generated graph.

title: Grace and FM EWH Delta over Mississippi basin
→ title defines the title of the graph which should be displayed on the graph.

layer
<u>layer: linesAndPoints</u> → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. <u>inputfileMatrix: data/TimeSeries/FMtestMississippi.txt</u> → inputfileMatrix defines the path and the filename of the forward modelled time series .txt input file. <u>valueX: data0</u> → valueX defines that the x-values should be the monthly modified julian date. <u>valueY: data1</u> → valueY defines that the y-values should be the averaged, filtered and forward modelled equivalent water height values. The unit of the averaged and filtered equivalent water height values is metre. <u>valueZ: ---</u> → valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar. <u>valueErrorBar: ---</u>

→ valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar.

description: FM signal

→ description defines that the text of the legend should be “FM signal”.

line: solid

→ line defines that the line style of the forward modelled equivalent water height values should be solid.

width: 1.5

→ width defines that the width of the equivalent water height value line should be 1.5 points.

color: red

→ color defines that the colour of the equivalent water height value line should be red.

symbol: <none>

→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.

plotOnSecondAxis: no

→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

layer
layer: linesAndPoints → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. inputfileMatrix: data/TimeSeries/GRACEtestMississippi.txt → inputfileMatrix defines the path and the filename of the time series .txt input file. valueX: data0 → valueX defines that the x-values should be the monthly modified julian date. valueY: data1 → valueY defines that the y-values should indicate the processed equivalent water height values which were derived from GRACE observations. The unit of the equivalent water height value is metre. valueZ: --- → valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar. valueErrorBar: ---

→ valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar. <u>description: Grace signal</u> → description defines that the text of the legend should be “Grace signal”. <u>line: solid</u> → line defines that the line style of the processed equivalent water height values, which were derived from GRACE observations, should be solid. <u>width: 1.5</u> → width defines that the width of the equivalent water height value line should be 1.5 points. <u>color: blue</u> → color defines that the colour of the equivalent water height value line should be blue. <u>symbol: <none></u> → symbol defines that each data point should not be visualized by a symbol such as a circle or a star. <u>plotOnSecondAxis: no</u> → plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

layer
<u>layer: linesAndPoints</u> → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. <u>inputfileMatrix: data/TimeSeries/GRACE-FMtestMississippi.txt</u> → inputfileMatrix defines the path and the filename of the time series .txt input file. <u>valueX: data0</u> → valueX defines that the x-values should be the monthly modified julian date. <u>valueY: data1</u> → valueY defines that the y-values should be the difference between the averaged, filtered and forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations. The unit of this difference is metre. <u>valueZ: ---</u> → valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar.

valueErrorBar: ---
→ valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar.
description: Grace minus FM
→ description defines that the text of the legend should be "Grace minus FM".
line: solid
→ line defines that the line style of the corrected equivalent water height values should be solid.
width: 1.5
→ width defines that the width of the equivalent water height value line should be 1.5 points.
color: green
→ color defines that the colour of the equivalent water height value line should be green.
symbol: <none>
→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.
plotOnSecondAxis: no
→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

layer
layer: linesAndPoints
→ layer defines the content of the map. Hence, a line and / or points of xy data should be plotted.
inputfileMatrix: data/TimeSeries/FM_Mississippi_u1.txt
→ inputfileMatrix defines the path and the filename of the forward modelled time series .txt input file for the unit 1 of the Mississippi Basin.
valueX: data0
→ valueX defines that the x-values should be the monthly modified julian date.
valueY: data1
→ valueY defines that the y-values should be the averaged, filtered and forward modelled equivalent water height values from the unit Herman. The unit of the forward modelled equivalent water height values is metre.
valueZ: ---

→ valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar.

valueErrorBar: ---

→ valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar.

description: Unit 1 - Hermann

→ description defines that the text of the legend should be "Unit 1 - Hermann".

line: solid

→ line defines that the line style of the forward modelled equivalent water height values should be solid.

width: 1.5

→ width defines that the width of the equivalent water height value line should be 1.5 points.

color: blue

→ color defines that the colour of the equivalent water height value line should be blue.

symbol: <none>

→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.

plotOnSecondAxis: no

→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

layer
layer: linesAndPoints → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. inputfileMatrix: data/TimeSeries/FM_Mississippi_u2.txt → inputfileMatrix defines the path and the filename of the forward modelled time series .txt input file for the unit 2 of the Mississippi Basin. valueX: data0 → valueX defines that the x-values should be the monthly modified julian date. valueY: data1 → valueY defines that the y-values should be the averaged, filtered and forward modelled equivalent water height values from the unit Alton. The unit of the forward modelled equivalent water height values is metre.

valueZ: ---

→ valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar.

valueErrorBar: ---

→ valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar.

description: Unit 2 - Alton

→ description defines that the text of the legend should be "Unit 2 - Alton".

line: solid

→ line defines that the line style of the forward modelled equivalent water height values should be solid.

width: 1.5

→ width defines that the width of the equivalent water height value line should be 1.5 points.

color: blue

→ color defines that the colour of the equivalent water height value line should be blue.

symbol: <none>

→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.

plotOnSecondAxis: no

→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

layer
layer: linesAndPoints → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. inputfileMatrix: data/TimeSeries/FM_Mississippi_u3.txt → inputfileMatrix defines the path and the filename of the forward modelled time series .txt input file for the unit 3 of the Mississippi Basin. valueX: data0 → valueX defines that the x-values should be the monthly modified julian date. valueY: data1

→ valueY defines that the y-values should be the averaged, filtered and forward modelled equivalent water height values from the unit Metropolis. The unit of the forward modelled equivalent water height values is metre.

valueZ: ---

→ valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar.

valueErrorBar: ---

→ valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar.

description: Unit 3 - Metropolis

→ description defines that the text of the legend should be “Unit 3 - Metropolis”.

line: solid

→ line defines that the line style of the forward modelled equivalent water height values should be solid.

width: 1.5

→ width defines that the width of the equivalent water height value line should be 1.5 points.

color: yellow

→ color defines that the colour of the equivalent water height value line should be yellow.

symbol: <none>

→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.

plotOnSecondAxis: no

→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

layer

layer: linesAndPoints

→ layer defines the content of the map. Hence, a line and / or points of xy data should be plotted.

inputfileMatrix: data/TimeSeries/FM_Mississippi_u4.txt

→ inputfileMatrix defines the path and the filename of the forward modelled time series .txt input file for the unit 4 of the Mississippi Basin.

valueX: data0

→ valueX defines that the x-values should be the monthly modified julian date.

valueY: data1
→ valueY defines that the y-values should be the averaged, filtered and forward modelled equivalent water height values from the unit Alton. The unit of the forward modelled equivalent water height values is metre.
valueZ: ---
→ valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar.
valueErrorBar: ---
→ valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar.
description: Unit 4 - Vicksburg
→ description defines that the text of the legend should be "Unit 4 - Vicksburg".
line: solid
→ line defines that the line style of the forward modelled equivalent water height values should be solid.
width: 1.5
→ width defines that the width of the equivalent water height value line should be 1.5 points.
color: orange
→ color defines that the colour of the equivalent water height value line should be orange.
symbol: <none>
→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.
plotOnSecondAxis: no
→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

axisX
axisX: time
→ axisX defines the style of the x-axis of the graph. In this case, the input data are interpreted as modified julian date.
min: ---
→ min defines that there is no specified minimum value of the x-axis. Hence, the minimum scale value is set automatically.
max: ---

→ max defines that there is no specified maximum value of the x-axis. Hence, the maximum scale value is set automatically.

majorTickSpacing: 2Y

→ majorTickSpacing defines that the boundary annotation of the x-axis should be set every second year.

minorTickSpacing: 2Y

→ minorTickSpacing defines that the spacing of the frame tick intervals on the x-axis should be set every second year.

gridLineSpacing: 1Y

→ gridLineSpacing defines that that the spacing of the grid lines on the x-axis should be set every year.

secondary: <none>

→ secondary defines that no additional time axis should be established.

color: black

→ color defines that the colour of the x-axis should be black.

gridline: solid

→ gridline defines that the style of the grid lines should be solid.

width: 0.25

→ width defines that the width of the grid lines should be 0.25 points.

color: black

→ color defines that the colour of the grid lines should be black.

changeDirection: no

→ changeDirection defines that the direction of the x-axis should not be changed from right / up to left / down.

options: FORMAT_DATE_MAP=yyyy-mm-dd

→ options defines that the output data string should be given in the format year-month-day.

options: FORMAT_CLOCK_MAP=hh:mm

→ options defines that the output clock string should be given in the format hour-minute.

options: TIME_EPOCH=1858-11-17T00:00:00

→ options defines the value of the calendar and the clock at the origin (0 point) of relative time units.

options: TIME_UNIT=d

→ options defines that the units of the relative time data since the TIME_EPOCH should be daily.

axisY
axisY: standard → axisY defines the style of the y-axis of the graph. In this case, the input data should be interpreted as arbitrary input data. min: --- → min defines that there is no specified minimum value of the y-axis. Hence, the minimum scale value is set automatically. max: --- → max defines that there is no specified maximum value of the y-axis. Hence, the maximum scale value is set automatically. majorTickSpacing: 0.02 → majorTickSpacing defines that the boundary annotation of the y-axis should be set every 0.02. Hence, it is set for every 0.02 m of equivalent water height. minorTickSpacing: 0.002 → minorTickSpacing defines that the spacing of the frame tick intervals on the y-axis should be set every 0.002. Hence, it is set for every 0.002 m of equivalent water height. gridLineSpacing: 0.02 → gridLineSpacing defines that that the spacing of the grid lines on the y-axis should be set every 0.02. Hence, it is set for every 0.02 m of equivalent water height. gridline: solid → gridline defines that the style of the grid lines should be solid. width: 0.25 → width defines that the width of the grid lines should be 0.25 points. color: black → color defines that the colour of the grid lines should be black. unit: --- → unit defines that the no unit name should be appended to the y-axis values. Label: EWH [m] → label defines that the description of the y-axis should be “EWH [m]”. logarithmic: no

→ logarithmic defines that no logarithmic scale should be used. color: black → color defines that the colour of the bars and labels of the y-axis should be black. changeDirection: no → changeDirection defines that the direction of the x-axis should not be changed from right / up to left / down.

axisY2: <none>
→ axisY2 defines that no second Y-axis should be plotted.

colorbar: <none>
→ colorbar defines that no colour bar should be plotted.

legend
legend: <enabled> → legend defines that a legend with descriptions should be plotted. width: 10 → width defines that length of the legend should be 10 cm. height: --- → height defines that the height of the plot given in centimetre should not be further specified. positionX: 1.05 → positionX defines that the x-position of the legend should be 1.05. positionY: 1.0 [= 1] → positionY defines that the y-position of the legend should be 1.0. anchorPoint: TL → anchorPoint defines that the anchor point should be located at the top left. Hence, the anchor point is the point where the related edges link to. columns: 1 → columns defines that the legend should consist of one column. textColor: <none> → textColor defines that there is no specified colour of the text of the legend.

fillColor: <none>

→ fillColor defines that there is no specified colour with which the box of the legend should be filled.

edgeLine: <none>

→ edgeLine defines that there is no specified style of the edge of the box of the legend.

options
width: 12 → width defines that the width of the plot should be 12 cm. height: 7 → height defines that height of the plot should be 7 cm. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. options: FONT_ANNOT_PRIMARY=10p → options defines that the font which is used for primary annotations should be 10 pixels. options: MAP_ANNOT_OFFSET_PRIMARY=0.1c → options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm. options: FONT_LABEL=10p → options defines that the font, which is used to plot the labels below the annotation, should be 10 points. options: MAP_LABEL_OFFSET=0.1c → options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm. options: FONT_ANNOT_SECONDARY=10p → options defines that the font for a secondary time axis should be 10 points. options: TIME_SYSTEM=MJD → options defines that the relative time should refer to the modified julian date.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: no

→ viewPlot defines that the plot should not be automatically shown after the computation.

Result:

The function PlotGraph generates one graph which illustrates the temporal variation of the equivalent water height values over the Mississippi Basin. The x-axis indicates the year and reaches from 01/2003 to 12/2016. Meanwhile, the y-axis indicates the equivalent water height values in the unit of metre. In total, there are seven curves. The first curve represents the forward modelled equivalent water height values. The second curve illustrates the processed equivalent water height values which were derived from GRACE observations and the third curve visualizes the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations. The remaining four curves indicate the forward modelled equivalent water height values for the four units of the Mississippi Basin, namely Hermann, Alton, Metropolis and Vicksburg. These forward modelled equivalent water height values express the gravity field and function as removal correction. Hence, each forward modelled signal visualizes the size of the forward modelled equivalent water height values that has to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact, that the prevailing water body has on the processed equivalent water height values, which were derived from GRACE observations, can be removed. By subtracting for instance the removal correction of the entire Mississippi Basin from the GRACE signal, the influence, that the Mississippi Basin has on the GRACE signal, can be removed. Hence, the GRACE signal can be corrected. This procedure is also denoted as removal approach.

7 GroupPrograms

Goal:

The goal is to run the individually defined programs in a group.

Parameters:

outputfileLog: ---
→ outpufileLog defines that no additional log file should be created.

silently: no
→ silently defines that the output should be shown.

7.1 Gravityfield2PotentialCoefficientsTimeSeries

Goal:

The goal is to compute a time series of a time variable gravity field and to convert this gravity field to coefficients of a spherical harmonic expansion. Hence, a time series of potential coefficients should be computed.

Parameters:

outputfileTimeSeries: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_1_PotentialCoefficientsTimeSeries.txt
→ outputfileTimeSeries defines the path and the filename of the forward modelled potential coefficient time series output file.

gravityfield
<u>gravityfield: timeSplines</u> → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. <u>inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc]</u> → inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file.

inputfileTimeSplinesCovariance: ---
→ inputfileTimeSplinesCovariance defines that no covariance time spline should be used.
minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.
maxDegree: ---
→ maxDegree defines that there is no specified maximum degree of the expansion.
factor: 1.0 [= 1]
→ factor defines that the result should be multiplied by 1. This factor is defined by default.

timeSeries: Θ timeSeriesMonthly [= everyMonth]
→ timeSeries defines that a monthly time series should be generated.

minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]
→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

numbering: degreewise
→ numbering defines that the numbering scheme of the spherical harmonic coefficients in a parameter vector should be from degree to degree.

Result:

The function Gravityfield2PotentialCoefficientsTimeSeries generates one .txt file which contains 9409 columns. The first column contains the monthly time stamps which are expressed as modified julian date. The remaining columns indicate the potential coefficients, which are numbered by degree. Hence, the 9408 columns can be imagined as being c21, s21, c22, s22 etc.

7.2 InstrumentDetrend

Goal:

The goal is to reduce the temporal parametrization, such as the trend, per arc from the potential coefficient time series.

Parameters:

outputfileInstrument: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_2_InstrumentDetrend.txt
→ outputfileInstrument defines the path and the filename of the forward modelled potential coefficient time series output file.

outputfileTimeSeriesArcParameters: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_2_InstrumentDetrend_Parameter.txt
→ outputfileTimeSeriesArcParameters defines the path and the filename of the output file which contains the estimated parameters for each epoch.

inputfileInstrument: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_1_PotentialCoefficientsTimeSeries.txt
→ inputfileInstrument defines the path and the filename of the potential coefficient time series input file.

parametrizationTemporal
<u>parametrizationTemporal: constant</u> → parametrizationTemporal parametrizes time depending parameters. In this case, constant refers to a parameter, which is constant in each time interval. <u>interval: uniformInterval</u> → interval defines that a time series with a uniform sampling should be generated.

timeStart: Θ timeStart [= 2003-01-01 (52640)]
→ timeStart defines that the first point in time should be the 2003-01-01 which is the first available modified julian date.
timeEnd: Θ timeEnd [= 2016-12-31 (57753)]
→ timeEnd defines that the last point in time should be the 2016-12-31, which is the last available modified julian date.
intervalCount: 1
→ intervalCount defines the count of intervals should be 1.
includeLastTime: no
→ includeLastTime defines that the last point in time should not be included.

parametrizationTemporal
parametrizationTemporal: trend
→ parametrizationTemporal parametrizes time depending parameters. In this case, trend refers to a time variable function which is given by a linear trend. This time variable function is given by
$f(x,t) = \frac{1}{T} \cdot (t - t_0) \cdot f_t(x)$
Equation 67: Time variable function given by a linear trend
Source: Mayer-Gürr et al., n.d.
with T = timeStep in days and t_0 = timeStart.
timeStart: Θ referenceTime [= 2010-01-01 12:00:00 (55197.5)]
→ timeStart defines that the reference time should be the 2010-01-01 12:00:00. Thus, the reference time is in the middle of the selected time frame. If the reference time would be outside the selected time frame, the estimation would become more inaccurate.
timeStep: 365.25 [= 365d 06:00:00]
→ timeStep defines that the time interval should be 365.25 days. By introducing the .25, leap years, which occur on average every four years, can be balanced.

parametrizationTemporal
parametrizationTemporal: oscillation → parametrizationTemporal parametrizes time depending parameters. In this case, oscillation refers to a time variable function which is given by an oscillation. This time variable function is given by $f(x,t) = f^c(x) \cdot \cos(\omega_i(t)) + f^s(x) \cdot \sin(\omega_i(t))$ Equation 68: Time variable function given by an oscillation Source: Mayer-Gürr et al., n.d. with $\omega_i = \frac{2\pi}{T_i}(t - t_0)$, T = timeStep in days and t_0 = timeStart. period: 365.25 [= 365d 06:00:00] → timeStep defines that the time interval should be 365.25 days. By introducing the .25, leap years, which occur on average every four years, can be balanced. time0: Θ referenceTime [= 2010-01-01 12:00:00 (55197.5)] → time0 defines that the reference time should be the 2010-01-01 12:00:00. Thus, the reference time is in the middle of the selected time frame. If the reference time would be outside the selected time frame, the estimation would become more inaccurate.

startDataFields: 0
→ startDataFields defines that the start data field should be the first one.

countDataFields: ---
→ countDataFields defines that the number of data fields should not be counted.

huber: 2.5
→ huber defines that the pre-determined tuning constant should be set to 2.5 (Dawber et al., 2011).

huberPower: 1.5
→ huberPower defines that the ratio of the residuals and the redundancies should be potentiated with a huber power of 1.5.

huberMaxIteration: 5
→ huberMaxIteration defines that the robust estimation of the least squares parameters should be repeated 5 times.

Result:

The function InstrumentDetrend generates two .txt files. The first .txt file contains 37636 columns. The first column contains time stamp of the reference time which is expressed as modified julian date. The next 9408 columns indicate the constant value of each potential coefficient column. Hence, the next 9408 columns indicate the trend values. Following, the sine and the cosine values, which represent the oscillation, are denoted. Besides, also a .txt file which contains the estimated parameters for each arc, is created. This .txt file contains 9409 columns. The first column contains the monthly time stamps which are expressed as modified julian date. The remaining columns indicate all data of the first temporal parameter. This is then followed by all data of the second temporal parameter and so on.

7.3 MatrixCalculate

Goal:

The goal is to compute a matrix which should contain all mean values from the Instrument Detrend Parameter file.

Parameters:

outputfileMatrix: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_3_ MatrixCalculate_Mean.txt
→ outputfileMatrix defines the path and the filename of the forward modelled mean matrix output file.

matrix
matrix: transpose → matrix defines that a matrix should be generated. This matrix should be transposed. matrix: slice → matrix defines that the matrix should be sliced. matrix: file → matrix defines that the matrix should be generated from a file.

inputfileMatrix: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_2_InstrumentDetrend_Parameter.txt → inputfileMatrix defines the path and the filename of the forward modelled time spline parameter matrix input file. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default. startRow: 0 → startRow defines that the start row of the matrix should be the first row. Hence, from row 0 and column 1, 1 row and 9409 columns should be sliced out. startColumn: 1+0*({maxDegree}+1)^2 [= 1] → startColumn defines that the start column should be shifted by 1. Hence, from row 0 and column 1, 1 row and 9409 columns should be sliced out. rows: 1 → rows defines that the start row should be the first one. Hence, from row 0 and column 1, 1 row and 9409 columns should be sliced out. columns: ({maxDegree}+1)^2 [= 9409] → columns defines that the start column should be the 9409th one. Hence, from row 0 and column 1, 1 row and 9409 columns should be sliced out.

Result:

The function MatrixCalculate generates one .txt file. This .txt file contains a vector with the dimensions 9409 x 1. Hence, all mean values from the Instrument Detrend Parameter file are listed below each other.

7.4 MatrixCalculate

Goal:

The goal is to compute a matrix which should contain all trend values from the Instrument Detrend Parameter file.

Parameters:

outputfileMatrix: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_3_MatrixCalculate_Trend.txt
→ outputfileMatrix defines the path and the filename of the forward modelled trend matrix output file.

matrix
matrix: transpose → matrix defines that a matrix should be generated. This matrix should be transposed. matrix: slice → matrix defines that the matrix should be sliced. matrix: file → matrix defines that the matrix should be generated from a file. inputfileMatrix: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_2_InstrumentDetrend_Parameter.txt → inputfileMatrix defines the path and the filename of the forward modelled time spline parameter matrix input file. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default. startRow: 0 → startRow defines that the start row of the matrix should be the first row. Hence, from row 0 and column 9410, 1 row and 9409 columns should be sliced out. startColumn: 1+1*({maxDegree}+1)^2 [= 9410] → startColumn defines that the start column should be shifted by 1. Hence, from row 0 and column 9410, 1 row and 9409 columns should be sliced out. rows: 1 → rows defines that the start row should be the first one. Hence, from row 0 and column 9410, 1 row and 9409 columns should be sliced out. columns: ({maxDegree}+1)^2 [= 9409] → columns defines that the start column should be the 9409th one. Hence, from row 0 and column 9410, 1 row and 9409 columns should be sliced out.

Result:

The function MatrixCalculate generates one .txt file. This .txt file contains a vector with the dimensions 9409 x 1. Hence, all trend values from the Instrument Detrend Parameter file are listed below each other.

7.5 MatrixCalculate

Goal:

The goal is to compute a matrix which should contain all cosine values from the Instrument Detrend Parameter file.

Parameters:

outputfileMatrix: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_3_ MatrixCalculate_Cos.txt
→ outputfileMatrix defines the path and the filename of the forward modelled cosine matrix output file.

matrix
matrix: transpose → matrix defines that a matrix should be generated. This matrix should be transposed. matrix: slice → matrix defines that the matrix should be sliced. matrix: file → matrix defines that the matrix should be generated from a file. inputfileMatrix: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_2_InstrumentDetrend_Parameter.txt → inputfileMatrix defines the path and the filename of the forward modelled time spline parameter matrix input file. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default. startRow: 0 → startRow defines that the start row of the matrix should be the first row. Hence, from row 0 and column 18819, 1 row and 9409 columns should be sliced out. startColumn: 1+2*({maxDegree}+1)^2 [= 18819] → startColumn defines that the start column should be shifted by 1. Hence, from row 0 and column 18819, 1 row and 9409 columns should be sliced out. rows: 1 → rows defines that the start row should be the first one. Hence, from row 0 and column 18819, 1 row and 9409 columns should be sliced out.

columns: ({maxDegree}+1)^2 [= 9409] → columns defines that the start column should be the 9409th one. Hence, from row 0 and column 18819, 1 row and 9409 columns should be sliced out.

Result:

The function MatrixCalculate generates one .txt file. This .txt file contains a vector with the dimensions 9409 x 1. Hence, all cosine values from the Instrument Detrend Parameter file are listed below each other.

7.6 MatrixCalculate

Goal:

The goal is to compute a matrix which should contain all sinus values from the Instrument Detrend Parameter file.

Parameters:

outputfileMatrix: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_3_ MatrixCalculate_Sin.txt
→ outputfileMatrix defines the path and the filename of the forward modelled sinus matrix output file.

matrix
matrix: transpose → matrix defines that a matrix should be generated. This matrix should be transposed. matrix: slice → matrix defines that the matrix should be sliced. matrix: file → matrix defines that the matrix should be generated from a file. inputfileMatrix: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_2_In-strumentDetrend_Parameter.txt → inputfileMatrix defines the path and the filename of the forward modelled time spline parameter matrix input file. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

startRow: 0
→ startRow defines that the start row of the matrix should be the first row. Hence, from row 0 and column 28228, 1 row and 9409 columns should be sliced out.
startColumn: 1+3*({maxDegree}+1)^2 [= 28228]
→ startColumn defines that the start column should be shifted by 1. Hence, from row 0 and column 28228, 1 row and 9409 columns should be sliced out.
rows: 1
→ rows defines that the start row should be the first one. Hence, from row 0 and column 28228, 1 row and 9409 columns should be sliced out.
columns: ({maxDegree}+1)^2 [= 9409]
→ columns defines that the start column should be the 9409th one. Hence, from row 0 and column 28228, 1 row and 9409 columns should be sliced out.

Result:

The function MatrixCalculate generates one .txt file. This .txt file contains a vector with the dimensions 9409 x 1. Hence, all sinus values from the Instrument Detrend Parameter file are listed below each other.

7.7 Gravityfield2PotentialCoefficients

Goal:

The goal is to evaluate a time variable gravity field from a mean value solution vector at a given time and to write the respective potential coefficients to a file.

Parameters:

outputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/FM/{listName}_ TimeSpline_4_Gravityfield2PotentialCoefficients_Mean.gfc
→ outputfilePotentialCoefficients defines the path and the filename of the forward modelled potential coefficient output file.

gravityfield
gravityfield: fromParametrization
→ gravityfield defines that functionals of the time dependent gravity field are computed. In respect of fromParametrization, the potential coefficients are derived from a solution vector.

parametrization: sphericalHarmonics

→ parametrization defines that the potential is parametrized by an expansion of spherical harmonics. Hence, the Equation

$$V(\lambda, \vartheta, r) = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{R}{r}\right)^{n+1} (c_{nm} C_{nm}(\lambda, \vartheta) + s_{nm} S_{nm}(\lambda, \vartheta))$$

Equation 69: Spherical Harmonic Expansion Equation

Source: Mayer-Gürr et al., n.d.

with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude, is applied.

minDegree: {minDegree} [= 0]

→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]

→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]

→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]

→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

numbering: degreewise

→ numbering defines that the numbering scheme of the spherical harmonic coefficients in a parameter vector should be from degree to degree.

inputfileSolution: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_3_MatrixCalculate_Mean.txt
→ inputfileSolution defines the path and the filename of the forward modelled mean value solution input vector file.

inputfileSigmax: ---
→ inputfileSigmax defines that no standard deviations or covariance matrix of the solution should be considered.

indexStart: 0
→ indexStart defines that the position with the index 0 of the solution vector should be used.

rightSide: ---
→ rightSide defines that no specific right-hand side should be selected. This can be traced back to the fact that the inputfileSolution file only contains one column.

factor: 1.0 [= 1]
→ factor defines that the result should be multiplied by 1. This factor is defined by default.

minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]
→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

Result:

The function Gravityfield2PotentialCoefficients generates one .txt file. This .txt file contains the potential coefficients which were interpreted from the mean value solution vector file.

7.8 Gravityfield2PotentialCoefficients

Goal:

The goal is to evaluate a time variable gravity field from a trend value solution vector at a given time and to write the respective potential coefficients to a file.

Parameters:

outputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/FM/{listName}_ TimeSpline_4_Gravityfield2PotentialCoefficients_Trend.gfc
→ outputfilePotentialCoeffieicnts defines the path and the filename of the forward modelled potential coefficient output file.

gravityfield
gravityfield: fromParametrization → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. parametrization: sphericalHarmonics → parametrization defines that the potential is parametrized by an expansion of spherical harmonics. Hence, the Equation $V(\lambda, \vartheta, r) = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{R}{r}\right)^{n+1} (c_{nm} C_{nm}(\lambda, \vartheta) + s_{nm} S_{nm}(\lambda, \vartheta))$ Equation 70: Spherical Harmonic Expansion Equation Source: Mayer-Gürr et al., n.d. with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude, is applied. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. GM: 3.986004415e+14 [= 398600441500000] → GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.
numbering: degreewise
→ numbering defines that the numbering scheme of the spherical harmonic coefficients in a parameter vector should be from degree to degree.

inputfileSolution: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_3_ MatrixCalculate_Trend.txt
→ inputfileSolution defines the path and the filename of the forward modelled trend value solution input vector file.

inputfileSigmax: ---
→ inputfileSigmax defines that no standard deviations or covariance matrix of the solution should be considered.

indexStart: 0
→ indexStart defines that the position with the index 0 of the solution vector should be used.

rightSide: 0
→ rightSide defines that the column with the index 0 of the inputfileSolution should be used.

factor: 1.0 [= 1]
→ factor defines that the result should be multiplied by 1. This factor is defined by default.

minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]
→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{\mathrm{m}^2}{\mathrm{s}^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

Result:

The function Gravityfield2PotentialCoefficients generates one .txt file. This .txt file contains the potential coefficients which were interpreted from the trend value solution vector file.

7.9 Gravityfield2PotentialCoefficients

Goal:

The goal is to evaluate a time variable gravity field from a cosine value solution vector at a given time and to write the respective potential coefficients to a file.

Parameters:

outputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/FM/{listName}_ TimeSpline_4_Gravityfield2PotentialCoefficients_Cos.gfc
→ outputfilePotentialCoefficients defines the path and the filename of the forward modelled potential coefficient output file.

gravityfield
<u>gravityfield: fromParametrization</u> → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. <u>parametrization: sphericalHarmonics</u>

→ parametrization defines that the potential is parametrized by an expansion of spherical harmonics. Hence, the Equation $V(\lambda, \vartheta, r) = \frac{GM}{R}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\left(\frac{R}{r}\right)^{n+1}(c_{nm}C_{nm}(\lambda, \vartheta) + s_{nm}S_{nm}(\lambda, \vartheta))$ Equation 71: Spherical Harmonic Expansion Equation Source: Mayer-Gürr et al., n.d. with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude, is applied. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. GM: 3.986004415e+14 [= 398600441500000] → GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$. R: 6378137.0 [= 6378137] → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. numbering: degreewise → numbering defines that the numbering scheme of the spherical harmonic coefficients in a parameter vector should be from degree to degree.

inputfileSolution: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_3_ MatrixCalculate_Cos.txt
→ inputfileSolution defines the path and the filename of the forward modelled cosine value solution input vector file.

inputfileSigmax: ---
→ inputfileSigmax defines that no standard deviations or covariance matrix of the solution should be considered.

indexStart: 0
→ indexStart defines that the position with the index 0 of the solution vector should be used.

rightSide: 0
→ rightSide defines that the column with the index 0 of the inputfileSolution should be used.

factor: 1.0 [= 1]
→ factor defines that the result should be multiplied by 1. This factor is defined by default.

minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]
→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

Result:

The function Gravityfield2PotentialCoefficients generates one .txt file. This .txt file contains the potential coefficients which were interpreted from the cosine value solution vector file.

7.10 Gravityfield2PotentialCoefficients

Goal:

The goal is to evaluate a time variable gravity field from a sinus value solution vector at a given time and to write the respective potential coefficients to a file.

Parameters:

outputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/FM/{listName}_ TimeSpline_4_Gravityfield2PotentialCoefficients_Sin.gfc
→ outputfilePotentialCoefficients defines the path and the filename of the forward modelled potential coefficient output file.

gravityfield
gravityfield: fromParametrization → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. parametrization: sphericalHarmonics → parametrization defines that the potential is parametrized by an expansion of spherical harmonics. Hence, the Equation $V(\lambda, \vartheta, r) = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{R}{r}\right)^{n+1} (c_{nm} C_{nm}(\lambda, \vartheta) + s_{nm} S_{nm}(\lambda, \vartheta))$ Equation 72: Spherical Harmonic Expansion Equation Source: Mayer-Gürr et al., n.d. with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude, is applied. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. GM: 3.986004415e+14 [= 398600441500000] → GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.
numbering: degreewise
→ numbering defines that the numbering scheme of the spherical harmonic coefficients in a parameter vector should be from degree to degree.

inputfileSolution: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_3_MatrixCalculate_Sin.txt
→ inputfileSolution defines the path and the filename of the forward modelled sinus value solution input vector file.

inputfileSigmax: ---
→ inputfileSigmax defines that no standard deviations or covariance matrix of the solution should be considered.

indexStart: 0
→ indexStart defines that the position with the index 0 of the solution vector should be used.

rightSide: 0
→ rightSide defines that the column with the index 0 of the inputfileSolution should be used.

factor: 1.0 [= 1]
→ factor defines that the result should be multiplied by 1. This factor is defined by default.

minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]
→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

Result:

The function Gravityfield2PotentialCoefficients generates one .txt file. This .txt file contains the potential coefficients which were interpreted from the sinus value solution vector file.

7.11 Gravityfield2GriddedData

Goal:

The goal is to compute gridded mean values of the time variable gravity field.

Parameters:

outputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_5_Gravityfield2GriddedData_Mean.txt
→ outputfileGriddedData defines the path and the filename of the forward modelled mean gravity field grid output file.

grid
grid: Θ gridCoarse [= geograph]
→ grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. The resolution is 0.5 ° x 0.5 °.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $$k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$$ Equation 73: Coefficients of the Kernel   Source: Mayer-Gürr et al., n.d.   includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: potentialCoefficients   → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of potentialCoefficients, the potential is given by $$V(\lambda, \vartheta, r) = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{R}{r}\right)^{n+1} (c_{nm} C_{nm}(\lambda, \vartheta) + s_{nm} S_{nm}(\lambda, \vartheta))$$ Equation 74: Spherical Harmonic Expansion Equation   Source: Mayer-Gürr et al., n.d.   with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude.   inputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/FM/{listName}_ TimeSpline_4_Gravityfield2PotentialCoefficients_Mean.gfc   → inputfilePotentialCoefficients defines the path and the filename of the forward modelled input potential coefficient file.   minDegree: {minDegree} [= 0]   → minDegree defines that the minimum degree of the expansion should be 0 °.   maxDegree: {maxDegree} [= 96]   → maxDegree defines that the maximum degree of the expansion should be 96 °.   factor: 1.0 [= 1]   → factor defines that the result should be multiplied by 1. This factor is defined by default.   setSigmasToZero: no

→ setSigmasToZero defines that the variance should not be set to 0.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

time: ---
→ time defines that the gravity field should be evaluated once a month.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 75: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 76: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

Result:

The function Gravityfield2GriddedData generates one .txt file with gridded data. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded mean values of the time variable gravity field. Since the gravity field is expressed in terms of forward modelled equivalent water height values, the mean values also refer to equivalent water height values and thus the unit is metres.

7.12 Gravityfield2GriddedData

Goal:

The goal is to compute gridded trend values of the time variable gravity field.

Parameters:

outputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_5_Gravityfield2GriddedData_Trend.txt
→ outputfileGriddedData defines the path and the filename of the forward modelled trend gravity field grid output file.

grid
grid: Θ gridCoarse [= geograph] → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. The resolution is 0.5 ° x 0.5 °.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $$k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$$ Equation 77: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: potentialCoefficients → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of potentialCoefficients, the potential is given by $$V(\lambda, \vartheta, r) = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{R}{r}\right)^{n+1} (c_{nm} C_{nm}(\lambda, \vartheta) + s_{nm} S_{nm}(\lambda, \vartheta))$$ Equation 78: Spherical Harmonic Expansion Equation Source: Mayer-Gürr et al., n.d. with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude. inputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/FM/{listName}_ TimeSpline_4_Gravityfield2PotentialCoefficients_Trend.gfc → inputfilePotentialCoefficients defines the path and the filename of the forward modelled input potential coefficient file. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default. setSigmasToZero: no

→ setSigmasToZero defines that the variance should not be set to 0.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$\mathrm{f} = \frac{(\text{Semimajor axis} \;-\; \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 79: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by

$$\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$$

Equation 80: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$\mathrm{f} = \frac{(6378137\text{ m} \;-\; 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$\mathrm{f} = 0.003352810681$$

and thus, the inverseFlattening is

$\bar{f} = \dfrac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

Result:

The function Gravityfield2GriddedData generates one .txt file with gridded data. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded trend values of the time variable gravity field. Since the gravity field is expressed in terms of forward modelled equivalent water height values, the trend values also refer to equivalent water height values and thus the unit is metres.

7.13 Gravityfield2GriddedData

Goal:

The goal is to compute gridded cosine values of the time variable gravity field.

Parameters:

outputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_5_Gravityfield2GriddedData_Cos.txt
→ outputfileGriddedData defines the path and the filename of the forward modelled cosine gravity field grid output file.

grid
grid: Θ gridCoarse [= geograph]   → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. The resolution is 0.5 ° x 0.5 °.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 81: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: potentialCoefficients → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of potentialCoefficients, the potential is given by $V(\lambda, \vartheta, r) = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{R}{r}\right)^{n+1} (c_{nm} C_{nm}(\lambda, \vartheta) + s_{nm} S_{nm}(\lambda, \vartheta))$ Equation 82: Spherical Harmonic Expansion Equation Source: Mayer-Gürr et al., n.d. with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude. inputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_4_Gravityfield2PotentialCoefficients_Cos.gfc → inputfilePotentialCoefficients defines the path and the filename of the forward modelled input potential coefficient file. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default. setSigmasToZero: no

→ setSigmasToZero defines that the variance should not be set to 0.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 83: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by

$$\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$$

Equation 84: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$\mathrm{f} = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$$

$$\mathrm{f} = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

Result:

The function Gravityfield2GriddedData generates one .txt file with gridded data. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded cosine values of the time variable gravity field. Since the gravity field is expressed in terms of forward modelled equivalent water height values, the cosine values also refer to equivalent water height values and thus the unit is metres.

7.14 Gravityfield2GriddedData

Goal:

The goal is to compute gridded sinus values of the time variable gravity field.

Parameters:

outputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_5_Gravityfield2GriddedData_Sin.txt
→ outputfileGriddedData defines the path and the filename of the forward modelled sinus gravity field grid output file.

grid
grid: Θ gridCoarse [= geograph] → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. The resolution is 0.5 ° x 0.5 °.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $$k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$$ Equation 85: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
<u>gravityfield: potentialCoefficients</u> → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of potentialCoefficients, the potential is given by $$V(\lambda, \vartheta, r) = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{R}{r}\right)^{n+1} (c_{nm} C_{nm}(\lambda, \vartheta) + s_{nm} S_{nm}(\lambda, \vartheta))$$ Equation 86: Spherical Harmonic Expansion Equation Source: Mayer-Gürr et al., n.d. with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude. <u>inputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_4_Gravityfield2PotentialCoefficients_Sin.gfc</u> → inputfilePotentialCoefficients defines the path and the filename of the forward modelled input potential coefficient file. <u>minDegree: {minDegree} [= 0]</u> → minDegree defines that the minimum degree of the expansion should be 0 °. <u>maxDegree: {maxDegree} [= 96]</u> → maxDegree defines that the maximum degree of the expansion should be 96 °. <u>factor: 1.0 [= 1]</u> → factor defines that the result should be multiplied by 1. This factor is defined by default. <u>setSigmasToZero: no</u>

→ setSigmasToZero defines that the variance should not be set to 0.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 87: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 88: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$\bar{\mathrm{f}} = \dfrac{1}{0.003352810681}$ $\bar{\mathrm{f}} = 298.2572221.$

Result:

The function Gravityfield2GriddedData generates one .txt file with gridded data. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded sinus values of the time variable gravity field. Since the gravity field is expressed in terms of forward modelled equivalent water height values, the cosine values also refer to equivalent water height values and thus the unit is metres.

7.15 GriddedDataCalculate

Goal:

The goal is to compute gridded amplitude values of the time variable gravity field.

Parameters:

outputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_ TimeSpline_6_GriddedDataCalculate_Amplitude.txt
→ outputfileGriddedData defines the path and the filename of the forward modelled amplitude gravity field grid output file.

inputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline _5_Gravityfield2GriddedData_Cos.txt
→ inputfileGriddedData defines the path and the filename of the forward modelled gridded input file which contains gridded cosine values of the time variable gravity field.

inputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline _5_Gravityfield2GriddedData_Sin.txt
→ inputfileGriddedData defines the path and the filename of the forward modelled gridded input file which contains gridded sinus values of the time variable gravity field.

constant: ---
→ constant defines that no further constant is defined.

parameter: ---
→ parameter defines that no additional parameter is defined.

leastSquares: ---
→ leastSquares defines that the expression should not be minimized by adjusting the parameters.

removalCriteria: ---
→ removalCriteria defines that points should not be removed if one criterion evaluates true.

longitude: longitude
→ longitude is described by the expression longitude.

latitude: latitude
→ latitude is described by the expression latitude.

height: height
→ height is described by the expression height.

area: area
→ area is described by the expression area.

value: sqrt(data0^2+data1^2)
→ value defines that the value of the amplitude should be computed by calculating the square root of the squared and summed cosine and sinus values.

computeArea: no
→ computeArea defines that no automatic area computation of rectangular grids, which will overwrite the area information, should be performed.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

<u>inverseFlattening: 298.2572221010 [= 298.2572221]</u>

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 89: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 90: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

statistics: <none>
→ statistics defines that no statistic columns should be computed.

Result:

The function GriddedDataCalculate generates one .txt file with gridded data. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of $0.5\,°$ x $0.5\,°$. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded amplitude values of the time variable gravity field. Since the gravity field is expressed in terms of equivalent water height values, the amplitude values also refer to equivalent water height values and thus the unit is metres.

8 PlotMap

Goal:

The goal is to generate a global map which visualizes the mean values of the forward modelled equivalent water height values. These forward modelled equivalent water height values express the gravity field and function as removal correction.

Parameters:

outputfile: data/Maps/{listName}/{listName}_TimeSpline_6_FM_Mean.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_FM_Mean
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: griddedData → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. inputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_5_Gravityfield2GriddedData_Mean.txt → inputfileGriddedData defines the path and the filename of the forward modelled mean gridded gravity field input file. value: data0*100 → value defines that data0, which contains the gridded mean values of the forward modelled equivalent water height values, should be multiplied with 100 to change the unit from metre to centimetre. increment: 0.5 → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid.

illuminate: no

→ illuminate defines that the grid should not be brightened.

resample: <none>

→ resample defines that the concatenated gravity field grid input values should not be resampled.

gridlineRegistered: yes

→ gridlineRegistered defines that the input should be treated as point values and not as cell means

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid. width: 1 → width defines that the width of the coastlines should be 1 point. color: black → color defines that the colour of the coastlines should be black. landColor: <none> → landColor defines that there is no specific colour with which the land area should be filled. oceanColor: <none> → oceanColor defines that there is no specific colour with which the ocean area should be filled. minArea: 10000 → minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 91: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$ Equation 92: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $\mathrm{f} = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$ $\mathrm{f} = 0.003352810681$ and thus, the inverseFlattening is $\bar{\mathrm{f}} = \frac{1}{0.003352810681}$ $\bar{\mathrm{f}} = 298.2572221.$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 60
→ majorTickSpacing defines that the boundary annotation should be set every 60 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 30
→ gridLineSpacing defines that the spacing of the grid lines should be set every 30 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: --- → min defines that the minimum value of the colour bar should not be further specified. max: --- → max defines that the maximum value of the colour bar should not be further specified. annotation: --- → annotation defines that no boundary annotation should be drawn. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [cm] → label defines that the axis description and hence the description of the colour bar should be set to "EWH [cm]". logarithmic: no → logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values.

<u>triangleRight: yes</u> → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. <u>illuminate: no</u> → illuminate defines that the grid should not be brightened. <u>vertical: no</u> → vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. <u>length: 100</u> → length defines that the length of the colour bar should be 100 %. <u>margin: 0.4</u> → margin defines that the space between the colour bar and the figure should be 0.4 cm. <u>colorTable: haxby</u> → colorTable defines that the colour bar with the name "haxby" should be used. This colour bar ranges from dark blue to light red. <u>reverse: yes</u> → reverse defines that the colour bar should be reversed. Hence, the colour bar ranges from light red to dark blue. <u>showColorbar: yes</u> → showColorbar defines that the colour bar should be plotted.

projection
projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. <u>centralMeridian: 0</u> → centralMeridian defines that the central meridian should be set at 0 °.

options
width: 16 → width defines that the width of the plot should be 16 cm. height: --- → height defines that the height of the plot given in centimetre should not be further specified. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. options: FONT_ANNOT_PRIMARY=10p → options defines that the font which is used for primary annotations should be 10 pixels. options: MAP_ANNOT_OFFSET_PRIMARY=0.1c → options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm. options: FONT_LABEL=10p → options defines that the font, which is used to plot the labels below the annotation, should be 10 points. options: MAP_LABEL_OFFSET=0.1c → options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm. options: FONT_ANNOT_SECONDARY=10p → options defines that the font for a secondary time axis should be 10 points. transparent: no → transparent defines that the background of the plot should not be transparent. dpi = 300 → dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch. removeFiles: yes → removeFiles defines that the .gmt and script files should be removed after the computation. viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one global map which represents the mean values of the forward modelled equivalent water height values. These forward modelled equivalent water height values express the gravity field and function as removal correction. They are given in the unit of centimetre. Hence, the map visualizes the average size of the forward modelled equivalent water height values that have to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact that the prevailing water body has on the processed equivalent water height values, which were derived from GRACE observations, can be removed. Hence, the GRACE signal can be corrected. Consequently, each map functions as an indicator which shows how strong each inland water body influences the mass change observed by GRACE in the average mean. This information is extremely helpful to make the estimates of GRACE more consistent with the output from hydrological models.

9 PlotMap

Goal:

The goal is to generate a global map which visualizes the trend values of the forward modelled equivalent water height values. These forward modelled equivalent water height values express the gravity field and function as removal correction.

Parameters:

outputfile: data/Maps/{listName}/{listName}_TimeSpline_6_FM_Trend.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_FM_Trend
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: griddedData → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. inputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_5_Gravityfield2GriddedData_Trend.txt → inputfileGriddedData defines the path and the filename of the forward modelled trend gridded gravity field input file. value: data0*100 → value defines that data0, which contains the gridded trend values of the forward modelled equivalent water height values, should be multiplied with 100 to change the unit from metre to centimetre. increment: 0.5 → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid.

illuminate: no → illuminate defines that the grid should not be brightened. resample: <none> → resample defines that the concatenated gravity field grid input values should not be resampled. gridlineRegistered: no → gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid. width: 1 → width defines that the width of the coastlines should be 1 point. color: black → color defines that the colour of the coastlines should be black. landColor: <none> → landColor defines that there is no specific colour with which the land area should be filled. oceanColor: <none> → oceanColor defines that there is no specific colour with which the ocean area should be filled. minArea: 10000 → minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 93: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by $\bar{f} = \frac{1}{f}.$ Equation 94: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 60
→ majorTickSpacing defines that the boundary annotation should be set every 60 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 30
→ gridLineSpacing defines that the spacing of the grid lines should be set every 30 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: - 3 → min defines that the minimum value of the colour bar should be set to - 3. max: 3 → max defines that the maximum value of the colour bar should be set to 3. annotation: --- → annotation defines that no boundary annotation should be drawn. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [cm] → label defines that the axis description and hence the description of the colour bar should be set to “EWH [cm]”. logarithmic: no → logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values.

<u>triangleRight: yes</u> → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. <u>illuminate: no</u> → illuminate defines that the grid should not be brightened. <u>vertical: no</u> → vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. <u>length: 100</u> → length defines that the length of the colour bar should be 100 %. <u>margin: 0.4</u> → margin defines that the space between the colour bar and the figure should be 0.4 cm. <u>colorTable: haxby</u> → colorTable defines that the colour bar with the name "haxby" should be used. This colour bar ranges from dark blue to light red. <u>reverse: yes</u> → reverse defines that the colour bar should be reversed. Hence, the colour bar ranges from light red to dark blue. <u>showColorbar: yes</u> → showColorbar defines that the colour bar should be plotted.

projection
projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. <u>centralMeridian: 0</u> → centralMeridian defines that the central meridian should be set at 0 °.

options
width: 16 → width defines that the width of the plot should be 16 cm. height: --- → height defines that the height of the plot given in centimetre should not be further specified. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. options: FONT_ANNOT_PRIMARY=10p → options defines that the font which is used for primary annotations should be 10 pixels. options: MAP_ANNOT_OFFSET_PRIMARY=0.1c → options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm. options: FONT_LABEL=10p → options defines that the font, which is used to plot the labels below the annotation, should be 10 points. options: MAP_LABEL_OFFSET=0.1c → options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm. options: FONT_ANNOT_SECONDARY=10p → options defines that the font for a secondary time axis should be 10 points. transparent: no → transparent defines that the background of the plot should not be transparent. dpi = 300 → dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch. removeFiles: yes → removeFiles defines that the .gmt and script files should be removed after the computation. viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one global map which represents the trend values of the forward modelled equivalent water height values. These forward modelled equivalent water height values express the gravity field and function as removal correction. They are given in the unit of centimetre. Hence, the map visualizes the trend of the size of the forward modelled equivalent water height values that has to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact that the prevailing water body has on the processed equivalent water height values, which were derived from GRACE observations, can be removed. Hence, the GRACE signal can be corrected. Consequently, each map functions as an indicator which shows if the influence each inland water body has on the mass change observed by GRACE increases or decreases on the long term. This information is extremely helpful to make the estimates of GRACE more consistent with the output from hydrological models.

10 PlotMap

Goal:

The goal is to generate a global map which visualizes the amplitude values of the forward modelled equivalent water height values. These forward modelled equivalent water height values express the gravity field and function as removal correction.

Parameters:

outputfile: data/Maps/{listName}/{listName}_TimeSpline_6_FM_Amplitude.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_FM_Amplitude
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
<u>layer: griddedData</u> → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. <u>inputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_5_Gravityfield2GriddedData_Amplitude.txt</u> → inputfileGriddedData defines the path and the filename of the forward modelled amplitude gridded gravity field input file. <u>value: data0*100</u> → value defines that data0, which contains the gridded amplitude values of the forward modelled equivalent water height values, should be multiplied with 100 to change the unit from metre to centimetre. <u>increment: 0.5</u> → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid.

illuminate: no

→ illuminate defines that the grid should not be brightened.

resample: <none>

→ resample defines that the concatenated gravity field grid input values should not be resampled.

gridlineRegistered: no

→ gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid. width: 1 → width defines that the width of the coastlines should be 1 point. color: black → color defines that the colour of the coastlines should be black. landColor: <none> → landColor defines that there is no specific colour with which the land area should be filled. oceanColor: <none> → oceanColor defines that there is no specific colour with which the ocean area should be filled. minArea: 10000 → minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 95: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$ Equation 96: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $\mathrm{f} = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$ $\mathrm{f} = 0.003352810681$ and thus, the inverseFlattening is $\bar{\mathrm{f}} = \frac{1}{0.003352810681}$ $\bar{\mathrm{f}} = 298.2572221.$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 60
→ majorTickSpacing defines that the boundary annotation should be set every 60 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 30
→ gridLineSpacing defines that the spacing of the grid lines should be set every 30 °.

colorbar
<u>colorbar: <enabled></u> → colorbar defines that a colour bar should be plotted. <u>min: ---</u> → min defines that the minimum value of the colour bar should not be further specified. <u>max: 5</u> → max defines that the maximum value of the colour bar should be set to 5. <u>annotation: ---</u> → annotation defines that no boundary annotation should be drawn. <u>unit: ---</u> → unit defines that no unit information should be appended to the values of the axis. <u>label: EWH [cm]</u> → label defines that the axis description and hence the description of the colour bar should be set to “EWH [cm]”. <u>logarithmic: no</u> → logarithmic defines that no logarithmic scale should be used. <u>triangleLeft: yes</u> → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values.

triangleRight: yes → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. illuminate: no → illuminate defines that the grid should not be brightened. vertical: no → vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. length: 100 → length defines that the length of the colour bar should be 100 %. margin: 0.4 → margin defines that the space between the colour bar and the figure should be 0.4 cm. colorTable: /data1/colors/custom_palettes/temperature_cont.cpt → colorTable defines that the colour bar with the name "temperature_cont.cpt" should be used. This colour bar ranges from dark blue to dark red. reverse: no → reverse defines that the colour bar should not be reversed. showColorbar: yes → showColorbar defines that the colour bar should be plotted.

projection
Projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. centralMeridian: 0 → centralMeridian defines that the central meridian should be set at 0 °.

options
<u>width: 16</u> → width defines that the width of the plot should be 16 cm. <u>height: ---</u> → height defines that the height of the plot given in centimetre should not be further specified. <u>titleFontSize: 12</u> → titleFontSize defines that the fontsize of the title should be 12 points. <u>marginTitle: 0.4</u> → marginTitle defines that the space between the figure title should be 0.4 cm. <u>drawGridOnTop: no</u> → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. <u>options: FONT_ANNOT_PRIMARY=10p</u> → options defines that the font which is used for primary annotations should be 10 pixels. <u>options: MAP_ANNOT_OFFSET_PRIMARY=0.1c</u> → options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm. <u>options: FONT_LABEL=10p</u> → options defines that the font, which is used to plot the labels below the annotation, should be 10 points. <u>options: MAP_LABEL_OFFSET=0.1c</u> → options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm. <u>options: FONT_ANNOT_SECONDARY=10p</u> → options defines that the font for a secondary time axis should be 10 points. <u>transparent: no</u> → transparent defines that the background of the plot should not be transparent. <u>dpi = 300</u> → dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch. <u>removeFiles: yes</u> → removeFiles defines that the .gmt and script files should be removed after the computation. <u>viewPlot: yes</u>

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one global map which represents the amplitude values of the forward modelled equivalent water height values. These forward modelled equivalent water height values express the gravity field and function as removal correction. They are given in the unit of centimetre. Hence, the map visualizes the amplitude of the forward modelled equivalent water height values that has to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact that the prevailing water body has on the processed equivalent water height values, which were derived from GRACE observations, can be removed. Hence, the GRACE signal can be corrected. Consequently, each map functions as an indicator which shows how strong the influence of each inland water body on the mass change, observed by GRACE, fluctuates. This information is extremely helpful to make the estimates of GRACE more consistent with the output from hydrological models.

11 PlotMap

Goal:

The goal is to generate a global map which visualizes the location of all considered lakes and reservoirs.

Parameters:

outputfile: data/Maps/{listName}/{listName}_LakeMap.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_LakeMap
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
<u>layer: griddedData</u> → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. <u>inputfileGriddedData: data/Grids/GriddedWaterLevelCombinedFine/{listName}/{listName}_LGFine_54952.txt</u> → inputfileGriddedData defines the path and the filename of the fine gridded water level values from 01/05/2003. <u>value: sqrt(data0*data0)</u> → value defines that data0, which contains the gridded water level values, should be displayed. By squaring data0 and taking the root, absolute values could be derived. <u>increment: 0.5</u> → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid. <u>illuminate: no</u> → illuminate defines that the grid should not be brightened.

resample: <none>

→ resample defines that the grid input values should not be resampled.

gridlineRegistered: no

→ gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer

layer: coast

→ layer defines the content of the map. Hence, coastlines should be plotted.

resolution: medium

→ resolution defines that the resolution of the coastlines should be medium.

line: solid

→ line defines that the line style of the coastlines should be solid.

width: 0.2

→ width defines that the width of the coastlines should be 0.2 points.

color: black

→ color defines that the colour of the coastlines should be black.

landColor: <none>

→ landColor defines that there is no specific colour with which the land area should be filled.

oceanColor: <none>

→ oceanColor defines that there is no specific colour with which the ocean area should be filled.

minArea: 10000

→ minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]

→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the

inverse of the flattening parameter f. While the flattening parameter can be computed by applying $$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$ Equation 97: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by $$\bar{f} = \frac{1}{f}.$$ Equation 98: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$ $$f = 0.003352810681$$ and thus, the inverseFlattening is $$\bar{f} = \frac{1}{0.003352810681}$$ $$\bar{f} = 298.2572221.$$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 60
→ majorTickSpacing defines that the boundary annotation should be set every 60 °.

minorTickSpacing: ---
→ minorTickSpacing defines that the frame tick spacing should not be further specified.

gridLineSpacing: 30
→ gridLineSpacing defines that the spacing of the grid lines should be set every 30 °.

colorbar
<u>colorbar: <enabled></u> → colorbar defines that a colour bar should be plotted. <u>min: - 0.001</u> → min defines that the minimum value of the colour bar should be set to - 0.001. <u>max: 0.001</u> → max defines that the maximum value of the colour bar should be set to 0.001. <u>annotation: 60</u> → annotation defines that a boundary annotation should be drawn every 60 °. <u>unit: ---</u> → unit defines that no unit information should be appended to the values of the axis. <u>label: EWH [m]</u> → label defines that the axis description and hence the description of the colour bar should be set to "EWH [m]". <u>logarithmic: no</u> → logarithmic defines that no logarithmic scale should be used. <u>triangleLeft: yes</u> → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. <u>triangleRight: yes</u> → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. <u>illuminate: no</u>

→ illuminate defines that the grid should not be brightened.

vertical: no

→ vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot.

length: 100

→ length defines that the length of the colour bar should be 100 %.

margin: 0.4

→ margin defines that the space between the colour bar and the figure should be 0.4 cm.

colorTable: rainbow

→ colorTable defines that the colour bar with the name "rainbow" should be used. This colour bar ranges from violet to red.

reverse: no

→ reverse defines that the colour bar should not be reversed.

showColorbar: no

→ showColorbar defines that no colour bar should be plotted.

projection
Projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. centralMeridian: 0 → centralMeridian defines that the central meridian should be set at 0 °.

options
width: 16 → width defines that the width of the plot should be 16 cm. height: --- → height defines that the height of the plot given in centimetre should not be further specified. titleFontSize: 12

→ titleFontSize defines that the fontsize of the title should be 12 points.

marginTitle: 0.4

→ marginTitle defines that the space between the figure title should be 0.4 cm.

drawGridOnTop: no

→ drawGridOnTop defines that no grid lines should be drawn above all other lines and points.

options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels.

options: MAP_ANNOT_OFFSET_PRIMARY=0.1c

→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.

options: FONT_LABEL=10p

→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.

options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one global map which illustrates the location of each considered lake and reservoir for one point in time, being 01/05/2003. In order to illustrate the location, not the polygon, which characterises the shape of each water body, but the high-resolution gridded water level grid, was considered. Hence, each water body is technically a representation of grid values which indicate a water level value.

12 PlotMap

Goal:

The goal is to generate a global map which visualizes the forward modelled equivalent water height values on a coarse grid for the 01/06/2004. These forward modelled equivalent water height values express the gravity field and function as removal correction.

Parameters:

outputfile: data/Maps/{listName}/{listName}_53157.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_testCoarse
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: griddedData → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_FM_53157 .txt → inputfileGriddedData defines the path and the filename of the forward modelled gridded gravity field input file from the 01/06/2004. value: data0 → value defines that data0, which contains the forward modelled equivalent water height values in the unit of metre, should be displayed. increment: 0.5 → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid. illuminate: no

→ illuminate defines that the grid should not be brightened.
resample: <none>
→ resample defines that the grid input values should not be resampled.
gridlineRegistered: no
→ gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
layer: coast
→ layer defines the content of the map. Hence, coastlines should be plotted.
resolution: medium
→ resolution defines that the resolution of the coastlines should be medium.
line: solid
→ line defines that the line style of the coastlines should be solid.
width: 0.2
→ width defines that the width of the coastlines should be 0.2 points.
color: black
→ color defines that the colour of the coastlines should be black.
landColor: <none>
→ landColor defines that there is no specific colour with which the land area should be filled.
oceanColor: <none>
→ oceanColor defines that there is no specific colour with which the ocean area should be filled.
minArea: 10000
→ minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 99: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by $\bar{f} = \frac{1}{f}$. Equation 100: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 60
→ majorTickSpacing defines that the boundary annotation should be set every 60 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 30
→ gridLineSpacing defines that the spacing of the grid lines should be set every 30 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: - 0.5 → min defines that the minimum value of the colour bar should be set to - 0.5. max: 0.5 → max defines that the maximum value of the colour bar should be set to 0.5. annotation: --- → annotation defines that no boundary annotation should be drawn. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [m] → label defines that the axis description and hence the description of the colour bar should be set to "EWH [m]". logarithmic: no → logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values.

triangleRight: yes

→ triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values.

illuminate: no

→ illuminate defines that the grid should not be brightened.

vertical: no

→ vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot.

length: 100

→ length defines that the length of the colour bar should be 100 %.

margin: 0.4

→ margin defines that the space between the colour bar and the figure should be 0.4 cm.

colorTable: rainbow

→ colorTable defines that the colour bar with the name "rainbow" should be used. This colour bar ranges from violet to red.

reverse: no

→ reverse defines that the colour bar should not be reversed.

showColorbar: yes

→ showColorbar defines that the colour bar should be plotted.

projection
Projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. centralMeridian: 0 → centralMeridian defines that the central meridian should be set at 0 °.

options
<u>width: 16</u> → width defines that the width of the plot should be 16 cm. <u>height: ---</u> → height defines that the height of the plot given in centimetre should not be further specified. <u>titleFontSize: 12</u> → titleFontSize defines that the fontsize of the title should be 12 points. <u>marginTitle: 0.4</u> → marginTitle defines that the space between the figure title should be 0.4 cm. <u>drawGridOnTop: no</u> → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. <u>options: FONT_ANNOT_PRIMARY=10p</u> → options defines that the font which is used for primary annotations should be 10 pixels. <u>options: MAP_ANNOT_OFFSET_PRIMARY=0.1c</u> → options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm. <u>options: FONT_LABEL=10p</u> → options defines that the font, which is used to plot the labels below the annotation, should be 10 points. <u>options: MAP_LABEL_OFFSET=0.1c</u> → options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm. <u>options: FONT_ANNOT_SECONDARY=10p</u> → options defines that the font for a secondary time axis should be 10 points. <u>transparent: no</u> → transparent defines that the background of the plot should not be transparent. <u>dpi = 300</u> → dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch. <u>removeFiles: yes</u> → removeFiles defines that the .gmt and script files should be removed after the computation. <u>viewPlot: yes</u>

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one global map which the forward modelled equivalent water height values on a coarse grid for the 01/06/2004. The grid has a resolution of 0.5 ° x 0.5 °. These forward modelled equivalent water height values express the gravity field and function as removal correction.

13 GroupPrograms

Goal:

The goal is to run the individually defined programs in a group.

Parameters:

outputfileLog: ---
→ outpufileLog defines that no additional log file should be created.

silently: no
→ silently defines that the output should be shown.

13.1 PlotMap

Goal:

The goal is to generate a global map which visualizes the trend value of the forward modelled equivalent water height values with focus on the Great Lakes. These forward modelled equivalent water height values express the gravity field and function as removal correction.

Parameters:

outputfile: data/Maps/{listName}/{listName}_GreatLakes_FM_Trend.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_GreatLakes_FM_Trend
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: griddedData
→ layer defines the content of the map. Hence, a regular grid of yxz values should be plotted.
inputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_5_Gravityfield2GriddedData_Trend.txt
→ inputfileGriddedData defines the path and the filename of the forward modelled trend gridded gravity field input file.
value: data0
→ value defines that data0, which contains the gridded trend values of the forward modelled equivalent water height values, should be displayed.
increment: 0.5
→ increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid.
illuminate: no
→ illuminate defines that the grid should not be brightened.
resample: <none>
→ resample defines that the grid input values should not be resampled.
gridlineRegistered: no
→ gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
layer: coast
→ layer defines the content of the map. Hence, coastlines should be plotted.
resolution: medium
→ resolution defines that the resolution of the coastlines should be medium.
line: solid
→ line defines that the line style of the coastlines should be solid.
width: 1
→ width defines that the width of the coastlines should be 1 point.
color: black
→ color defines that the colour of the coastlines should be black.
landColor: <none>

→ landColor defines that there is no specific colour with which the land area should be filled.
oceanColor: <none>
→ oceanColor defines that there is no specific colour with which the ocean area should be filled.
minArea: 10000
→ minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 101: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 102: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137 \text{ m} - 6356752.3141 \text{ m})}{6378137 \text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

minLambda: - 100
→ minLambda defines that the minimum degree of longitude should be - 100 °.

maxLambda: - 70
→ maxLambda defines that the maximum degree of longitude should be - 70 °.

minPhi: 37.5
→ minPhi defines that the minimum degree of latitude should be 37.5 °.

maxPhi: 52.5
→ maxPhi defines that the maximum degree of latitude should be 52.5 °.

majorTickSpacing: 5
→ majorTickSpacing defines that the boundary annotation should be set every 5 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 5
→ gridLineSpacing defines that the spacing of the grid lines should be set every 5 °.

colorbar
<u>colorbar: <enabled></u> → colorbar defines that a colour bar should be plotted. <u>min: - 0.012</u> → min defines that the minimum value of the colour bar should be set to - 0.012. <u>max: 0.012</u> → max defines that the maximum value of the colour bar should be set to 0.012. <u>annotation: 0.002</u>

→ annotation defines that a boundary annotation should be drawn every 0.002 °.

unit: ---

→ unit defines that no unit information should be appended to the values of the axis.

label: EWH [m]

→ label defines that the axis description and hence the description of the colour bar should be set to "EWH [m]".

logarithmic: no

→ logarithmic defines that no logarithmic scale should be used.

triangleLeft: yes

→ triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values.

triangleRight: yes

→ triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values.

illuminate: no

→ illuminate defines that the grid should not be brightened.

vertical: no

→ vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot.

length: 100

→ length defines that the length of the colour bar should be 100 %.

margin: 0.4

→ margin defines that the space between the colour bar and the figure should be 0.4 cm.

colorTable: haxby

→ colorTable defines that the colour bar with the name "haxby" should be used. This colour bar ranges from dark blue to light red.

reverse: yes

→ reverse defines that the colour bar should be reversed. Hence, the colour bar ranges from light red to dark blue.

showColorbar: yes

→ showColorbar defines that the colour bar should be plotted.

projection
projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. centralMeridian: 0 → centralMeridian defines that the central meridian should be set at 0 °.

options
width: 16 → width defines that the width of the plot should be 16 cm. height: 10 → height defines that the height of the plot should be 10 cm. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. options: FONT_ANNOT_PRIMARY=10p → options defines that the font which is used for primary annotations should be 10 pixels. options: MAP_ANNOT_OFFSET_PRIMARY=0.1c → options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm. options: FONT_LABEL=10p → options defines that the font, which is used to plot the labels below the annotation, should be 10 points. options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one global map which represents the trend values of the forward modelled equivalent water height values with the focus on the Great Lakes. These forward modelled equivalent water height values express the gravity field and function as removal correction. They are given in the unit of metre. Hence, the map visualizes the trend of the size of the processed equivalent water height values that have to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact that the Great Lakes have on the processed equivalent water height values, which were derived from GRACE observations, can be removed. Hence, the GRACE signal can be corrected. Consequently, each map functions as an indicator which shows if the influence that the Great Lakes have on the mass change observed by GRACE increases or decreases on the long term. This information is extremely helpful to make the estimates of GRACE more consistent with the output from hydrological models for this respective region.

13.2 PlotMap

Goal:

The goal is to generate a global map which visualizes the amplitude value of the forward modelled equivalent water height values with focus on the Great Lakes. These forward modelled equivalent water height values express the gravity field and function as removal correction.

Parameters:

outputfile: data/Maps/{listName}/{listName}_GreatLakes_FM_Amplitude.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_GreatLakes_FM_Amplitude
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: griddedData → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. inputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_6_GriddedDataCalculate_Amplitude.txt → inputfileGriddedData defines the path and the filename of the forward modelled amplitude gridded gravity field input file. value: data0 → value defines that data0, which contains the gridded amplitude values of the forward modelled equivalent water height values, should be displayed. increment: 0.5 → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid. illuminate: no → illuminate defines that the grid should not be brightened. resample: <none> → resample defines that the grid input values should not be resampled. gridlineRegistered: no → gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid. width: 1 → width defines that the width of the coastlines should be 1 point. color: black → color defines that the colour of the coastlines should be black. landColor: <none> → landColor defines that there is no specific colour with which the land area should be filled. oceanColor: <none> → oceanColor defines that there is no specific colour with which the ocean area should be filled. minArea: 10000 → minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 103: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by

$\bar{f} = \frac{1}{f}$.
Equation 104: Inverse Flattening of the rotation ellipsoid
Source: Mayer-Gürr et al., n.d.
Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is
$f = \frac{(6378137 \text{ m} - 6356752.3141 \text{ m})}{6378137 \text{ m}}$
$f = 0.003352810681$
and thus, the inverseFlattening is
$\bar{f} = \frac{1}{0.003352810681}$
$\bar{f} = 298.2572221.$

minLambda: - 95
→ minLambda defines that the minimum degree of longitude should be - 95 °.

maxLambda: - 73
→ maxLambda defines that the maximum degree of longitude should be - 73 °.

minPhi: 40
→ minPhi defines that the minimum degree of latitude should be 40 °.

maxPhi: 50
→ maxPhi defines that the maximum degree of latitude should be 50 °.

majorTickSpacing: 5
→ majorTickSpacing defines that the boundary annotation should be set every 5 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 5
→ gridLineSpacing defines that the spacing of the grid lines should be set every 5 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: 0 → min defines that the minimum value of the colour bar should be set to 0. max: 0.10 [= 0.10] → max defines that the maximum value of the colour bar should be set to 0.10. annotation: 0.01 → annotation defines that a boundary annotation should be drawn every 0.01 °. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [m] → label defines that the axis description and hence the description of the colour bar should be set to "EWH [m]". logarithmic: no → logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. triangleRight: yes → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. illuminate: no → illuminate defines that the grid should not be brightened. vertical: no → vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. length: 100 → length defines that the length of the colour bar should be 100 %. margin: 0.4

→ margin defines that the space between the colour bar and the figure should be 0.4 cm.
colorTable: /data1/colors/custom_palettes/temperature_cont.cpt
→ colorTable defines that the colour bar with the name “haxby” should be used. This colour bar ranges from dark blue to light red.
reverse: no
→ reverse defines that the colour bar should not be reversed.
showColorbar: yes
→ showColorbar defines that the colour bar should be plotted.

projection
projection: robinson
→ projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions.
centralMeridian: 0
→ centralMeridian defines that the central meridian should be set at 0 °.

options
width: 16
→ width defines that the width of the plot should be 16 cm.
height: 9
→ height defines that the height of the plot should be 9 cm.
titleFontSize: 12
→ titleFontSize defines that the fontsize of the title should be 12 points.
marginTitle: 0.4
→ marginTitle defines that the space between the figure title should be 0.4 cm.
drawGridOnTop: no
→ drawGridOnTop defines that no grid lines should be drawn above all other lines and points.
options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels.

options: MAP_ANNOT_OFFSET_PRIMARY=0.1c

→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.

options: FONT_LABEL=10p

→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.

options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one global map which represents the amplitude values of the forward modelled equivalent water height values with the focus on the Great Lakes. These forward modelled equivalent water height values express the gravity field and function as removal correction. They are given in the unit of metre. Hence, the map visualizes the amplitude of the processed equivalent water height values that have to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact that the Great Lakes have on the processed equivalent water height values derived from GRACE observations, can be removed. Hence, the GRACE signal can be corrected. Consequently, each map functions as an indicator which shows how strong the influence of the Great Lakes on the mass change, observed by GRACE, fluctuates. This information is extremely helpful to make the estimates of GRACE more consistent with the output from hydrological models for this respective region.

13.3 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean forward modelled equivalent water height values which express the time variable gravity field over the Great Lakes.

Parameters:

outputfileTimeSeries: data/TimeSeries/FM_GreatLakes.txt
→ outputfileTimeSeries defines the path and the filename of the mean forward modelled equivalent water height value time series output file for the Great Lakes.

grid
<u>grid: geograph</u> → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. <u>deltaLambda: {gridSizeCoarse} [= 0.5]</u> → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. <u>deltaPhi: {gridSizeCoarse} [= 0.5]</u> → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. <u>height: 0.0 [= 0]</u> → height defines that the distance of the points above the ellipsoid should be 0 m. <u>R: 6378137.0 [= 6378137]</u> → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. <u>inverseFlattening: 298.2572221010 [= 298.2572221]</u> → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 105: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by $\bar{f} = \frac{1}{f}$. Equation 106: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221$. <u>border: rectangle</u> → border defines that a rectangular region should be extracted from the global grid. Hence, the rectangular region is restricted along the lines of geographical coordinates. <u>minLambda: - 95</u> → minLambda defines that the minimum degree of longitude should be - 95 °. <u>maxLambda: - 73</u> → maxLambda defines that the maximum degree of longitude should be - 73 °. <u>minPhi: 40</u> → minPhi defines that the minimum degree of latitude should be 40 °. <u>maxPhi: 50</u> → maxPhi defines that the maximum degree of longitude should be 50 °. <u>exclude: no</u> → exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel
kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n
$k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$
Equation 107: Coefficients of the Kernel
Source: Mayer-Gürr et al., n.d.
includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.
radius: 300
→ radius defines the filter radius in kilometres.

gravityfield
gravityfield: timeSplines
→ gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain.
inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc]
→ inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file.
inputfileTimeSplinesCovariance: ---
→ inputfileTimeSplinesCovariance defines that no covariance time spline should be used.
minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.
maxDegree: 60
→ maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time.
factor: 1.0 [= 1]

→ factor defines that the result should be multiplied by 1. This factor is defined by default.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the Great Lakes. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the gravity field is expressed in terms of an averaged and forward modelled equivalent water height value. The unit of the averaged equivalent water height value is metre.

13.4 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean equivalent water height values which express the time variable gravity field and which were derived from GRACE observations over the Great Lakes.

Parameters:

outputfileTimeSeries: data/TimeSeries/GRACE_GreatLakes.txt
→ outputfileTimeSeries defines the path and the filename of the mean equivalent water height value time series output file for the Great Lakes.

grid
<u>grid: geograph</u> → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. <u>deltaLambda: {gridSizeCoarse} [= 0.5]</u> → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. <u>deltaPhi: {gridSizeCoarse} [= 0.5]</u> → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. <u>height: 0.0 [= 0]</u> → height defines that the distance of the points above the ellipsoid should be 0 m. <u>R: 6378137.0 [= 6378137]</u> → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. <u>inverseFlattening: 298.2572221010 [= 298.2572221]</u> → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 108: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by $\bar{f} = \frac{1}{f}$. Equation 109: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$ <u>border: rectangle</u> → border defines that a rectangular region should be extracted from the global grid. Hence, the rectangular region is restricted along the lines of geographical coordinates. <u>minLambda: - 95</u> → minLambda defines that the minimum degree of longitude should be - 95 °. <u>maxLambda: - 73</u> → maxLambda defines that the maximum degree of longitude should be - 73 °. <u>minPhi: 40</u> → minPhi defines that the minimum degree of latitude should be 40 °. <u>maxPhi: 50</u> → maxPhi defines that the maximum degree of longitude should be 50 °. <u>exclude: no</u> → exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel
kernel: Θ kernel [= waterHeight] → kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 110: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2016200212201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2016/itsg-grace2016_MD90_deg1c20repl_no1502_GIAreduced_mean-red_DDK3_interp_200212-201706.dat] → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the Great Lakes. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the gravity field is expressed in terms of an equivalent water height value. The unit of this equivalent water height value is metre. In this case, the processed equivalent water height values are not forward modelled, but directly derived from the GRACE observations. These observations are already pre-processed. Hence, the data is already interpolated and the effect of the glacial isostatic adjustment is also removed.

13.5 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean equivalent water height values which express the corrected time variable gravity field over the Great Lakes.

Parameters:

outputfileTimeSeries: data/TimeSeries/GRACE-FM_GreatLakes.txt
→ outputfileTimeSeries defines the path and the filename of the corrected mean equivalent water height value time series output file for the Great Lakes.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. deltaPhi: {gridSizeCoarse} [= 0.5] → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. height: 0.0 [= 0] → height defines that the distance of the points above the ellipsoid should be 0 m. R: 6378137.0 [= 6378137] → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. inverseFlattening: 298.2572221010 [= 298.2572221] → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 111: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 112: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\ \mathrm{m}\ -\ 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

<u>border: rectangle</u>

→ border defines that a rectangular region should be extracted from the global grid. Hence, the rectangular region is restricted along the lines of geographical coordinates.

<u>minLambda: - 95</u>

→ minLambda defines that the minimum degree of longitude should be - 95 °.

<u>maxLambda: - 73</u>

→ maxLambda defines that the maximum degree of longitude should be - 73 °.

<u>minPhi: 40</u>

→ minPhi defines that the minimum degree of latitude should be 40 °.

<u>maxPhi: 50</u>

→ maxPhi defines that the maximum degree of longitude should be 50 °.

<u>exclude: no</u>

→ exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel
kernel: Θ kernel [= waterHeight] → kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 113: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2016200212201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2016/itsg-grace2016_MD90_deg1c20repl_no1502_GIAreduced_mean-red_DDK3_interp_200212-201706.dat] → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc] → inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: - 1 → factor defines that the forward modelled equivalent water height values, which represent the gravity field, should be subtracted from the processed equivalent water height values that were derived from GRACE observations.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the Great Lakes. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the corrected time variable gravity field is expressed in terms of an averaged equivalent water height value. The unit of the averaged equivalent water height value is metre. Hence, the corrected equivalent water height values refer to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations.

13.6 FunctionsCalculate

Goal:

The goal is to manipulate the data columns of the forward modelled signal matrix in a way, that the annual signal and the semi-annual signal as well as the trend are removed. The focus should be set on the Great Lakes.

Parameters:

outputfile: data/TimeSeries/FM_GreatLakes_TrendSemiAnnualRemoved.txt
→ outputfile defines the path and the filename of the forward modelled matrix output file for the Great Lakes. This matrix should contain one column in which the annual signal and the semi-annual signal are simultaneously removed from the forward modelled signal.

inputfile: data/TimeSeries/FM_GreatLakes.txt
→ inputfile defines the path and the filename of the mean forward modelled equivalent water height value time series input file for the Great Lakes.

constant: annual=2*pi/365.25
→ constant defines that the annual signal should have an angular frequency of 2*pi/365.25. By introducing the .25, leap years, which occur on average every four years, can be balanced.

constant: t0=54750
→ constant defines that the start point in time should be 11/10/2008.

parameter: a
→ parameter defines that the parameter a should be estimated in a least squares adjustment.

parameter: b
→ parameter defines that the parameter b should be estimated in a least squares adjustment.

parameter: c
→ parameter defines that the parameter c should be estimated in a least squares adjustment.

parameter: d
→ parameter defines that the parameter d should be estimated in a least squares adjustment.

parameter: e
→ parameter defines that the parameter e should be estimated in a least squares adjustment.

parameter: f
→ parameter defines that the parameter f should be estimated in a least squares adjustment.

leastSquares: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)*annual *2)+f*cos((data0-t0)*annual*2)-data1
→ leastSquares defines that the parameters should be adjusted by applying this expression. Hence, the Equation does not only include a description of the trend, but also of the annual signal and the semi-annual signal as well the equivalent water level value itself.

outcolumn: data0
→ outcolumn defines that the points in time, which are expressed as modified julian date, should be stored in the data0 column of the matrix.

outcolumn: data1
→ outcolumn defines that the forward modelled equivalent water height values should be stored in the data1 column of the matrix.

outcolumn: a+b*(data0-t0)
→ outcolumn defines that the trend should be stored in the data2 column of the matrix.

outcolumn: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)
→ outcolumn defines that the trend and the annual signal should be stored in the data3 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual))
→ outcolumn defines that the forward modelled equivalent water height values, which are reduced by the trend and the annual signal, should be stored in the data4 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e* sin((data0-t0)*annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the forward modelled equivalent water height values, which are reduced by the trend and the semi-annual signal, should be stored in the data5 column of the matrix.

outcolumn: data1-(c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)* annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the forward modelled equivalent water height values, which are simultaneously reduced by the annual signal and the semi-annual signal, should be stored in the data6 column of the matrix.

Statistics: <none>
→ statistics defines that no statistic columns should be computed.

Result:

The function FunctionsCalculate generates one .txt file for the Great Lakes. This .txt file contains a matrix with the dimensions of 168 x 7. Each row represents one point in time. The first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. The second column indicates the forward modelled equivalent water height values. The third column contains the trend value. The fourth column contains the trend values and the annual signal values. Meanwhile, the fifth column contains the forward modelled equivalent water height values which are already reduced by the annual signal values and the trend values. The sixth column indicates the forward modelled equivalent water height values which are already reduced by the semi-annual signal values and the trend values. The seventh and last column contains the forward modelled equivalent water height values from which the annual signal and the semi-annual signal values are removed. The unit of the forward modelled equivalent water height values is metre. Since the time series values are computed by using the forward modelled time spline, the equivalent water height values are also forward modelled.

13.7 FunctionsCalculate

Goal:

The goal is to manipulate the data columns of the GRACE signal matrix in a way, that the annual signal and the semi-annual signal as well as the trend are removed. The focus should be set on the Great Lakes.

Parameters:

outputfile: data/TimeSeries/GRACE_GreatLakes_TrendSemiAnnualRemoved.txt
→ outputfile defines the path and the filename of the matrix output file for the Great Lakes. This matrix should contain one column in which the annual signal and the semi-annual signal are simultaneously removed from the GRACE signal.

inputfile: data/TimeSeries/GRACE_GreatLakes.txt
→ inputfile defines the path and the filename of the mean equivalent water height value time series input file for the Great Lakes.

constant: annual=2*pi/365.25
→ constant defines that the annual signal should have an angular frequency of 2*pi/365.25. By introducing the .25, leap years, which occur on average every four years, can be balanced.

constant: t0=54750
→ constant defines that the start point in time should be 11/10/2008.

parameter: a
→ parameter defines that the parameter a should be estimated in a least squares adjustment.

parameter: b
→ parameter defines that the parameter b should be estimated in a least squares adjustment.

parameter: c
→ parameter defines that the parameter c should be estimated in a least squares adjustment.

parameter: d
→ parameter defines that the parameter d should be estimated in a least squares adjustment.

parameter: e
→ parameter defines that the parameter e should be estimated in a least squares adjustment.

parameter: f
→ parameter defines that the parameter f should be estimated in a least squares adjustment.

leastSquares: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)*annual *2)+f*cos((data0-t0)*annual*2)-data1
→ leastSquares defines that the parameters should be adjusted by applying this expression. Hence, the Equation does not only include a description of the trend, but also of the annual signal and the semi-annual signal as well the equivalent water level value itself.

outcolumn: data0
→ outcolumn defines that the points in time, which are expressed as modified julian date, should be stored in the data0 column of the matrix.

outcolumn: data1
→ outcolumn defines that the processed equivalent water height values, which were derived from GRACE observations, should be stored in the data1 column of the matrix.

outcolumn: a+b*(data0-t0)
→ outcolumn defines that the trend should be stored in the data2 column of the matrix.

outcolumn: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)
→ outcolumn defines that the trend and the annual signal should be stored in the data3 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual))
→ outcolumn defines that the processed equivalent water height values derived from GRACE observations, which are reduced by the trend and the annual signal, should be stored in the data4 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e* sin((data0-t0)*annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the processed equivalent water height values derived from GRACE observations, which are reduced by the trend and the semi-annual signal, should be stored in the data5 column of the matrix.

outcolumn: data1-(c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)* annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the processed equivalent water height values derived from GRACE observations, which are simultaneously reduced by the annual signal and the semi-annual signal, should be stored in the data6 column of the matrix.

Statistics: <none>
→ statistics defines that no statistic columns should be computed.

Result:

The function FunctionsCalculate generates one .txt file for the Great Lakes. This .txt file contains a matrix with the dimensions of 168 x 7. Each row represents one point in time. The first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. The second column indicates the processed equivalent water height values which were derived from GRACE observations. The third column contains the trend value. The fourth column contains the trend values and the annual signal values. Meanwhile, the fifth column contains the processed equivalent water height values which were derived from GRACE observations and which are already reduced by the annual signal values and the trend values. The sixth column indicates the processed equivalent water height values which were derived from GRACE observations and which are already reduced by the semi-annual signal values and the trend values. The seventh and last column contains the GRACE signal in terms of equivalent water height values from which the annual signal values and the semi-annual signal values are removed. The unit of the processed equivalent water height values is metre. In this case, the processed equivalent water height values were directly derived from the GRACE observations. These observations are already pre-processed. Hence, the data is already interpolated and the effect of the glacial isostatic adjustment is also removed.

13.8 FunctionsCalculate

Goal:

The goal is to manipulate the data columns of the corrected GRACE signal matrix in a way, that the annual signal and the semi-annual signal as well as the trend are removed. The focus should be set on the Great Lakes.

Parameters:

outputfile: data/TimeSeries/GRACE-FM_GreatLakes_TrendSemiAnnualRemoved.txt
→ outputfile defines the path and the filename of the corrected matrix output file for the Great Lakes. This matrix should contain one column in which the annual signal and the semi-annual signal are simultaneously removed from the corrected GRACE signal.

inputfile: data/TimeSeries/GRACE-FM_GreatLakes.txt
→ inputfile defines the path and the filename of the corrected mean equivalent water height value time series output file for the Great Lakes.

constant: annual=2*pi/365.25
→ constant defines that

constant: annual=2*pi/365.25
→ constant defines that the annual signal should have an angular frequency of 2*pi/365.25. By introducing the .25, leap years, which occur on average every four years, can be balanced.

constant: t0=54750
→ constant defines that the start point in time should be 11/10/2008.

parameter: a
→ parameter defines that the parameter a should be estimated in a least squares adjustment.

parameter: b
→ parameter defines that the parameter b should be estimated in a least squares adjustment.

parameter: c
→ parameter defines that the parameter c should be estimated in a least squares adjustment.

parameter: d
→ parameter defines that the parameter d should be estimated in a least squares adjustment.

parameter: e
→ parameter defines that the parameter e should be estimated in a least squares adjustment.

parameter: f
→ parameter defines that the parameter f should be estimated in a least squares adjustment.

leastSquares: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)*annual *2)+f*cos((data0-t0)*annual*2)-data1
→ leastSquares defines that the parameters should be adjusted by applying this expression. Hence, the Equation does not only include a description of the trend, but also of the annual signal and the semi-annual signal as well the equivalent water level value itself.

outcolumn: data0
→ outcolumn defines that the points in time, which are expressed as modified julian date, should be stored in the data0 column of the matrix.

outcolumn: data1
→ outcolumn defines that the corrected equivalent water height values should be stored in the data1 column of the matrix.

outcolumn: a+b*(data0-t0)
→ outcolumn defines that the trend should be stored in the data2 column of the matrix.

outcolumn: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)
→ outcolumn defines that the trend and the annual signal should be stored in the data3 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual))
→ outcolumn defines that corrected equivalent water height values, which are further reduced by the trend and the annual signal, should be stored in the data4 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e* sin((data0-t0)*annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the corrected equivalent water height values, which are further reduced by the trend and the semi-annual signal, should be stored in the data5 column of the matrix.

outcolumn: data1-(c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)* annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the corrected equivalent water height values, which are further reduced by the annual signal and the semi-annual signal, should be stored in the data6 column of the matrix.

Statistics: <none>
→ statistics defines that no statistic columns should be computed.

Result:

The function FunctionsCalculate generates one .txt file for the Great Lakes. This .txt file contains a matrix with the dimensions of 168 x 7. Each row represents one point in time. The first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. The second column indicates the corrected equivalent water height values. The third column contains the trend value. The fourth column contains the trend values and the annual signal values. Meanwhile, the fifth column contains the corrected equivalent water height values which are already reduced by the annual signal values and the trend values. The sixth column indicates the corrected equivalent water height values which are already reduced by the semi-annual signal values and the trend values. The seventh and last column contains the corrected equivalent water height values from which the annual signal values and the semi-annual signal values, are removed. The unit of the corrected equivalent water height values is metre. In this case the corrected equivalent water height values refer to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations.

13.9 PlotGraph

Goal:

The goal is to generate a two-dimensional plot which visualizes the temporal variation of the total water height values over the Great Lakes for every month from 01/2003 to 12/2016. Hence, the graph should not only illustrate the forward modelled equivalent water height values from which the annual signal and the semi-annual signal were simultaneously removed, but also the processed equivalent water height values which were derived from GRACE observations and which were also simultaneously reduced by the annual signal and the semi-annual signal. Finally, the graph should also visualize the corrected GRACE signal. Hence, the corrected GRACE signal refers to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations.

Parameters:

outputfile: data/Graphs/{listName}/GreatLakes.png
→ outputfile defines the path and the filename of the generated graph.

title: EWH Delta over Great Lakes (annual / semiannual signals removed)
→ title defines the title of the graph which should be displayed on the graph.

layer
<u>layer: linesAndPoints</u> → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. <u>inputfileMatrix: data/TimeSeries/FM_GreatLakes_TrendSemiAnnualRemoved.txt</u>

→ inputfileMatrix defines the path and the filename of the forward modelled matrix input file for the Great Lakes. This matrix contains one column in which the annual signal and the semi-annual signal were simultaneously removed from the forward modelled signal.

valueX: data0

→ valueX defines that the x-values should be the monthly modified julian date.

valueY: data6

→ valueY defines that the y-values should be the forward modelled equivalent water height values from which the annual signal and the semi-annual signal were simultaneously removed. The unit of the forward modelled equivalent water height values is metre.

valueZ: ---

→ valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar.

valueErrorBar: ---

→ valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar.

description: FM signal

→ description defines that the text of the legend should be "FM signal".

line: solid

→ line defines that the line style of the forward modelled equivalent water height values should be solid.

width: 1.5

→ width defines that the width of the equivalent water height value line should be 1.5 points.

color: red

→ color defines that the colour of the equivalent water height value line should be red.

symbol: <none>

→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.

plotOnSecondAxis: no

→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

layer
layer: linesAndPoints → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. inputfileMatrix: data/TimeSeries/GRACE_GreatLakes_TrendSemiAnnualRemoved.txt → inputfileMatrix defines the path and the filename of the matrix input file for the Great Lakes. This matrix contains one column in which the annual signal and the semi-annual signal were simultaneously removed from the GRACE signal. valueX: data0 → valueX defines that the x-values should be the monthly modified julian date. valueY: data6 → valueY defines that the y-values should indicate the processed equivalent water height values which were derived from GRACE observations and from which the semi-annual and the annual signal were simultaneously removed. The unit of the equivalent water height value is metre. valueZ: --- → valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar. valueErrorBar: --- → valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar. description: GRACE signal → description defines that the text of the legend should be "GRACE signal". line: solid → line defines that the line style of the processed equivalent water height values, which were derived from GRACE observations, should be solid. width: 1.5 → width defines that the width of the equivalent water height value line should be 1.5. color: blue → color defines that the colour of the equivalent water height value line should be blue. symbol: <none> → symbol defines that each data point should not be visualized by a symbol such as a circle or a star. plotOnSecondAxis: no

→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

layer
<u>layer: linesAndPoints</u> → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. <u>inputfileMatrix: data/TimeSeries/GRACE-FM_GreatLakes_TrendSemiAnnualRemoved.txt</u> → inputfileMatrix defines the path and the filename of the corrected matrix input file for the Great Lakes. This matrix contains one column in which the annual signal and the semi-annual signal were simultaneously removed from the corrected GRACE signal. <u>valueX: data0</u> → valueX defines that the x-values should be the monthly modified julian date. <u>valueY: data6</u> → valueY defines that the y-values should be the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations and which were then further reduced by the annual signal and the semi-annual signal. The unit of this difference is metre. <u>valueZ: ---</u> → valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar. <u>valueErrorBar: ---</u> → valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar. <u>description: Grace minus FM</u> → description defines that the text of the legend should be “Grace minus FM”. <u>line: solid</u> → line defines that the line style of the corrected equivalent water height values should be solid. <u>width: 1.5</u> → width defines that the width of the equivalent water height value line should be 1.5 points. <u>color: green</u> → color defines that the colour of the equivalent water height value line should be green. <u>symbol: <none></u>

→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.

plotOnSecondAxis: no

→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

axisX
axisX: time → axisX defines the style of the x-axis of the graph. In this case, the input data are interpreted as modified julian date. min: --- → min defines that there is no specified minimum value of the x-axis. Hence, the minimum scale value is set automatically. max: --- → max defines that there is no specified maximum value of the x-axis. Hence, the maximum scale value is set automatically. majorTickSpacing: 2Y → majorTickSpacing defines that the boundary annotation of the x-axis should be set every second year. minorTickSpacing: 2Y → minorTickSpacing defines that the spacing of the frame tick intervals on the x-axis should be set every second year. gridLineSpacing: 1Y → gridLineSpacing defines that that the spacing of the grid lines on the x-axis should be set every year. secondary: <none> → secondary defines that no additional time axis should be established. color: black → color defines that the colour of the x-axis should be black. gridline: solid → gridline defines that the style of the grid lines should be solid. width: 0.25 → width defines that the width of the grid lines should be 0.25 points. color: gray

→ color defines that the colour of the grid lines should be gray. changeDirection: no → changeDirection defines that the direction of the x-axis should not be changed from right / up to left / down. options: FORMAT_DATE_MAP=yyyy-mm-dd → options defines that the output data string should be given in the format year-month-day. options: FORMAT_CLOCK_MAP=hh:mm → options defines that the output clock string should be given in the format hour-minute. options: TIME_EPOCH=1858-11-17T00:00:00 → options defines the value of the calendar and the clock at the origin (0 point) of relative time units. options: TIME_UNIT=d → options defines that the units of the relative time data since the TIME_EPOCH should be daily.

axisY
axisY: standard → axisY defines the style of the y-axis of the graph. In this case, the input data should be interpreted as arbitrary input data. min: - 0.08 → min defines that the minimum value of the y-axis should be set to - 0.08. max: 0.08 → max defines that the maximum value of the y-axis should be set to 0.08. majorTickSpacing: 0.02 → majorTickSpacing defines that the boundary annotation of the y-axis should be set every 0.02. Hence, it is set for every 0.02 m of equivalent water height. minorTickSpacing: 0.002 → minorTickSpacing defines that the spacing of the frame tick intervals on the y-axis should be set every 0.002. Hence, it is set for every 0.002 m of equivalent water height. gridLineSpacing: --- → gridLineSpacing defines that the spacing of the grid lines on the y-axis should not be further specified. gridline: solid

→ gridline defines that the style of the grid lines should be solid.

width: 0.25

→ width defines that the width of the grid lines should be 0.25 points.

color: gray

→ color defines that the colour of the grid lines should be gray.

unit: ---

→ unit defines that the no unit name should be appended to the y-axis values.

Label: EWH [m]

→ label defines that the description of the y-axis should be “EWH [m]”.

logarithmic: no

→ logarithmic defines that no logarithmic scale should be used.

color: black

→ color defines that the colour of the bars and labels of the y-axis should be black.

changeDirection: no

→ changeDirection defines that the direction of the x-axis should not be changed from right / up to left / down.

axisY2: <none>
→ axisY2 defines that no second Y-axis should be plotted.

colorbar: <none>
→ colorbar defines that no colour bar should be plotted.

legend
legend: <enabled> → legend defines that a legend with descriptions should be plotted. width: 10 → width defines that length of the legend should be 10 cm. height: --- → height defines that the height of the plot given in centimetre should not be further specified. positionX: 1.05

→ positionX defines that the x-position of the legend should be 1.05.

positionY: 1.0 [= 1]

→ positionY defines that the y-position of the legend should be 1.0.

anchorPoint: TL

→ anchorPoint defines that the anchor point should be located at the top left. Hence, the anchor point is the point where the related edges link to.

columns: 1

→ columns defines that the legend should consist of one column.

textColor: <none>

→ textColor defines that there is no specified colour of the text of the legend.

fillColor: <none>

→ fillColor defines that there is no specified colour with which the box of the legend should be filled.

edgeLine: <none>

→ edgeLine defines that there is no specified style of the edge of the box of the legend.

options
width: 12 → width defines that the width of the plot should be 12 cm. height: 7 → height defines that height of the plot should be 7 cm. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. options: FONT_ANNOT_PRIMARY=10p → options defines that the font which is used for primary annotations should be 10 pixels. options: MAP_ANNOT_OFFSET_PRIMARY=0.1c → options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.

options: FONT_LABEL=10p

→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.

options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

options: TIME_SYSTEM=MJD

→ options defines that the relative time should refer to the modified julian date.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotGraph generates one graph which illustrates the temporal variation of the equivalent water height values over the Great Lakes. The x-axis indicates the year and reaches from 01/2003 to 12/2016. Meanwhile, the y-axis indicates the equivalent water height values in the unit metre. In total, there are three curves. The first curve represents the forward modelled equivalent water height values from which the annual signal and the semi-annual signal were simultaneously removed. The second curve illustrates the processed equivalent water height values which were derived from GRACE observations and from which the annual signal and the semi-annual signal were also simultaneously removed. The third curve visualizes the corrected GRACE signal. The corrected GRACE signal refers to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations. The forward modelled equivalent water height values express the gravity field and function as removal correction. Hence, the forward modelled signal visualizes the size of the forward modelled equivalent water height values that has to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact, that the prevailing water body has on the processed equivalent water height values, which were derived from GRACE observations, can be removed. By subtracting the removal correction of for instance the Great Lakes from the GRACE signal, the influence, that the Great Lakes have on the GRACE signal, can be removed. Hence, the GRACE signal can be corrected. This procedure is also denoted as removal approach.

14 GroupPrograms

Goal:

The goal is to run the individually defined programs in a group.

Parameters:

outputfileLog: ---
→ outpufileLog defines that no additional log file should be created.

silently: no
→ silently defines that the output should be shown.

14.1 GroupPrograms

Goal:

The goal is to run the individually defined programs in a group.

Parameters:

outputfileLog: ---
→ outpufileLog defines that no additional log file should be created.

silently: no
→ silently defines that the output should be shown.

14.1.1 Gravityfield2PotentialCoefficientsTimeSeries

Goal:

The goal is to compute a time series of a time variable gravity field and to convert this gravity field to coefficients of a spherical harmonic expansion. Hence, a time series of potential coefficients should be computed.

Parameters:

outputfileTimeSeries: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_1_PotentialCoefficientsTimeSeries.txt
→ outputfileTimeSeries defines the path and the filename of the processed potential coefficient time series output file.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2018200204201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2018/timeSplines/old_monthly/timeSpline_ITSG-Grace2018_monthly_n96_deg1_c20_replaced_noGIA_noMean_2002-04_2017-06_interp_ddk3.dat] → inputfileTimeSplinesGravityfield defines the path and the filename of the input time spline. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: --- → maxDegree defines that there is no specified maximum degree of the expansion. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

timeSeries: Θ timeSeriesMonthly [= everyMonth]
→ timeSeries defines that a monthly time series should be generated.

minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]
→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

numbering: degreewise
→ numbering defines that the numbering scheme of the spherical harmonic coefficients in a parameter vector should be from degree to degree.

Result:

The function Gravityfield2PotentialCoefficientsTimeSeries generates one .txt file which contains 9409 columns. The first column contains the monthly time stamps which are expressed as modified julian date. The remaining columns indicate the potential coefficients, which are numbered by degree. Hence, the 9408 columns can be imagined as being c21, s21, c22, s22 etc.

14.1.2 InstrumentDetrend

Goal:

The goal is to reduce the temporal parametrization, such as the trend, per arc from the potential coefficient time series.

Parameters:

outputfileInstrument: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_2_InstrumentDetrend.txt
→ outputfileInstrument defines the path and the filename of the processed potential coefficient time series output file.

outputfileTimeSeriesArcParameters: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_2_InstrumentDetrend_Parameter.txt
→ outputfileTimeSeriesArcParameters defines the path and the filename of the output file which contains the estimated parameters for each epoch.

inputfileInstrument: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_1_PotentialCoefficientsTimeSeries.txt
→ inputfileInstrument defines the path and the filename of the potential coefficient time series input file.

parametrizationTemporal
<u>parametrizationTemporal: constant</u> → parametrizationTemporal parametrizes time depending parameters. In this case, constant refers to a parameter, which is constant in each time interval. <u>interval: uniformInterval</u> → interval defines that a time series with a uniform sampling should be generated. <u>timeStart: Θ timeStart [= 2003-01-01 (52640)]</u> → timeStart defines that the first point in time should be the 2003-01-01 which is the first available modified julian date. <u>timeEnd: Θ timeEnd [= 2016-12-31 (57753)]</u> → timeEnd defines that the last point in time should be the 2016-12-31, which is the last available modified julian date. <u>intervalCount: 1</u> → intervalCount defines the count of intervals should be 1. <u>includeLastTime: no</u> → includeLastTime defines that the last point in time should not be included.

parametrizationTemporal
<u>parametrizationTemporal: trend</u> → parametrizationTemporal parametrizes time depending parameters. In this case, trend refers to a time variable function which is given by a linear trend. This time variable function is given by

$f(x,t) = \frac{1}{T} \cdot (t - t_0) \cdot f_t(x)$ Equation 114: Time variable function given by a linear trend Source: Mayer-Gürr et al., n.d. with T = timeStep in days and t_0 = timeStart. <u>timeStart: Θ referenceTime [= 2010-01-01 12:00:00 (55197.5)]</u> → timeStart defines that the reference time should be the 2010-01-01 12:00:00. Thus, the reference time is in the middle of the selected time frame. If the reference time would be outside the selected time frame, the estimation would become more inaccurate. <u>timeStep: 365.25 [= 365d 06:00:00]</u> → timeStep defines that the time interval should be 365.25 days. By introducing the .25, leap years, which occur on average every four years, can be balanced.

parametrizationTemporal
<u>parametrizationTemporal: oscillation</u> → parametrizationTemporal parametrizes time depending parameters. In this case, oscillation refers to a time variable function which is given by an oscillation. This time variable function is given by $f(x,t) = f^c(x) \cdot \cos(\omega_i(t)) + f^s(x) \cdot \sin(\omega_i(t))$ Equation 115: Time variable function given by an oscillation Source: Mayer-Gürr et al., n.d. with $\omega_i = \frac{2\pi}{T_i}(t - t_0)$, T = timeStep in days and t_0 = timeStart. <u>period: 365.25 [= 365d 06:00:00]</u> → timeStep defines that the time interval should be 365.25 days. By introducing the .25, leap years, which occur on average every four years, can be balanced. <u>time0: Θ referenceTime [= 2010-01-01 12:00:00 (55197.5)]</u> → time0 defines that the reference time should be the 2010-01-01 12:00:00. Thus, the reference time is in the middle of the selected time frame. If the reference time would be outside the selected time frame, the estimation would become more inaccurate.

startDataFields: 0
→ startDataFields defines that the start data field should be the first one.

countDataFields: ---
→ countDataFields defines that the number of data fields should not be counted.

huber: 2.5
→ huber defines that the pre-determined tuning constant should be set to 2.5 (Dawber et al., 2011)

huberPower: 1.5
→ huberPower defines that the ratio of the residuals and the redundancies should be potentiated with a huber power of 1.5.

huberMaxIteration: 5
→ huberMaxIteration defines that the robust estimation of the least squares parameters should be repeated 5 times.

Result:

The function InstrumentDetrend generates two .txt files. The first .txt file contains 37636 columns. The first column contains time stamp of the reference time which is expressed as modified julian date. The next 9408 columns indicate the constant value of each potential coefficient column. Hence, the next 9408 columns indicate the trend values. Following, the sine and the cosine values, which represent the oscillation, are denoted. Besides, also a .txt file which contains the estimated parameters for each arc, is created. This .txt file contains 9409 columns. The first column contains the monthly time stamps which are expressed as modified julian date. The remaining columns indicate all data of the first temporal parameter. This is then followed by all data of the second temporal parameter and so on.

14.1.3 MatrixCalculate

Goal:

The goal is to compute a matrix which should contain all mean values from the Instrument Detrend Parameter file.

Parameters:

outputfileMatrix: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_3_MatrixCalculate_Mean.txt
→ outputfileMatrix defines the path and the filename of the mean matrix output file.

matrix
matrix: transpose → matrix defines that a matrix should be generated. This matrix should be transposed. matrix: slice → matrix defines that the matrix should be sliced. matrix: file → matrix defines that the matrix should be generated from a file. inputfileMatrix: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_2_InstrumentDetrend_Parameter.txt → inputfileMatrix defines the path and the filename of the time spline parameter matrix input file. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default. startRow: 0 → startRow defines that the start row of the matrix should be the first row. Hence, from row 0 and column 1, 1 row and 9409 columns should be sliced out. startColumn: 1+0*({maxDegree}+1)^2 [= 1] → startColumn defines that the start column should be shifted by 1. Hence, from row 0 and column 1, 1 row and 9409 columns should be sliced out. rows: 1 → rows defines that the start row should be the first one. Hence, from row 0 and column 1, 1 row and 9409 columns should be sliced out. columns: ({maxDegree}+1)^2 [= 9409] → columns defines that the start column should be the 9409th one. Hence, from row 0 and column 1, 1 row and 9409 columns should be sliced out.

Result:

The function MatrixCalculate generates one .txt file. This .txt file contains a vector with the dimensions 9409 x 1. Hence, all mean values from the Instrument Detrend Parameter file are listed below each other.

14.1.4 MatrixCalculate

Goal:

The goal is to merge several matrices.

Parameters:

outputfileMatrix: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_3_MatrixCalculate_Trend.txt
→ outputfileMatrix defines the path and the filename of the trend matrix output file.

matrix
matrix: transpose → matrix defines that a matrix should be generated. This matrix should be transposed. matrix: slice → matrix defines that the matrix should be sliced. matrix: file → matrix defines that the matrix should be generated from a file. inputfileMatrix: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_2_InstrumentDetrend_Parameter.txt → inputfileMatrix defines the path and the filename of the time spline parameter matrix input file. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default. startRow: 0 → startRow defines that the start row of the matrix should be the first row. Hence, from row 0 and column 9410, 1 row and 9409 columns should be sliced out. startColumn: 1+1*({maxDegree}+1)^2 [= 9410] → startColumn defines that the start column should be shifted by 1. Hence, from row 0 and column 9410, 1 row and 9409 columns should be sliced out.

rows: 1 → rows defines that the start row should be the first one. Hence, from row 0 and column 9410, 1 row and 9409 columns should be sliced out. columns: ({maxDegree}+1)^2 [= 9409] → columns defines that the start column should be the 9409th one. Hence, from row 0 and column 9410, 1 row and 9409 columns should be sliced out.

Result:

The function MatrixCalculate generates one .txt file. This .txt file contains a vector with the dimensions 9409 x 1. Hence, all trend values from the Instrument Detrend Parameter file are listed below each other.

14.1.5 MatrixCalculate

Goal:

The goal is to compute a matrix which should contain all cosine values from the Instrument Detrend Parameter file.

Parameters:

outputfileMatrix: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_3_MatrixCalculate_Cos.txt
→ outputfileMatrix defines the path and the filename of the cosine matrix output file.

matrix
matrix: transpose → matrix defines that a matrix should be generated. This matrix should be transposed. matrix: slice → matrix defines that the matrix should be sliced. matrix: file → matrix defines that the matrix should be generated from a file. inputfileMatrix: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_2_InstrumentDetrend_Parameter.txt → inputfileMatrix defines the path and the filename of the time spline parameter matrix input file.

factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default. startRow: 0 → startRow defines that the start row of the matrix should be the first row. Hence, from row 0 and column 18819, 1 row and 9409 columns should be sliced out. startColumn: 1+2*({maxDegree}+1)^2 [= 18819] → startColumn defines that the start column should be shifted by 1. Hence, from row 0 and column 18819, 1 row and 9409 columns should be sliced out. rows: 1 → rows defines that the start row should be the first one. Hence, from row 0 and column 18819, 1 row and 9409 columns should be sliced out. columns: ({maxDegree}+1)^2 [= 9409] → columns defines that the start column should be the 9409th one. Hence, from row 0 and column 18819, 1 row and 9409 columns should be sliced out.

Result:

The function MatrixCalculate generates one .txt file. This .txt file contains a vector with the dimensions 9409 x 1. Hence, all cosine values from the Instrument Detrend Parameter file are listed below each other.

14.1.6 MatrixCalculate

Goal:

The goal is to compute a matrix which should contain all sinus values from the Instrument Detrend Parameter file.

Parameters:

outputfileMatrix: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_3_MatrixCalculate_Sin.txt
→ outputfileMatrix defines the path and the filename of the sinus matrix output file.

matrix
matrix: transpose → matrix defines that a matrix should be generated. This matrix should be transposed. matrix: slice → matrix defines that the matrix should be sliced. matrix: file → matrix defines that the matrix should be generated from a file. inputfileMatrix: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_2_InstrumentDetrend_Parameter.txt → inputfileMatrix defines the path and the filename of the forward modelled time spline parameter matrix input file. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default. startRow: 0 → startRow defines that the start row of the matrix should be the first row. Hence, from row 0 and column 28228, 1 row and 9409 columns should be sliced out. startColumn: 1+3*({maxDegree}+1)^2 [= 28228] → startColumn defines that the start column should be shifted by 1. Hence, from row 0 and column 28228, 1 row and 9409 columns should be sliced out. rows: 1 → rows defines that the start row should be the first one. Hence, from row 0 and column 28228, 1 row and 9409 columns should be sliced out. columns: ({maxDegree}+1)^2 [= 9409] → columns defines that the start column should be the 9409th one. Hence, from row 0 and column 28228, 1 row and 9409 columns should be sliced out.

Result:

The function MatrixCalculate generates one .txt file. This .txt file contains a vector with the dimensions 9409 x 1. Hence, all sinus values from the Instrument Detrend Parameter file are listed below each other.

14.1.7 Gravityfield2PotentialCoefficients

Goal:

The goal is to evaluate a time variable gravity field from a mean value solution vector at a given time and to write the respective potential coefficients to a file.

Parameters:

outputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_4_Gravityfield2PotentialCoefficients_Mean.gfc
→ outputfilePotentialCoefficients defines the path and the filename of the potential coefficient output file.

gravityfield
<u>gravityfield: fromParametrization</u> → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of fromParametrization, the potential coefficients are derived from a solution vector. <u>parametrization: sphericalHarmonics</u> → parametrization defines that the potential is parametrized by an expansion of spherical harmonics. Hence, the Equation $V(\lambda,\vartheta,r) = \frac{GM}{R}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\left(\frac{R}{r}\right)^{n+1}(c_{nm}C_{nm}(\lambda,\vartheta) + s_{nm}S_{nm}(\lambda,\vartheta))$ Equation 116: Spherical Harmonic Expansion Equation Source: Mayer-Gürr et al., n.d. with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude, is applied. <u>minDegree: {minDegree} [= 0]</u> → minDegree defines that the minimum degree of the expansion should be 0 °. <u>maxDegree: {maxDegree} [= 96]</u> → maxDegree defines that the maximum degree of the expansion should be 96 °. <u>GM: 3.986004415e+14 [= 398600441500000]</u> → GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$. <u>R: 6378137.0</u>

→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m. numbering: degreewise → numbering defines that the numbering scheme of the spherical harmonic coefficients in a parameter vector should be from degree to degree.

inputfileSolution: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_3_MatrixCalculate_Mean.txt
→ inputfileSolution defines the path and the filename of the mean value solution input vector file.

inputfileSigmax: ---
→ inputfileSigmax defines that no standard deviations or covariance matrix of the solution should be considered.

indexStart: 0
→ indexStart defines that the position with the index 0 of the solution vector should be used.

rightSide: ---
→ rightSide defines that no specific right-hand side should be selected. This can be traced back to the fact that the inputfileSolution file only contains one column.

factor: 1.0 [= 1]
→ factor defines that the result should be multiplied by 1. This factor is defined by default.

minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]
→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

Result:

The function Gravityfield2PotentialCoefficients generates one .txt file. This .txt file contains the potential coefficients which were interpreted from the mean value solution vector.

14.1.8 Gravityfield2PotentialCoefficients

Goal:

The goal is to evaluate a time variable gravity field from a trend value solution vector at a given time and to write the respective potential coefficients to a file.

Parameters:

outputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_4_Gravityfield2PotentialCoefficients_Trend.gfc
→ outputfilePotentialCoefficients defines the path and the filename of the potential coefficient output file.

gravityfield
<u>gravityfield: fromParametrization</u> → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. <u>parametrization: sphericalHarmonics</u>

→ parametrization defines that the potential is parametrized by an expansion of spherical harmonics. Hence, the Equation

$$V(\lambda, \vartheta, r) = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{R}{r}\right)^{n+1} (c_{nm}C_{nm}(\lambda, \vartheta) + s_{nm}S_{nm}(\lambda, \vartheta))$$

Equation 117: Spherical Harmonic Expansion Equation

Source: Mayer-Gürr et al., n.d.

with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude, is applied.

minDegree: {minDegree} [= 0]

→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]

→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]

→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]

→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

numbering: degreewise

→ numbering defines that the numbering scheme of the spherical harmonic coefficients in a parameter vector should be from degree to degree.

inputfileSolution: data/PotentialCoefficients/TimeSplines/GRACE/ GRACE_TimeSplines_3_MatrixCalculate_Trend.txt
→ inputfileSolution defines the path and the filename of the trend value solution input vector file.

inputfileSigmax: ---
→ inputfileSigmax defines that no standard deviations or covariance matrix of the solution should be considered.

indexStart: 0
→ indexStart defines that the position with the index 0 of the solution vector should be used.

rightSide: 0
→ rightSide defines that the column with the index 0 of the inputfileSolution should be used.

factor: 1.0 [= 1]
→ factor defines that the result should be multiplied by 1. This factor is defined by default.

minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]
→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

Result:

The function Gravityfield2PotentialCoeffieicnts generates one .txt file. This .txt file contains the potential coefficients which were interpreted from the trend value solution vector.

14.1.9 Gravityfield2PotentialCoefficients

Goal:

The goal is to evaluate a time variable gravity field from a cosine value solution vector at a given time and to write the respective potential coefficients to a file.

Parameters:

outputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/GRACE/ GRACE_ TimeSplines_4_Gravityfield2PotentialCoefficients_Cos.gfc
→ outputfilePotentialCoefficients defines the path and the filename of the potential coefficient output file.

gravityfield
gravityfield: fromParametrization → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. parametrization: sphericalHarmonics → parametrization defines that the potential is parametrized by an expansion of spherical harmonics. Hence, the Equation $V(\lambda, \vartheta, r) = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{R}{r}\right)^{n+1} (c_{nm} C_{nm}(\lambda, \vartheta) + s_{nm} S_{nm}(\lambda, \vartheta))$ Equation 118: Spherical Harmonic Expansion Equation Source: Mayer-Gürr et al., n.d. with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude, is applied. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. GM: 3.986004415e+14 [= 398600441500000] → GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.
numbering: degreewise
→ numbering defines that the numbering scheme of the spherical harmonic coefficients in a parameter vector should be from degree to degree.

inputfileSolution: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_3_MatrixCalculate_Cos.txt
→ inputfileSolution defines the path and the filename of the cosine value solution input vector file.

inputfileSigmax: ---
→ inputfileSigmax defines that no standard deviations or covariance matrix of the solution should be considered.

indexStart: 0
→ indexStart defines that the position with the index 0 of the solution vector should be used.

rightSide: 0
→ rightSide defines that the column with the index 0 of the inputfileSolution should be used.

factor: 1.0 [= 1]
→ factor defines that the result should be multiplied by 1. This factor is defined by default.

minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]
→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

Result:

The function Gravityfield2PotentialCoeffieicnts generates one .txt file. This .txt file contains the potential coefficients which were interpreted from the cosine value solution vector.

14.1.10 Gravityfield2PotentialCoefficients

Goal:

The goal is to evaluate a time variable gravity field from a sinus value solution vector at a given time and to write the respective potential coefficients to a file.

Parameters:

outputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_ TimeSplines_4_Gravityfield2PotentialCoefficients_Sin.gfc
→ outputfilePotentialCoefficients defines the path and the filename of the potential coefficient output file.

gravityfield
gravityfield: fromParametrization → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. parametrization: sphericalHarmonics

→ parametrization defines that the potential is parametrized by an expansion of spherical harmonics. Hence, the Equation $$V(\lambda, \vartheta, r) = \frac{GM}{R}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\left(\frac{R}{r}\right)^{n+1}(c_{nm}C_{nm}(\lambda, \vartheta) + s_{nm}S_{nm}(\lambda, \vartheta))$$ Equation 119: Spherical Harmonic Expansion Equation Source: Mayer-Gürr et al., n.d. with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude, is applied. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. GM: 3.986004415e+14 [= 398600441500000] → GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$. R: 6378137.0 [= 6378137] → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. numbering: degreewise → numbering defines that the numbering scheme of the spherical harmonic coefficients in a parameter vector should be from degree to degree.

inputfileSolution: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_3_MatrixCalculate_Sin.txt
→ inputfileSolution defines the path and the filename of the sinus value solution input vector file.

inputfileSigmax: ---
→ inputfileSigmax defines that no standard deviations or covariance matrix of the solution should be considered.

indexStart: 0
→ indexStart defines that the position with the index 0 of the solution vector should be used.

rightSide: 0
→ rightSide defines that the column with the index 0 of the inputfileSolution should be used.

factor: 1.0 [= 1]
→ factor defines that the result should be multiplied by 1. This factor is defined by default.

minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]
→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

Result:

The function Gravityfield2PotentialCoeffieicnts generates one .txt file. This .txt file contains the potential coefficients which were interpreted from the sinus value solution vector.

14.1.11 Gravityfield2GriddedData

Goal:

The goal is to compute gridded mean values of the time variable gravity field.

Parameters:

outputfileGriddedData: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_Time-Splines_5_Gravityfield2GriddedData_Mean.txt
→ outputfileGriddedData defines the path and the filename of the mean gravity field grid output file.

grid
grid: Θ gridCoarse [= geograph]
→ grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. The resolution is 0.5 ° x 0.5 °.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 120: Coefficients of the Kernel   Source: Mayer-Gürr et al., n.d.   includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: potentialCoefficients
→ gravityfield defines that functionals of the time dependent gravity field are computed. In respect of potentialCoefficients, the potential is given by

$$V(\lambda, \vartheta, r) = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{R}{r}\right)^{n+1} (c_{nm} C_{nm}(\lambda, \vartheta) + s_{nm} S_{nm}(\lambda, \vartheta))$$ Equation 121: Spherical Harmonic Expansion Equation Source: Mayer-Gürr et al., n.d. with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude. inputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_ TimeSplines_4_Gravityfield2PotentialCoefficients_Mean.gfc → inputfilePotentialCoefficients defines the path and the filename of the input potential coefficient file. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default. setSigmasToZero: no → setSigmasToZero defines that the variance should not be set to 0.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the

inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 122: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 123: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

Result:

The function Gravityfield2GriddedData generates one .txt file with gridded data. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded mean values of the time variable gravity field. Since the gravity field is expressed in terms of processed equivalent water height values, which were derived from GRACE observations, the mean values also refer to equivalent water height values and thus the unit is metres.

14.1.12 Gravityfield2GriddedData

Goal:

The goal is to compute gridded trend values of the time variable gravity field.

Parameters:

outputfileGriddedData: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_Time-Splines_5_Gravityfield2GriddedData_Trend.txt
→ outputfileGriddedData defines the path and the filename of the trend gravity field grid output file.

grid
grid: Θ gridCoarse [= geograph]
→ grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. The resolution is 0.5 ° x 0.5 °.

kernel: Θ kernel [= waterHeight]

→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n

$$k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$$

Equation 124: Coefficients of the Kernel

Source: Mayer-Gürr et al., n.d.

includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield

gravityfield: potentialCoefficients

→ gravityfield defines that functionals of the time dependent gravity field are computed. In respect of potentialCoefficients, the potential is given by

$$V(\lambda, \vartheta, r) = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{R}{r}\right)^{n+1} (c_{nm} C_{nm}(\lambda, \vartheta) + s_{nm} S_{nm}(\lambda, \vartheta))$$

Equation 125: Spherical Harmonic Expansion Equation

Source: Mayer-Gürr et al., n.d.

with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude.
<u>inputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_4_Gravityfield2PotentialCoefficients_Trend.gfc</u>
→ inputfilePotentialCoefficients defines the path and the filename of the input potential coefficient file.
<u>minDegree: {minDegree} [= 0]</u>
→ minDegree defines that the minimum degree of the expansion should be 0 °.
<u>maxDegree: {maxDegree} [= 96]</u>
→ maxDegree defines that the maximum degree of the expansion should be 96 °.
<u>factor: 1.0 [= 1]</u>
→ factor defines that the result should be multiplied by 1. This factor is defined by default.
<u>setSigmasToZero: no</u>
→ setSigmasToZero defines that the variance should not be set to 0.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$

Equation 126: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 127: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137 \text{ m} - 6356752.3141 \text{ m})}{6378137 \text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

Result:

The function Gravityfield2GriddedData generates one .txt file with gridded data. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded trend values of the time variable gravity field. Since the gravity field is expressed in terms of processed equivalent water height values, which were derived from GRACE observations, the trend values also refer to equivalent water heights and thus the unit is metres.

14.1.13 Gravityfield2GriddedData

Goal:

The goal is to compute gridded cosine values of the time variable gravity field.

Parameters:

outputfileGriddedData: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_Time-Splines_5_Gravityfield2GriddedData_Cos.txt
→ outputfileGriddedData defines the path and the filename of the cosine gravity field grid output file.

grid
grid: Θ gridCoarse [= geograph] → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. The resolution is 0.5 ° x 0.5 °.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 128: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: potentialCoefficients → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of potentialCoefficients, the potential is given by $V(\lambda, \vartheta, r) = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{R}{r}\right)^{n+1} (c_{nm} C_{nm}(\lambda, \vartheta) + s_{nm} S_{nm}(\lambda, \vartheta))$ Equation 129: Spherical Harmonic Expansion Equation Source: Mayer-Gürr et al., n.d.

with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude.
inputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_ TimeSplines_4_Gravityfield2PotentialCoefficients_Cos.gfc
→ inputfilePotentialCoefficients defines the path and the filename of the input potential coefficient file.
minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.
maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.
factor: 1.0 [= 1]
→ factor defines that the result should be multiplied by 1. This factor is defined by default.
setSigmasToZero: no
→ setSigmasToZero defines that the variance should not be set to 0.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$

Equation 130: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 131: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

Result:

The function Gravityfield2GriddedData generates one .txt file with gridded data. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded cosine values of the time variable gravity field. Since the gravity field is expressed in terms of processed equivalent water height values, which were derived from GRACE observations, the cosine values also refer to equivalent water height values and thus the unit is metres.

14.1.14 Gravityfield2GriddedData

Goal:

The goal is to compute gridded sinus values of the time variable gravity field.

Parameters:

outputfileGriddedData: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_Time-Splines_5_Gravityfield2GriddedData_Sin.txt
→ outputfileGriddedData defines the path and the filename of the sinus gravity field grid output file.

grid
grid: Θ gridCoarse [= geograph] → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. The resolution is 0.5 ° x 0.5 °.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 132: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: potentialCoefficients → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of potentialCoefficients, the potential is given by $V(\lambda, \vartheta, r) = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{R}{r}\right)^{n+1} (c_{nm} C_{nm}(\lambda, \vartheta) + s_{nm} S_{nm}(\lambda, \vartheta))$ Equation 133: Spherical Harmonic Expansion Equation Source: Mayer-Gürr et al., n.d.

with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude.
inputfilePotentialCoefficients: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_4_Gravityfield2PotentialCoefficients_Sin.gfc
→ inputfilePotentialCoefficients defines the path and the filename of the input potential coefficient file.
minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.
maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.
factor: 1.0 [= 1]
→ factor defines that the result should be multiplied by 1. This factor is defined by default.
setSigmasToZero: no
→ setSigmasToZero defines that the variance should not be set to 0.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

time: ---
→ time defines that the gravity field should not be evaluated at a specific point in time.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$

Equation 134: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 135: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\ \mathrm{m}\ -\ 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

Result:

The function Gravityfield2GriddedData generates one .txt file with gridded data. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded sinus values of the time variable gravity field. Since the gravity field is expressed in terms of processed equivalent water height values, which were derived from GRACE observations, the cosine values also refer to equivalent water height values and thus the unit is metres.

14.1.15 GriddedDataCalculate

Goal:

The goal is to compute gridded amplitude values of the time variable gravity field.

Parameters:

outputfileGriddedData: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_6_GriddedDataCalculate_Amplitude.txt
→ outputfileGriddedData defines the path and the filename of the amplitude gravity field grid output file.

inputfileGriddedData: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_5_Gravityfield2GriddedData_Cos.txt
→ inputfileGriddedData defines the path and the filename of the grid input which contains gridded cosine values of the time variable gravity field.

inputfileGriddedData: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_5_Gravityfield2GriddedData_Sin.txt
→ inputfileGriddedData defines the path and the filename of the grid input which contains gridded sinus values of the time variable gravity field.

constant: ---
→ constant defines that no additional constant should be defined.

parameter: ---
→ parameter defines that no additional parameter is defined.

leastSquares: ---
→ leastSquares defines that the expression should not be minimized by adjusting the parameters.

removalCriteria: ---
→ removalCriteria defines that points should not be removed if one criterion evaluates true.

longitude: longitude
→ longitude is described by the expression longitude.

latitude: latitude
→ latitude is described by the expression latitude.

height: height
→ height is described by the expression height.

area: area
→ area is described by the expression area.

value: sqrt(data0^2+data1^2)
→ value defines that the value of the amplitude should be computed by calculating the square root of the squared and summed cosine and sinus values.

computeArea: no
→ computeArea defines that no automatic area computation of rectangular grids, which will overwrite the area information, should be performed.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 136: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.
the inverseFlattening value $\bar{f}$ can simply be computed by
$\bar{f} = \frac{1}{f}$.
Equation 137: Inverse Flattening of the rotation ellipsoid
Source: Mayer-Gürr et al., n.d.
Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is
$f = \frac{(6378137 \text{ m} - 6356752.3141 \text{ m})}{6378137 \text{ m}}$
$f = 0.003352810681$
and thus, the inverseFlattening is
$\bar{f} = \frac{1}{0.003352810681}$
$\bar{f} = 298.2572221.$

statistics: <none>
→ statistics defines that no statistic columns should be computed.

Result:

The function GriddedDataCalculate generates one .txt file with gridded data. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded amplitude values of the time variable gravity field. Since the gravity field is expressed in terms of processed equivalent water height values, which were derived from GRACE observations, the amplitude values also refer to equivalent water height values and thus the unit is metres.

14.2 PlotMap

Goal:

The goal is to generate a global map which visualizes the trend values of the processed equivalent water height values, which were derived from GRACE observations, with focus on the Mississippi Basin.

Parameters:

outputfile: data/Maps/{listName}/{listName}_MississippiBasin_GRACE_Trend.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_MississippiBasin_GRACE_Trend
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: griddedData → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. inputfileGriddedData: data/PotentialCoefficients/TimeSplines/GRACE/GRACE_TimeSplines_5_Gravityfield2GriddedData_Trend.txt → inputfileGriddedData defines the path and the filename of the trend gridded gravity field input file. value: data0 → value defines that data0, which contains the gridded trend values of the time variable gravity field, should be displayed. increment: 0.5 → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid. illuminate: no

→ illuminate defines that the grid should not be brightened.

resample: <none>

→ resample defines that the grid input values should not be resampled.

gridlineRegistered: no

→ gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid. width: 1 → width defines that the width of the coastlines should be 1 point. color: black → color defines that the colour of the coastlines should be black. landColor: <none> → landColor defines that there is no specific colour with which the land area should be filled. oceanColor: <none> → oceanColor defines that there is no specific colour with which the ocean area should be filled. minArea: 10000 → minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

layer
layer: polygon → layer defines the content of the map. Hence, a polygon around the Mississippi Basin is drawn. inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin.txt

→ inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the Mississippi Basin. <u>line: solid</u> → line defines that the line style of the polygon should be solid. <u>width: 1.5</u> → width defines that the width of the coastlines should be 1.5 points. <u>color: red</u> → color defines that the colour of the polygon should be red. <u>fillColor: <none></u> → fillColor defines that there is no specified colour with which the box of the legend should be filled. <u>value: ---</u> → value defines that the fillColor should not have a specified value. This can be traced back to the fact that no fillColor is used anyway. <u>drawLineAsGreatCircle: yes</u> → drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

layer
<u>layer: polygon</u> → layer defines the content of the map. Hence, a polygon around the unit Hermann of the Mississippi Basin should be drawn. <u>inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit1_Hermann.txt</u> → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for unit Hermann of the Mississippi Basin. <u>line: solid</u> → line defines that the line style of the polygon should be solid. <u>width: 1.5</u> → width defines that the width of the coastlines should be 1.5 points. <u>color: red</u> → color defines that the colour of the polygon should be red. <u>fillColor: <none></u>

→ fillColor defines that there is no specified colour with which the box of the legend should be filled.

value: ---

→ value defines that the fillColor should not have a specified value. This can be traced back to the fact that no fillColor is used anyway.

drawLineAsGreatCircle: yes

→ drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

layer
layer: polygon → layer defines the content of the map. Hence, a polygon around the unit Alton of the Mississippi Basin should be drawn. inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit2_Alton.txt → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Alton of the Mississippi Basin. line: solid → line defines that the line style of the polygon should be solid. width: 1.5 → width defines that the width of the coastlines should be 1.5 points. color: red → color defines that the colour of the polygon should be red. fillColor: <none> → fillColor defines that there is no specified colour with which the box of the legend should be filled. value: --- → value defines that the fillColor should not have a specified value. This can be traced back to the fact that no fillColor is used anyway. drawLineAsGreatCircle: yes → drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

layer
layer: polygon → layer defines the content of the map. Hence, a polygon around the unit Metropolis of the Mississippi Basin should be drawn. inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit3_Metropolis.txt → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Metropolis of the Mississippi Basin. line: solid → line defines that the line style of the polygon should be solid. width: 1.5 → width defines that the width of the coastlines should be 1.5 points. color: red → color defines that the colour of the polygon should be red. fillColor: <none> → fillColor defines that there is no specified colour with which the box of the legend should be filled. value: --- → value defines that the fillColor should not have a specified value. This can be traced back to the fact that no fillColor is used anyway. drawLineAsGreatCircle: yes → drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

layer
layer: polygon → layer defines the content of the map. Hence, a polygon around the unit Vicksburg of the Mississippi Basin should be drawn. inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit4_Vicksburg.txt → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Vicksburg of the Mississippi Basin. line: solid

→ line defines that the line style of the polygon should be solid. width: 1.5 → width defines that the width of the coastlines should be 1.5 points. color: red → color defines that the colour of the polygon should be red. fillColor: <none> → fillColor defines that there is no specified colour with which the box of the legend should be filled. value: --- → value defines that the fillColor should not have a specified value. This can be traced back to the fact that no fillColor is used anyway. drawLineAsGreatCircle: yes → drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 138: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$ Equation 139: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $\mathrm{f} = \frac{(6378137\ \mathrm{m}\ -\ 6356752.613\ \mathrm{m})}{6378137\ \mathrm{m}}$ $\mathrm{f} = 0.003352810681$ and thus, the inverseFlattening is $\bar{\mathrm{f}} = \frac{1}{0.003352810681}$ $\bar{\mathrm{f}} = 298.2572221.$

minLambda: - 115
→ minLambda defines that the minimum degree of longitude should be - 115 °.

maxLambda: - 70
→ maxLambda defines that the maximum degree of longitude should be - 70 °.

minPhi: 29
→ minPhi defines that the minimum degree of latitude should be 29 °.

maxPhi: 55
→ maxPhi defines that the maximum degree of latitude should be 55 °.

majorTickSpacing: 10
→ majorTickSpacing defines that the boundary annotation should be set every 10 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 10
→ gridLineSpacing defines that the spacing of the grid lines should be set every 10 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: - 0.015 → min defines that the minimum value of the colour bar should be set to - 0.015. max: 0.015 → max defines that the maximum value of the colour bar should be set to 0.015. annotation: 0.003 → annotation defines that a boundary annotation should be drawn every 0.003 °. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [m] → label defines that the axis description and hence the description of the colour bar should be set to "EWH [m]". logarithmic: no → logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. triangleRight: yes → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. illuminate: no → illuminate defines that the grid should not be brightened. vertical: no → vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. length: 100 → length defines that the length of the colour bar should be 100 %. margin: 0.4

→ margin defines that the space between the colour bar and the figure should be 0.4 cm. colorTable: haxby → colorTable defines that the colour bar with the name “haxby” should be used. This colour bar ranges from dark blue to light red. reverse: yes → reverse defines that the colour bar should be reversed. Hence, the colour bar ranges from light red to dark blue. showColorbar: yes → showColorbar defines that the colour bar should be plotted.

projection
projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. centralMeridian: 0 → centralMeridian defines that the central meridian should be set at 0 °.

options
width: -- → width defines that the width of the plot should not be further specified. height: 8 → height defines that the height of the plot should be 8 cm. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels.

options: MAP_ANNOT_OFFSET_PRIMARY=0.1c

→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.

options: FONT_LABEL=10p

→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.

options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one map which represents the trend values of the processed equivalent water height values, which were derived from GRACE observations, with the focus on the different units of the Mississippi Basin. The processed equivalent water height values and thus also the trend values are given in the unit of metre. They express the gravity field. Since the map visualizes the trend of the processed equivalent water height values which were derived from GRACE observations and thus also the trend of the gravity field, it also indicates whether the gravity and thus also the mass of the Mississippi Basin increases or decreases on the long term.

14.3 PlotMap

Goal:

The goal is to generate a global map which visualizes the trend values of the forward modelled equivalent water height values with focus on the Mississippi Basin. These forward modelled equivalent water height values express the gravity field and function as removal correction.

Parameters:

outputfile: data/Maps/{listName}/{listName}_MississippiBasin_FM_Trend.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_MississippiBasin_FM_Trend
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
<u>layer: griddedData</u> → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. <u>inputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_5_Gravityfield2GriddedData_Trend.txt</u> → inputfileGriddedData defines the path and the filename of the forward modelled trend gridded gravity field input file. <u>value: data0</u> → value defines that data0, which contains the gridded trend values of the forward modelled equivalent water height values, should be displayed. <u>increment: 0.5</u> → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid. <u>illuminate: no</u>

→ illuminate defines that the grid should not be brightened.

resample: <none>

→ resample defines that the grid input values should not be resampled.

gridlineRegistered: no

→ gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid. width: 1 → width defines that the width of the coastlines should be 1 point. color: black → color defines that the colour of the coastlines should be black. landColor: <none> → landColor defines that there is no specific colour with which the land area should be filled. oceanColor: <none> → oceanColor defines that there is no specific colour with which the ocean area should be filled. minArea: 10000 → minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

layer
layer: polygon → layer defines the content of the map. Hence, a polygon around the Mississippi Basin is drawn. inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin.txt

→ inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the Mississippi Basin.
<u>line: solid</u>
→ line defines that the line style of the polygon should be solid.
<u>width: 1.5</u>
→ width defines that the width of the coastlines should be 1.5 points.
<u>color: red</u>
→ color defines that the colour of the polygon should be red.
<u>fillColor: <none></u>
→ fillColor defines that there is no specified colour with which the box of the legend should be filled.
<u>value: ---</u>
→ value defines that the fillColor should not have a specified value. This can be traced back to the fact that no fillColor is used anyway.
<u>drawLineAsGreatCircle: yes</u>
→ drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

layer
<u>layer: polygon</u> → layer defines the content of the map. Hence, a polygon around the unit Hermann of the Mississippi Basin should be drawn. <u>inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit1_Hermann.txt</u> → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Hermann of the Mississippi Basin. <u>line: solid</u> → line defines that the line style of the polygon should be solid. <u>width: 1.5</u> → width defines that the width of the coastlines should be 1.5 points. <u>color: red</u> → color defines that the colour of the polygon should be red. <u>fillColor: <none></u>

→ fillColor defines that there is no specified colour with which the box of the legend should be filled.

value: ---

→ value defines that the fillColor should not have a specified value. This can be traced back to the fact that no fillColor is used anyway.

drawLineAsGreatCircle: yes

→ drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

layer

layer: polygon

→ layer defines the content of the map. Hence, a polygon around the unit Alton of the Mississippi Basin should be drawn.

inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit2_Alton.txt

→ inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Alton of the Mississippi Basin.

line: solid

→ line defines that the line style of the polygon should be solid.

width: 1.5

→ width defines that the width of the coastlines should be 1.5 points.

color: red

→ color defines that the colour of the polygon should be red.

fillColor: <none>

→ fillColor defines that there is no specified colour with which the box of the legend should be filled.

value: ---

→ value defines that the fillColor should not have a specified value. This can be traced back to the fact that no fillColor is used anyway.

drawLineAsGreatCircle: yes

→ drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

layer
<u>layer: polygon</u> → layer defines the content of the map. Hence, a polygon around the unit Metropolis of the Mississippi Basin should be drawn. <u>inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit3_Metropolis.txt</u> → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Metropolis of the Mississippi Basin. <u>line: solid</u> → line defines that the line style of the polygon should be solid. <u>width: 1.5</u> → width defines that the width of the coastlines should be 1.5 points. <u>color: red</u> → color defines that the colour of the polygon should be red. <u>fillColor: <none></u> → fillColor defines that there is no specified colour with which the box of the legend should be filled. <u>value: ---</u> → value defines that the fillColor should not have a specified value. This can be traced back to the fact that no fillColor is used anyway. <u>drawLineAsGreatCircle: yes</u> → drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

layer
<u>layer: polygon</u> → layer defines the content of the map. Hence, a polygon around the unit Vicksburg of the Mississippi Basin should be drawn. <u>inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit4_Vicksburg.txt</u> → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for unit Vicksburg of the Mississippi Basin. <u>line: solid</u>

→ line defines that the line style of the polygon should be solid.
width: 1.5
→ width defines that the width of the coastlines should be 1.5 points.
color: red
→ color defines that the colour of the polygon should be red.
fillColor: <none>
→ fillColor defines that there is no specified colour with which the box of the legend should be filled.
value: ---
→ value defines that the fillColor should not have a specified value. This can be traced back to the fact that no fillColor is used anyway.
drawLineAsGreatCircle: yes
→ drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 140: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 141: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $\mathrm{f} = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$ $\mathrm{f} = 0.003352810681$ and thus, the inverseFlattening is $\bar{\mathrm{f}} = \frac{1}{0.003352810681}$ $\bar{\mathrm{f}} = 298.2572221.$

minLambda: - 115
→ minLambda defines that the minimum degree of longitude should be - 115 °.

maxLambda: - 70
→ maxLambda defines that the maximum degree of longitude should be - 70 °.

minPhi: 29
→ minPhi defines that the minimum degree of latitude should be 29 °.

maxPhi: 55
→ maxPhi defines that the maximum degree of latitude should be 55 °.

majorTickSpacing: 10
→ majorTickSpacing defines that the boundary annotation should be set every 10 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 10
→ gridLineSpacing defines that the spacing of the grid lines should be set every 10 °.

colorbar

colorbar: <enabled>

→ colorbar defines that a colour bar should be plotted.

min: - 0.015

→ min defines that the minimum value of the colour bar should be set to - 0.015.

max: 0.015

→ max defines that the maximum value of the colour bar should be set to 0.015.

annotation: 0.003

→ annotation defines that a boundary annotation should be drawn every 0.003 °.

unit: ---

→ unit defines that no unit information should be appended to the values of the axis.

label: EWH [m]

→ label defines that the axis description and hence the description of the colour bar should be set to "EWH [m]".

logarithmic: no

→ logarithmic defines that no logarithmic scale should be used.

triangleLeft: yes

→ triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values.

triangleRight: yes

→ triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values.

illuminate: no

→ illuminate defines that the grid should not be brightened.

vertical: no

→ vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot.

length: 100

→ length defines that the length of the colour bar should be 100 %.

margin: 0.4

→ margin defines that the space between the colour bar and the figure should be 0.4 cm. colorTable: haxby → colorTable defines that the colour bar with the name “haxby” should be used. This colour bar ranges from dark blue to light red. reverse: yes → reverse defines that the colour bar should be reversed. Hence, the colour bar ranges from light red to dark blue. showColorbar: yes → showColorbar defines that the colour bar should be plotted.

projection
projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. centralMeridian: 0 → centralMeridian defines that the central meridian should be set at 0 °.

options
width: 12 → width defines that the width of the plot should be 12 cm. height: 8 → height defines that the height of the plot should be 8 cm. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels.

options: MAP_ANNOT_OFFSET_PRIMARY=0.1c

→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.

options: FONT_LABEL=10p

→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.

options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one map which represents the trend values of the forward modelled equivalent water height values with the focus on the different units of the Mississippi Basin. These forward modelled equivalent water height values express the gravity field and function as removal correction. They are given in the unit of centimetre. Hence, the map visualizes the trend of the size of the forward modelled equivalent water height values that has to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact that the Mississippi Basin has on the processed equivalent water height values, which were derived from GRACE observations, can be removed. Hence, the GRACE signal can be corrected. Consequently, the map functions as an indicator which shows if the influence that the Mississippi Basin has on the mass change observed by GRACE, increases or decreases on the long term. This information is extremely helpful to make the estimates of GRACE more consistent with the output from hydrological models for this respective region.

14.4 PlotMap

Goal:

The goal is to generate a global map which visualizes the amplitude values of the forward modelled equivalent water height values with the focus on the Mississippi Basin. These forward modelled equivalent water height values express the gravity field and act as removal correction.

Parameters:

outputfile: data/Maps/{listName}/{listName}_MississippiBasin_FM_Amplitude.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_Global_MississippiBasin_FM_Amplitude
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: griddedData → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. inputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_6_GriddedDataCalculate_Amplitude.txt → inputfileGriddedData defines the path and the filename of the forward modelled amplitude gridded gravity field input file. value: data0 → value defines that data0, which contains the gridded amplitude values of the forward modelled equivalent water height values, should be displayed. increment: 0.5 → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid. illuminate: no

→ illuminate defines that the grid should not be brightened.

resample: <none>

→ resample defines that the grid input values should not be resampled.

gridlineRegistered: no

→ gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid. width: 1 → width defines that the width of the coastlines should be 1 point. color: black → color defines that the colour of the coastlines should be black. landColor: <none> → landColor defines that there is no specific colour with which the land area should be filled. oceanColor: <none> → oceanColor defines that there is no specific colour with which the ocean area should be filled. minArea: 10000 → minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

layer
layer: polygon → layer defines the content of the map. Hence, a polygon around the Mississippi Basin should be drawn. inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin.txt

→ inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the Mississippi Basin.

line: solid

→ line defines that the line style of the polygon should be solid.

width: 1.5

→ width defines that the width of the coastlines should be 1.5 points.

color: red

→ color defines that the colour of the polygon should be red.

fillColor: <none>

→ fillColor defines that there is no specified colour with which the box of the legend should be filled.

value: ---

→ value defines that the fillColor should not have a specified value. This can be traced back to the fact that no fillColor is used anyway.

drawLineAsGreatCircle: yes

→ drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$\mathrm{f} = \frac{(\text{Semimajor axis } - \text{ semiminor axis})}{\text{semimajor axis}}$$

Equation 142: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by

$$\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$$

Equation 143: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

minLambda: - 115
→ minLambda defines that the minimum degree of longitude should be - 115 °.

maxLambda: - 75
→ maxLambda defines that the maximum degree of longitude should be - 75 °.

minPhi: 29
→ minPhi defines that the minimum degree of latitude should be 29 °.

maxPhi: 50
→ maxPhi defines that the maximum degree of latitude should be 50 °.

majorTickSpacing: 10
→ majorTickSpacing defines that the boundary annotation should be set every 10 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 10
→ gridLineSpacing defines that the spacing of the grid lines should be set every 10 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: - 0.10 [= 0.1] → min defines that the minimum value of the colour bar should be set to - 0.10. max: 0.10 [= 0.1] → max defines that the maximum value of the colour bar should be set to 0.10. annotation: 0.02 → annotation defines that a boundary annotation should be drawn every 0.02 °. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [m] → label defines that the axis description and hence the description of the colour bar should be set to "EWH [m]". logarithmic: no → logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. triangleRight: yes → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. illuminate: no → illuminate defines that the grid should not be brightened. vertical: no → vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. length: 100 → length defines that the length of the colour bar should be 100 %. margin: 0.4

→ margin defines that the space between the colour bar and the figure should be 0.4 cm.
colorTable: haxby
→ colorTable defines that the colour bar with the name “haxby” should be used. This colour bar ranges from dark blue to light red.
reverse: yes
→ reverse defines that the colour bar should be reversed. Hence, the colour bar ranges from light red to dark blue.
showColorbar: yes
→ showColorbar defines that the colour bar should be plotted.

projection
projection: robinson
→ projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions.
centralMeridian: 0
→ centralMeridian defines that the central meridian should be set at 0 °.

options
width: 12
→ width defines that the width of the plot should be 12 cm.
height: 7
→ height defines that the height of the plot should be 7 cm.
titleFontSize: 12
→ titleFontSize defines that the fontsize of the title should be 12 points.
marginTitle: 0.4
→ marginTitle defines that the space between the figure title should be 0.4 cm.
drawGridOnTop: no
→ drawGridOnTop defines that no grid lines should be drawn above all other lines and points.
options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels.
options: MAP_ANNOT_OFFSET_PRIMARY=0.1c
→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.
options: FONT_LABEL=10p
→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.
options: MAP_LABEL_OFFSET=0.1c
→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.
options: FONT_ANNOT_SECONDARY=10p
→ options defines that the font for a secondary time axis should be 10 points.
transparent: no
→ transparent defines that the background of the plot should not be transparent.
dpi = 300
→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.
removeFiles: yes
→ removeFiles defines that the .gmt and script files should be removed after the computation.
viewPlot: yes
→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one map which represents the amplitude values of the forward modelled equivalent water height values with the focus on the Mississippi Basin. These forward modelled equivalent water height values express the gravity field and function as removal correction. They are given in the unit of metre. Hence, the map visualizes the amplitude of the size of the forward modelled equivalent water height values that has to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact that the Mississippi Basin has on the processed equivalent water height values, which were derived from GRACE observations, can be removed. Hence, the GRACE signal can be corrected. Consequently, the map functions as an indicator which shows how strong the influence of the Mississippi Basin on the mass change observed by GRACE, fluctuates. This information is extremely helpful to make the estimates of GRACE more consistent with the output from hydrological models for this respective region.

14.5 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean forward modelled equivalent water height values which express the time variable gravity field over the Mississippi Basin.

Parameters:

outputfileTimeSeries: data/TimeSeries/FM_MississippiBasin.txt
→ outputfileTimeSeries defines the path and the filename of the mean forward modelled equivalent water height value time series output file for the Mississippi Basin.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. deltaPhi: {gridSizeCoarse} [= 0.5] → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. height: 0.0 [= 0] → height defines that the distance of the points above the ellipsoid should be 0 m. R: 6378137.0 [= 6378137] → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. inverseFlattening: 298.2572221010 [= 298.2572221] → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 144: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by $\bar{f} = \frac{1}{f}$. Equation 145: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$ <u>border: polygon</u> → border defines that a subset of points should be extracted from the global grid. <u>inputfilePolygon: /data1/border/riverbasins/mississippi.xml</u> → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the Mississippi Basin. <u>buffer: 0</u> → buffer defines that a barrier of 0 metre should be established around the polygon. <u>exclude: no</u> → exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel
<u>kernel: Θ kernel [= waterHeight]</u>
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the

effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $$k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$$ Equation 146: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc] → inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the Mississippi Basin. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the gravity field is expressed in terms of an averaged and forward modelled equivalent water height value. The unit of the averaged equivalent water height value is metre.

14.6 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean equivalent water height values which express the time variable gravity field and which were derived from GRACE observations over the Mississippi Basin.

Parameters:

outputfileTimeSeries: data/TimeSeries/GRACE_MississippiBasin.txt
→ outputfileTimeSeries defines the path and the filename of the mean equivalent water height value time series output file for the Mississippi Basin.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. deltaPhi: {gridSizeCoarse} [= 0.5] → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. height: 0.0 [= 0] → height defines that the distance of the points above the ellipsoid should be 0 m. R: 6378137.0 [= 6378137] → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. inverseFlattening: 298.2572221010 [= 298.2572221] → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 147: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by $\bar{f} = \frac{1}{f}.$ Equation 148: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$ $f = 0.003352810681$

and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$ <u>border: polygon</u> → border defines that a subset of points should be extracted from the global grid. <u>inputfilePolygon: /data1/border/riverbasins/mississippi.xml</u> → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the Mississippi Basin. <u>buffer: 0</u> → buffer defines that a barrier of 0 metre should be established around the polygon. <u>exclude: no</u> → exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel
<u>kernel: Θ kernel [= waterHeight]</u> → kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 149: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2016200212201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2016/itsg-grace2016_MD90_deg1c20repl_no1502_GIAreduced_mean-red_DDK3_interp_200212-201706.dat] → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the Mississippi Basin. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the gravity field is expressed in terms of the equivalent water height value. The unit of this equivalent water height value is metre. In this case, the processed equivalent water height values are not forward modelled, but directly derived from the GRACE observations. These observations are already pre-processed. Hence, the data is already interpolated and the effect of the glacial isostatic adjustment is also removed.

14.7 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean equivalent water height values which express the corrected time variable gravity field over the Mississippi Basin.

Parameters:

outputfileTimeSeries: data/TimeSeries/GRACE-FM_MississippiBasin.txt
→ outputfileTimeSeries defines the path and the filename of the corrected mean equivalent water height value time series output file for the Mississippi Basin.

grid
<u>grid: geograph</u> → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude.

deltaLambda: {gridSizeCoarse} [= 0.5]

→ deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °.

deltaPhi: {gridSizeCoarse} [= 0.5]

→ deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °.

height: 0.0 [= 0]

→ height defines that the distance of the points above the ellipsoid should be 0 m.

R: 6378137.0 [= 6378137]

→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 150: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 151: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: polygon

→ border defines that a subset of points should be extracted from the global grid.

inputfilePolygon: /data1/border/riverbasins/mississippi.xml → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the Mississippi Basin. buffer: 0 → buffer defines that a barrier of 0 metre should be established around the polygon. exclude: no → exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel
kernel: Θ kernel [= waterHeight] → kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 152: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2016200212201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2016/itsg-grace2016_

MD90_deg1c20repl_no1502_GIAreduced_mean-red_DDK3_interp_200212-201706.dat] → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc] → inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled input time spline inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: - 1

→ factor defines that the forward modelled equivalent water height values, which represent the gravity field, should be subtracted from the processed equivalent water height values which were derived from GRACE observations.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the Mississippi Basin. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the corrected time variable gravity field is expressed in terms of an averaged equivalent water height value. The unit of the averaged equivalent water height value is metre. Hence, the corrected equivalent water height values refer to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations.

14.8 FunctionsCalculate

Goal:

The goal is to manipulate the data columns of the forward modelled signal matrix in a way, that the annual signal and the semi-annual signal as well as the trend are removed. The focus should be set on the Mississippi Basin.

Parameters:

outputfile: data/TimeSeries/FM_MississippiBasin_TrendSemiAnnualRemoved.txt
→ outputfile defines the path and the filename of the forward modelled matrix output file for the Mississippi Basin. This matrix should contain one column in which the annual signal and the semi-annual signal are simultaneously removed from the forward modelled signal.

inputfile: data/TimeSeries/FM_MississippiBasin.txt
→ inputfile defines the path and the filename of the mean forward modelled equivalent water height value time series input file for the Mississippi Basin.

constant: annual=2*pi/365.25
→ constant defines that the annual signal should have an angular frequency of 2*pi/365.25. By introducing the .25, leap years, which occur on average every four years, can be balanced.

constant: t0=54750
→ constant defines that the start point in time should be 11/10/2008.

parameter: a
→ parameter defines that the parameter a should be estimated in a least squares adjustment.

parameter: b
→ parameter defines that the parameter b should be estimated in a least squares adjustment.

parameter: c
→ parameter defines that the parameter c should be estimated in a least squares adjustment.

parameter: d
→ parameter defines that the parameter d should be estimated in a least squares adjustment.

parameter: e
→ parameter defines that the parameter e should be estimated in a least squares adjustment.

parameter: f
→ parameter defines that the parameter f should be estimated in a least squares adjustment.

leastSquares: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)*annual *2)+f*cos((data0-t0)*annual*2)-data1
→ leastSquares defines that the parameters should be adjusted by applying this expression. Hence, the Equation does not only include a description of the trend, but also of the annual signal and the semi-annual signal as well the forward modelled equivalent water level value itself.

outcolumn: data0
→ outcolumn defines that the points in time, which are expressed as modified julian date, should be stored in the data0 column of the matrix.

outcolumn: data1
→ outcolumn defines that the forward modelled equivalent water height values should be stored in the data1 column of the matrix.

outcolumn: a+b*(data0-t0)
→ outcolumn defines that the trend should be stored in the data2 column of the matrix.

outcolumn: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)
→ outcolumn defines that the trend and the annual signal should be stored in the data3 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual))
→ outcolumn defines that the forward modelled equivalent water height values, which are reduced by the trend and the annual signal, should be stored in the data4 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e* sin((data0-t0)*annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the forward modelled equivalent water height values, which are reduced by the trend and the semi-annual signal, should be stored in the data5 column of the matrix.

outcolumn: data1-(c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)* annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the forward modelled equivalent water height values, which are simultaneously reduced by the annual and the semi-annual, should be stored in the data6 column of the matrix.

Statistics: <none>
→ statistics defines that no statistic columns should be computed.

Result:

The function FunctionsCalculate generates one .txt file for the Mississippi Basin. This .txt file contains a matrix with the dimensions of 168 x 7. Each row represents one point in time. The first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. The second column indicates the forward modelled equivalent water height values. The third column contains the trend value. The fourth column contains the trend values and the annual signal values. Meanwhile, the fifth column contains the forward modelled equivalent water height values which are already reduced by the annual signal values and the trend values. The sixth column indicates the forward modelled equivalent water height values which are already reduced by the semi-annual signal values and the trend values. The seventh and last column contains the forward modelled equivalent water height values from which the annual signal and the semi-annual signal values are removed. The unit of the forward modelled equivalent water height values is metre. Since the time series values are computed by using the forward modelled time spline, the equivalent water height values are also forward modelled.

14.9 FunctionsCalculate

Goal:

The goal is to manipulate the data columns of the GRACE signal matrix in a way, that the annual signal and the semi-annual signal as well as the trend are removed. The focus should be set on the Mississippi Basin.

Parameters:

outputfile: data/TimeSeries/GRACE_MississippiBasin_TrendSemiAnnualRemoved.txt
→ outputfile defines the path and the filename of the matrix output file for the Mississippi Basin. This matrix should contain one column in which the annual signal and the semi-annual signal are simultaneously removed from the GRACE signal.

inputfile: data/TimeSeries/GRACE_MississippiBasin.txt
→ inputfile defines the path and the filename of the mean equivalent water height value time series input file for the Mississippi Basin.

constant: annual=2*pi/365.25
→ constant defines that the annual signal should have an angular frequency of 2*pi/365.25. By introducing the .25, leap years, which occur on average every four years, can be balanced.

constant: t0=54750
→ constant defines that the start point in time should be 11/10/2008.

parameter: a
→ parameter defines that the parameter a should be estimated in a least squares adjustment.

parameter: b
→ parameter defines that the parameter b should be estimated in a least squares adjustment.

parameter: c
→ parameter defines that the parameter c should be estimated in a least squares adjustment.

parameter: d
→ parameter defines that the parameter d should be estimated in a least squares adjustment.

parameter: e
→ parameter defines that the parameter e should be estimated in a least squares adjustment.

parameter: f
→ parameter defines that the parameter f should be estimated in a least squares adjustment.

leastSquares: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)*annual *2)+f*cos((data0-t0)*annual*2)-data1
→ leastSquares defines that the parameters should be adjusted by applying this expression. Hence, the Equation does not only include a description of the trend, but also of the annual signal and the semi-annual signal as well the processed equivalent water height values, which were derived from GRACE observations.

outcolumn: data0
→ outcolumn defines that the points in time, which are expressed as modified julian date, should be stored in the data0 column of the matrix.

outcolumn: data1
→ outcolumn defines that the processed equivalent water height values, which were derived from GRACE observations, should be stored in the data1 column of the matrix.

outcolumn: a+b*(data0-t0)
→ outcolumn defines that the trend should be stored in the data2 column of the matrix.

outcolumn: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)
→ outcolumn defines that the trend and the annual signal should be stored in the data3 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual))
→ outcolumn defines that the processed equivalent water height values derived from GRACE observations, which are reduced by the trend and the annual signal, should be stored in the data4 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e* sin((data0-t0)*annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the processed equivalent water height values derived from GRACE observations, which are reduced by the trend and the semi-annual signal, should be stored in the data5 column of the matrix.

outcolumn: data1-(c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)* annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the processed equivalent water height values derived from GRACE observations, which are reduced by the annual and the semi-annual, should be stored in the data6 column of the matrix.

Statistics: <none>
→ statistics defines that no statistic columns should be computed.

Result:

The function FunctionsCalculate generates one .txt file for the Mississippi Basin. This .txt file contains a matrix with the dimensions of 168 x 7. Each row represents one point in time. The first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. The second column indicates the trend value. The third column contains the trend values and the annual signal values. Meanwhile, the fourth column contains equivalent water height values which were already reduced by the annual signal values and the trend values. The fifth column indicates the processed equivalent water height values which were derived from GRACE observations and which were already reduced by the semi-annual signal values and the trend values. The last column contains the GRACE signal in terms of equivalent water height values from which the annual signal and the semi-annual signal, were simultaneously removed. The unit of the processed equivalent water height values is metre. In this case, the processed equivalent water height values were directly derived from the GRACE observations. These observations are already pre-processed. Hence, the data is already interpolated and the effect of the glacial isostatic adjustment is also removed.

14.10 FunctionsCalculate

Goal:

The goal is to manipulate the data columns of the corrected GRACE signal matrix in a way, that the annual signal and the semi-annual signal as well as the trend are removed. The focus should be set on the Mississippi Basin.

Parameters:

outputfile: data/TimeSeries/GRACE-FM_MississippiBasin_Trend_Semi_AnnualRemoved .txt
→ outputfile defines the path and the filename of the corrected matrix output file for the Mississippi Basin. This matrix should contain one column in which the annual signal and the semi-annual signal are simultaneously removed from the corrected GRACE signal.

inputfile: data/TimeSeries/GRACE-FM_MississippiBasin.txt
→ inputfile defines the path and the filename of the corrected mean equivalent water height value time series output file for the Mississippi Basin.

constant: annual=2*pi/365.25
→ constant defines that the annual signal should have an angular frequency of 2*pi/365.25. By introducing the .25, leap years, which occur on average every four years, can be balanced.

constant: t0=54750
→ constant defines that the start point in time should be 11/10/2008.

parameter: a
→ parameter defines that the parameter a should be estimated in a least squares adjustment.

parameter: b
→ parameter defines that the parameter b should be estimated in a least squares adjustment.

parameter: c
→ parameter defines that the parameter c should be estimated in a least squares adjustment.

parameter: d
→ parameter defines that the parameter d should be estimated in a least squares adjustment.

parameter: e
→ parameter defines that the parameter e should be estimated in a least squares adjustment.

parameter: f
→ parameter defines that the parameter f should be estimated in a least squares adjustment.

leastSquares: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)*annual *2)+f*cos((data0-t0)*annual*2)-data1
→ leastSquares defines that the parameters should be adjusted by applying this expression. Hence, the Equation does not only include a description of the trend, but also of the annual signal and the semi-annual signal as well the corrected equivalent water level value itself.

outcolumn: data0
→ outcolumn defines that the points in time, which are expressed as modified julian date, should be stored in the data0 column of the matrix.

outcolumn: data1
→ outcolumn defines that the corrected equivalent water height values should be stored in the data1 column of the matrix.

outcolumn: a+b*(data0-t0)
→ outcolumn defines that the trend should be stored in the data2 column of the matrix.

outcolumn: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)
→ outcolumn defines that the trend and the annual signal should be stored in the data3 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual))
→ outcolumn defines that corrected equivalent water height values, which are further reduced by the trend and the annual signal, should be stored in the data4 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e* sin((data0-t0)*annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that corrected equivalent water height values, which are further reduced by the trend and the semi-annual signal, should be stored in the data5 column of the matrix.

outcolumn: data1-(c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)* annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the corrected equivalent water height values, which are further reduced by the annual and the semi-annual, should be stored in the data6 column of the matrix.

Statistics: <none>
→ statistics defines that no statistic columns should be computed.

Result:

The function FunctionsCalculate generates one .txt file for the Mississippi Basin. This .txt file contains a matrix with the dimensions of 168 x 7. Each row represents one point in time. The first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. The second column indicates the corrected equivalent water height values. The third column contains the trend value. The fourth column contains the trend values and the annual signal values. Meanwhile, the fifth column contains the corrected equivalent water height values which are already reduced by the annual signal values and the trend values. The sixth column indicates the corrected equivalent water height values which are already reduced by the semi-annual signal values and the trend values. The seventh and last column contains the corrected equivalent water height values from which the annual signal values and the semi-annual signal values, are removed. The unit of the corrected equivalent water height values is metre. In this case the corrected equivalent water height values refer to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations.

14.11 PlotGraph

Goal:

The goal is to generate a two-dimensional plot which visualizes the temporal variation of the total water height values over the Mississippi Basin for every month from 01/2003 to 12/2016. Hence, the graph should not only illustrate the forward modelled equivalent water height values from which the annual signal and the semi-annual signal were simultaneously removed, but also the processed equivalent water height values which were derived from GRACE observations and which were also simultaneously reduced by the annual signal and the semi-annual signal. Finally, the graph should also visualize the corrected GRACE signal. Hence, the corrected GRACE signal refers to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations.

Parameters:

outputfile: data/Graphs/{listName}/{listName}_MississippiBasin.png
→ outputfile defines the path and the filename of the generated graph.

title: TWS Delta over Mississippi Basin (annual / semiannual signal removed)
→ title defines the title of the graph which should be displayed on the graph.

layer
layer: linesAndPoints → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. inputfileMatrix: data/TimeSeries/FM_MississippiBasin_TrendSemiAnnualRemoved.txt → inputfileMatrix defines the path and the filename of the forward modelled matrix input file for the Mississippi Basin. This matrix contains one column in which the annual signal and the semi-annual signal were simultaneously removed from the forward modelled signal. valueX: data0 → valueX defines that the x-values should be the monthly modified julian date. valueY: data6 → valueY defines that the y-values should be the forward modelled equivalent water height values from which the annual signal and the semi-annual signal were simultaneously removed. The unit of the forward modelled equivalent water height values is metre. valueZ: --- → valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar. valueErrorBar: --- → valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar. description: FM signal → description defines that the text of the legend should be “FM signal”. line: solid → line defines that the line style of the forward modelled equivalent water height values should be solid. width: 1.5 → width defines that the width of the equivalent water height value line should be 1.5 points. color: red → color defines that the colour of the equivalent water height value line should be red. symbol: <none>

→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star. <u>plotOnSecondAxis: no</u> → plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

layer
<u>layer: linesAndPoints</u> → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. <u>inputfileMatrix: data/TimeSeries/GRACE_MississippiBasin_TrendSemiAnnualRemoved.txt</u> → inputfileMatrix defines the path and the filename of the matrix input file for the Mississippi Basin. This matrix contains one column in which the annual signal and the semi-annual signal were simultaneously removed from the GRACE signal. <u>valueX: data0</u> → valueX defines that the x-values should be the monthly modified julian date. <u>valueY: data6</u> → valueY defines that the y-values should indicate the processed equivalent water height values which were derived from GRACE observations and from which the semi-annual and the annual signal were simultaneously removed. The unit of the equivalent water height value is metre. <u>valueZ: ---</u> → valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar. <u>valueErrorBar: ---</u> → valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar. <u>description: GRACE signal</u> → description defines that the text of the legend should be “GRACE signal”. <u>line: solid</u> → line defines that the line style of the corrected equivalent water height values should be solid. <u>width: 1.5</u>

→ width defines that the width of the equivalent water height value line should be 1.5 points.

color: blue

→ color defines that the colour of the equivalent water height value line should be blue.

symbol: <none>

→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.

plotOnSecondAxis: no

→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

layer

layer: linesAndPoints

→ layer defines the content of the map. Hence, a line and / or points of xy data should be plotted.

inputfileMatrix: data/TimeSeries/GRACE-FM_MississippiBasin_Trend_Semi_AnnualRemoved.txt

→ inputfileMatrix defines the path and the filename of the corrected matrix input file for the Mississippi Basin. This matrix contains one column in which the annual signal and the semi-annual signal were simultaneously removed from the corrected GRACE signal.

valueX: data0

→ valueX defines that the x-values should be the monthly modified julian date.

valueY: data6

→ valueY defines that the y-values should be the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations and which were then further reduced by the annual signal and the semi-annual signal. The unit of this difference is metre.

valueZ: ---

→ valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar.

valueErrorBar: ---

→ valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar.

description: Grace minus FM

→ description defines that the text of the legend should be “Grace minus FM”.

line: solid
→ line defines that the line style of the corrected equivalent water height values should be solid.
width: 1.5
→ width defines that the width of the equivalent water height value line should be 1.5 points.
color: green
→ color defines that the colour of the equivalent water height value line should be green.
symbol: <none>
→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.
plotOnSecondAxis: no
→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

axisX
axisX: time
→ axisX defines the style of the x-axis of the graph. In this case, the input data are interpreted as modified julian date.
min: ---
→ min defines that there is no specified minimum value of the x-axis. Hence, the minimum scale value is set automatically.
max: ---
→ max defines that there is no specified maximum value of the x-axis. Hence, the maximum scale value is set automatically.
majorTickSpacing: 2Y
→ majorTickSpacing defines that the boundary annotation of the x-axis should be set every second year.
minorTickSpacing: 1Y
→ minorTickSpacing defines that the spacing of the frame tick intervals on the x-axis should be set every year.
gridLineSpacing: 1Y
→ gridLineSpacing defines that that the spacing of the grid lines on the x-axis should be set every year.
secondary: <none>

→ secondary defines that no additional time axis should be established. <u>color: black</u> → color defines that the colour of the x-axis should be black. <u>gridline: solid</u> → gridline defines that the style of the grid lines should be solid. <u>width: 0.25</u> → width defines that the width of the grid lines should be 0.25 points. <u>color: gray</u> → color defines that the colour of the grid lines should be gray. <u>changeDirection: no</u> → changeDirection defines that the direction of the x-axis should not be changed from right / up to left / down. <u>options: FORMAT_DATE_MAP=yyyy-mm-dd</u> → options defines that the output data string should be given in the format year-month-day. <u>options: FORMAT_CLOCK_MAP=hh:mm</u> → options defines that the output clock string should be given in the format hour-minute. <u>options: TIME_EPOCH=1858-11-17T00:00:00</u> → options defines the value of the calendar and the clock at the origin (0 point) of relative time units. <u>options: TIME_UNIT=d</u> → options defines that the units of the relative time data since the TIME_EPOCH should be daily.

axisY
<u>axisY: standard</u> → axisY defines the style of the y-axis of the graph. In this case, the input data should be interpreted as arbitrary input data. <u>min: ---</u> → min defines that the minimum value of the colour bar should not be further specified. <u>max: ---</u> → max defines that the maximum value of the colour bar should not be further specified. <u>majorTickSpacing: 0.02</u>

→ majorTickSpacing defines that the boundary annotation of the y-axis should be set every 0.02. Hence, it is set for every 0.02 m of equivalent water height.
minorTickSpacing: 0.002
→ minorTickSpacing defines that the spacing of the frame tick intervals on the y-axis should be set every 0.002. Hence, it is set for every 0.002 m of equivalent water height.
gridLineSpacing: ---
→ gridLineSpacing defines that the spacing of the grid lines on the y-axis should not be further specified.
gridline: solid
→ gridline defines that the style of the grid lines should be solid.
width: 0.25
→ width defines that the width of the grid lines should be 0.25 points.
color: gray
→ color defines that the colour of the grid lines should be gray.
unit: ---
→ unit defines that the no unit name should be appended to the y-axis values.
Label: EWH [m]
→ label defines that the description of the y-axis should be “EWH [m]”.
logarithmic: no
→ logarithmic defines that no logarithmic scale should be used.
color: black
→ color defines that the colour of the bars and labels of the y-axis should be black.
changeDirection: no
→ changeDirection defines that the direction of the x-axis should not be changed from right / up to left / down.

axisY2: <none>
→ axisY2 defines that no second Y-axis should be plotted.

colorbar: <none>
→ colorbar defines that no colour bar should be plotted.

legend
legend: <enabled>
→ legend defines that a legend with descriptions should be plotted.
width: 10
→ width defines that length of the legend should be 10 cm.
height: ---
→ height defines that the height of the plot given in centimetre should not be further specified.
positionX: 1.05
→ positionX defines that the x-position of the legend should be 1.05.
positionY: 1.0 [= 1]
→ positionY defines that the y-position of the legend should be 1.0.
anchorPoint: TL
→ anchorPoint defines that the anchor point should be located at the top left. Hence, the anchor point is the point where the related edges link to.
columns: 1
→ columns defines that the legend should consist of one column.
textColor: <none>
→ textColor defines that there is no specified colour of the text of the legend.
fillColor: <none>
→ fillColor defines that there is no specified colour with which the box of the legend should be filled.
edgeLine: <none>
→ edgeLine defines that there is no specified style of the edge of the box of the legend.

options
width: 12
→ width defines that the width of the plot should be 12 cm.
height: 7
→ height defines that height of the plot should be 7 cm.
titleFontSize: 12
→ titleFontSize defines that the fontsize of the title should be 12 points.
marginTitle: 0.4

→ marginTitle defines that the space between the figure title should be 0.4 cm.

drawGridOnTop: no

→ drawGridOnTop defines that no grid lines should be drawn above all other lines and points.

options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels.

options: MAP_ANNOT_OFFSET_PRIMARY=0.1c

→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.

options: FONT_LABEL=10p

→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.

options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

options: TIME_SYSTEM=MJD

→ options defines that the relative time should refer to the modified julian date.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotGraph generates one graph which illustrates the temporal variation of the equivalent water height values over the Mississippi Basin. The x-axis indicates the year and reaches from 01/2003 to 12/2016. Meanwhile, the y-axis indicates the equivalent water height values in the unit metre. In total, there are three curves. The first curve represents the forward modelled equivalent water height values from which the annual signal and the semi-annual signal were simultaneously removed. The second curve illustrates the processed equivalent water height values which were derived from GRACE observations and from which the annual signal and the semi-annual signal were also simultaneously removed. The third curve visualizes the corrected GRACE signal. The corrected GRACE signal refers to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations. The forward modelled equivalent water height values express the gravity field and function as removal correction. Hence, the forward modelled signal visualizes the size of the forward modelled equivalent water height values that has to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact, that the prevailing water body has on the processed equivalent water height values, which were derived from GRACE observations, can be removed. By subtracting the removal correction of for instance the Mississippi Basin from the GRACE signal, the influence, that the Mississippi Basin has on the GRACE signal, can be removed. Hence, the GRACE signal can be corrected. This procedure is also denoted as removal approach.

15 GroupPrograms

Goal:

The goal is to run the individually defined programs in a group.

Parameters:

outputfileLog: ---
→ outpufileLog defines that no additional log file should be created.

silently: no
→ silently defines that the output should be shown.

15.1 PlotMap

Goal:

The goal is to generate a global map which visualizes the trend values of the forward modelled equivalent water height values with focus on the unit Alton of the Mississippi Basin. These forward modelled equivalent water height values express the gravity field and function as removal correction.

Parameters:

outputfile: data/Maps/{listName}/{listName}_Unit2Alton_FM_Trend.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_Unit2Alton_FM_Trend
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: griddedData
→ layer defines the content of the map. Hence, a regular grid of yxz values should be plotted.
inputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_5_Gravityfield2GriddedData_Trend.txt
→ inputfileGriddedData defines the path and the filename of the forward modelled trend gridded gravity field input file.
value: data0
→ value defines that data0, which contains the gridded trend values of the forward modelled equivalent water height values, should be displayed.
increment: 0.5
→ increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid.
illuminate: no
→ illuminate defines that the grid should not be brightened.
resample: <none>
→ resample defines that the grid input values should not be resampled.
gridlineRegistered: no
→ gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
layer: coast
→ layer defines the content of the map. Hence, coastlines should be plotted.
resolution: medium
→ resolution defines that the resolution of the coastlines should be medium.
line: solid
→ line defines that the line style of the coastlines should be solid.
width: 1
→ width defines that the width of the coastlines should be 1 point.
color: black
→ color defines that the colour of the coastlines should be black.
landColor: <none>

→ landColor defines that there is no specific colour with which the land area should be filled. oceanColor: <none> → oceanColor defines that there is no specific colour with which the ocean area should be filled. minArea: 10000 → minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

layer
layer: polygon → layer defines the content of the map. Hence, a polygon around the unit Alton of the Mississippi Basin should be drawn. inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit2_Alton.txt → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Alton of the Mississippi Basin. line: solid → line defines that the line style of the polygon should be solid. width: 1.5 → width defines that the width of the coastlines should be 1.5 points. color: red → color defines that the colour of the polygon should be red. fillColor: <none> → fillColor defines that there is no specified colour with which the box of the legend should be filled. value: --- → value defines that the fillColor should not have a specified value. This can be traced back to the fact that no fillColor is used anyway. drawLineAsGreatCircle: yes → drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$ Equation 153: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by $$\bar{f} = \frac{1}{f}.$$ Equation 154: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$ $$f = 0.003352810681$$ and thus, the inverseFlattening is $$\bar{f} = \frac{1}{0.003352810681}$$ $$\bar{f} = 298.2572221.$$

minLambda: - 100
→ minLambda defines that the minimum degree of longitude should be - 100 °.

maxLambda: - 70
→ maxLambda defines that the maximum degree of longitude should be - 70 °.

minPhi: 37.5
→ minPhi defines that the minimum degree of latitude should be 37.5 °.

maxPhi: 50
→ maxPhi defines that the maximum degree of latitude should be 50 °.

majorTickSpacing: 10
→ majorTickSpacing defines that the boundary annotation should be set every 10 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 10
→ gridLineSpacing defines that the spacing of the grid lines should be set every 10 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: - 0.012 → min defines that the minimum value of the colour bar should be set to - 0.012. max: 0.012 → max defines that the maximum value of the colour bar should be set to 0.012. annotation: 0.002 → annotation defines that a boundary annotation should be drawn every 0.002 °. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [m] → label defines that the axis description and hence the description of the colour bar should be set to “EWH [m]”. logarithmic: no

→ logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. triangleRight: yes → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. illuminate: no → illuminate defines that the grid should not be brightened. vertical: no → vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. length: 100 → length defines that the length of the colour bar should be 100 %. margin: 0.4 → margin defines that the space between the colour bar and the figure should be 0.4 cm. colorTable: haxby → colorTable defines that the colour bar with the name "haxby" should be used. This colour bar ranges from dark blue to light red. reverse: yes → reverse defines that the colour bar should be reversed. Hence, the colour bar ranges from light red to dark blue. showColorbar: yes → showColorbar defines that the colour bar should be plotted.

projection
projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. centralMeridian: - 85

→ centralMeridian defines that the central meridian should be set at - 85 °. Hence, the central Meridian lies in the center of the unit Alton and a straight map can be plotted.

options
width: 16 → width defines that the width of the plot should be 16 cm. height: --- → height defines that the height of the plot given in centimetre should not be further specified. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. options: FONT_ANNOT_PRIMARY=10p → options defines that the font which is used for primary annotations should be 10 pixels. options: MAP_ANNOT_OFFSET_PRIMARY=0.1c → options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm. options: FONT_LABEL=10p → options defines that the font, which is used to plot the labels below the annotation, should be 10 points. options: MAP_LABEL_OFFSET=0.1c → options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm. options: FONT_ANNOT_SECONDARY=10p → options defines that the font for a secondary time axis should be 10 points. transparent: no → transparent defines that the background of the plot should not be transparent. dpi = 300 → dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes
→ removeFiles defines that the .gmt and script files should be removed after the computation.
viewPlot: yes
→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one map which represents the trend values of the forward modelled equivalent water height values with the focus on the unit Alton of the Mississippi Basin. These forward modelled equivalent water height values express the gravity field and function as removal correction. They are given in the unit of centimetre. Hence, the map visualizes the trend of the size of the forward modelled equivalent water height values that has to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact that the unit Alton of the Mississippi Basin has on the processed equivalent water height values, which were derived from GRACE observations, can be removed. Hence, the GRACE signal can be corrected. Consequently, the map functions as an indicator which shows if the influence that the unit Alton of the Mississippi Basin has on the mass change observed by GRACE, increases or decreases on the long term. This information is extremely helpful to make the estimates of GRACE more consistent with the output from hydrological models for this respective region.

15.2 PlotMap

Goal:

The goal is to generate a global map which visualizes the amplitude values of the forward modelled equivalent water height values with the focus on the unit Alton of the Mississippi Basin. These forward modelled equivalent water height values express the gravity field and function as removal correction.

Parameters:

outputfile: data/Maps/{listName}/{listName}_Unit2Alton_FM_Amplitude.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_Unit2Alton_FM_Amplitude
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: griddedData → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. inputfileGriddedData: data/PotentialCoefficients/TimeSplines/FM/{listName}_TimeSpline_6_GriddedDataCalculate_Amplitude.txt → inputfileGriddedData defines the path and the filename of the forward modelled amplitude gridded gravity field input file. value: data0 → value defines that data0, which contains the gridded amplitude values of the forward modelled equivalent water height values, should be displayed. increment: 0.5 → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid. illuminate: no → illuminate defines that the grid should not be brightened. resample: <none> → resample defines that the grid input values should not be resampled. gridlineRegistered: no → gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid.

width: 1

→ width defines that the width of the coastlines should be 1 point.

color: black

→ color defines that the colour of the coastlines should be black.

landColor: <none>

→ landColor defines that there is no specific colour with which the land area should be filled.

oceanColor: <none>

→ oceanColor defines that there is no specific colour with which the ocean area should be filled.

minArea: 10000

→ minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

layer
layer: polygon
→ layer defines the content of the map. Hence, a polygon around the Mississippi Basin should be drawn.
inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit2_Alton.txt
→ inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Alton of the Mississippi Basin.
line: solid
→ line defines that the line style of the polygon should be solid.
width: 1.5
→ width defines that the width of the coastlines should be 1.5 points.
color: red
→ color defines that the colour of the polygon should be red.
fillColor: <none>
→ fillColor defines that there is no specified colour with which the box of the legend should be filled.
value: ---
→ value defines that the fillColor should not have a specified value. This can be traced back to the fact that no fillColor is used anyway.

drawLineAsGreatCircle: yes
→ drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 155: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$ Equation 156: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $\mathrm{f} = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$ $\mathrm{f} = 0.003352810681$ and thus, the inverseFlattening is $\bar{\mathrm{f}} = \frac{1}{0.003352810681}$ $\bar{\mathrm{f}} = 298.2572221.$

minLambda: - 100
→ minLambda defines that the minimum degree of longitude should be - 100 °.

maxLambda: - 70
→ maxLambda defines that the maximum degree of longitude should be - 70 °.

minPhi: 37.5
→ minPhi defines that the minimum degree of latitude should be 37.5 °.

maxPhi: 50
→ maxPhi defines that the maximum degree of latitude should be 50 °.

majorTickSpacing: 10
→ majorTickSpacing defines that the boundary annotation should be set every 10 °.

minorTickSpacing: 10
→ minorTickSpacing defines that the frame tick spacing should be set every 10 °.

gridLineSpacing: 10
→ gridLineSpacing defines that the spacing of the grid lines should be set every 10 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: 0 → min defines that the minimum value of the colour bar should not be further specified. max: 0.10 [= 0.1] → max defines that the maximum value of the colour bar should be set to 0.10. annotation: 0.02 → annotation defines that a boundary annotation should be drawn every 0.02 °. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [m]

→ label defines that the axis description and hence the description of the colour bar should be set to “EWH [m]”. <u>logarithmic: no</u> → logarithmic defines that no logarithmic scale should be used. <u>triangleLeft: yes</u> → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. <u>triangleRight: yes</u> → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. <u>illuminate: no</u> → illuminate defines that the grid should not be brightened. <u>vertical: no</u> → vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. <u>length: 100</u> → length defines that the length of the colour bar should be 100 %. <u>margin: 0.4</u> → margin defines that the space between the colour bar and the figure should be 0.4 cm. <u>colorTable: /data1/colors/custom_palettes/temperature_cont.cpt</u> → colorTable defines that the colour bar with the name “temperature_cont.cpt” should be used. This colour bar ranges from dark blue to dark red. <u>reverse: no</u> → reverse defines that the colour bar should not be reversed. <u>showColorbar: yes</u> → showColorbar defines that the colour bar should be plotted.

projection
<u>projection: robinson</u> → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other

meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions.
centralMeridian: - 85
→ centralMeridian defines that the central meridian should be set at - 85 °. Hence, the central Meridian lies in the center of the unit Alton and a straight map can be plotted.

options
width: ---   → width defines that the width of the plot given in centimetre should not be further specified.   height: ---   → height defines that the height of the plot given in centimetre should not be further specified.   titleFontSize: 12   → titleFontSize defines that the fontsize of the title should be 12 points.   marginTitle: 0.4   → marginTitle defines that the space between the figure title should be 0.4 cm.   drawGridOnTop: no   → drawGridOnTop defines that no grid lines should be drawn above all other lines and points.   options: FONT_ANNOT_PRIMARY=10p   → options defines that the font which is used for primary annotations should be 10 pixels.   options: MAP_ANNOT_OFFSET_PRIMARY=0.1c   → options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.   options: FONT_LABEL=10p   → options defines that the font, which is used to plot the labels below the annotation, should be 10 points.   options: MAP_LABEL_OFFSET=0.1c   → options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.   options: FONT_ANNOT_SECONDARY=10p   → options defines that the font for a secondary time axis should be 10 points.   transparent: yes

→ transparent defines that the background of the plot should be transparent. dpi = 300 → dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch. removeFiles: yes → removeFiles defines that the .gmt and script files should be removed after the computation. viewPlot: yes → viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one map which represents the amplitude values of the forward modelled equivalent water height values with the focus on the unit Alton of the Mississippi Basin. These forward modelled equivalent water height values express the gravity field and function as removal correction. They are given in the unit of metre. Hence, the map visualizes the amplitude of the size of the forward modelled equivalent water height values that has to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact that the Mississippi Basin has on the processed equivalent water height values, which were derived from GRACE observations, can be removed. Hence, the GRACE signal can be corrected. Consequently, the map functions as an indicator which shows how strong the influence of the unit Alton of the Mississippi Basin on the mass change observed by GRACE, fluctuates. This information is extremely helpful to make the estimates of GRACE more consistent with the output from hydrological models for this respective region.

15.3 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean forward modelled equivalent water height values which express the time variable gravity field over the unit Alton of the Mississippi Basin.

Parameters:

outputfileTimeSeries: data/TimeSeries/FM_Unit2Alton.txt
→ outputfileTimeSeries defines the path and the filename of the forward modelled mean equivalent water height value time series output file for the unit Alton of the Mississippi Basin.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. deltaPhi: {gridSizeCoarse} [= 0.5] → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. height: 0.0 [= 0] → height defines that the distance of the points above the ellipsoid should be 0 m. R: 6378137.0 [= 6378137] → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. inverseFlattening: 298.2572221010 [= 298.2572221] → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 157: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by $\bar{f} = \frac{1}{f}.$ Equation 158: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$ $f = 0.003352810681$

and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$ <u>border: polygon</u> → border defines that a subset of points should be extracted from the global grid. <u>inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit2_Alton.txt</u> → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Alton of the Mississippi Basin. <u>buffer: 0</u> → buffer defines that a barrier of 0 metre should be established around the polygon. <u>exclude: no</u> → exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel
<u>kernel: Θ kernel [= waterHeight]</u> → kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 159: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc] → inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the unit Alton of the Mississippi Basin. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the gravity field is expressed in terms of an averaged and forward modelled equivalent water height value. The unit of the averaged equivalent water height value is metre.

15.4 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean equivalent water height values which express the time variable gravity field and which were derived from GRACE observations over the unit Alton of the Mississippi Basin.

Parameters:

outputfileTimeSeries: data/TimeSeries/GRACE_Unit2Alton.txt
→ outputfileTimeSeries defines the path and the filename of the processed mean equivalent water height value time series output file for the unit Alton of the Mississippi Basin.

grid
<u>grid: geograph</u> → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. <u>deltaLambda: {gridSizeCoarse} [= 0.5]</u>

→ deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °.

deltaPhi: {gridSizeCoarse} [= 0.5]

→ deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °.

height: 0.0 [= 0]

→ height defines that the distance of the points above the ellipsoid should be 0 m.

R: 6378137.0 [= 6378137]

→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 160: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 161: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137 \text{ m} - 6356752.3141 \text{ m})}{6378137 \text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: polygon

→ border defines that a subset of points should be extracted from the global grid.

inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit2_

Alton.txt → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Alton of the Mississippi Basin. buffer: 0 → buffer defines that a barrier of 0 metre should be established around the polygon. exclude: no → exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel
kernel: Θ kernel [= waterHeight] → kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 162: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2018200204201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2018/timeSplines/old_

monthly/timeSpline_ITSG-Grace2018_monthly_n96_deg1_c20_replaced_noGIA_noMean _2002-04_2017-06_interp_ddk3.dat] → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the unit Alton of the Mississippi Basin. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the gravity field is expressed in terms of the equivalent water height value. The unit of this equivalent water height value is metre. In this case, the processed equivalent water height values are not forward modelled, but directly derived from the GRACE observations. These observations are already pre-processed. Hence, the data is already interpolated and the effect of the glacial isostatic adjustment is also removed.

15.5 Gravityfield2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of mean equivalent water height values which express the corrected time variable gravity field over the unit Alton of the Mississippi Basin.

Parameters:

outputfileTimeSeries: data/TimeSeries/GRACE-FM_Unit2Alton.txt
→ outputfileTimeSeries defines the path and the filename of the corrected mean equivalent water height value time series output file for the unit Alton of the Mississippi Basin.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. deltaPhi: {gridSizeCoarse} [= 0.5] → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. height: 0.0 [= 0] → height defines that the distance of the points above the ellipsoid should be 0 m.

R: 6378137.0 [= 6378137]

→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 163: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 164: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: polygon

→ border defines that a subset of points should be extracted from the global grid.

inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin_unit2_Alton.txt

→ inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the unit Alton of the Mississippi Basin.

buffer: 0

→ buffer defines that a barrier of 0 metre should be established around the polygon.

exclude: no

→ exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

kernel
kernel: Θ kernel [= waterHeight] → kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 165: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2018200204201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2018/timeSplines/old_monthly/timeSpline_ITSG-Grace2018_monthly_n96_deg1_c20_replaced_noGIA_noMean_2002-04_2017-06_interp_ddk3.dat] → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {minDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time.
factor: 1.0 [= 1]
→ factor defines that the result should be multiplied by 1. This factor is defined by default.

gravityfield
gravityfield: timeSplines
→ gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain.
inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc]
→ inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled input time spline.
inputfileTimeSplinesCovariance: ---
→ inputfileTimeSplinesCovariance defines that no covariance time spline should be used.
minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.
maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time.
factor: - 1
→ factor defines that the forward modelled equivalent water height values, which represent the gravity field, should be subtracted from the processed equivalent water height values which were derived from GRACE observations.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: yes
→ removeMean defines that the temporal mean of the time series should be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

computeSigma: no
→ computeSigma defines that no additional error bars should be computed at each time step.

Result:

The function Gravityfield2AreaMeanTimeSeries generates one .txt file for the unit Alton of the Mississippi Basin. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the corrected time variable gravity field is expressed in terms of an averaged equivalent water height value. The unit of the averaged equivalent water height value is metre. Hence, the corrected equivalent water height values refer to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations.

15.6 FunctionsCalculate

Goal:

The goal is to manipulate the data columns of the forward modelled signal matrix in a way, that the annual signal and the semi-annual signal as well as the trend are removed. The focus should be set on the unit Alton of the Mississippi Basin.

Parameters:

outputfile: data/TimeSeries/FM_Unit2Alton_TrendSemiAnnualRemoved.txt
→ outputfile defines the path and the filename of the forward modelled matrix output file for the unit Alton of the Mississippi Basin. This matrix should contain one column in which the annual signal and the semi-annual signal are simultaneously removed from the forward modelled signal.

inputfile: data/TimeSeries/FM_Unit2Alton.txt
→ inputfile defines the path and the filename of the mean forward modelled equivalent water height value time series input file for the unit Alton of the Mississippi Basin.

constant: annual=2*pi/365.25
→ constant defines that the annual signal should have an angular frequency of 2*pi/365.25. By introducing the .25, leap years, which occur on average every four years, can be balanced.

constant: t0=54750
→ constant defines that the start point in time should be 11/10/2008.

parameter: a
→ parameter defines that the parameter a should be estimated in a least squares adjustment.

parameter: b
→ parameter defines that the parameter b should be estimated in a least squares adjustment.

parameter: c
→ parameter defines that the parameter c should be estimated in a least squares adjustment.

parameter: d
→ parameter defines that the parameter d should be estimated in a least squares adjustment.

parameter: e
→ parameter defines that the parameter e should be estimated in a least squares adjustment.

parameter: f
→ parameter defines that the parameter f should be estimated in a least squares adjustment.

leastSquares: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)*annual *2)+f*cos((data0-t0)*annual*2)-data1
→ leastSquares defines that the parameters should be adjusted by applying this expression. Hence, the Equation does not only include a description of the trend, but also of the annual signal and the semi-annual signal as well the forward modelled equivalent water level value itself.

outcolumn: data0
→ outcolumn defines that the points in time, which are expressed as modified julian date, should be stored in the data0 column of the matrix.

outcolumn: data1
→ outcolumn defines that the forward modelled equivalent water height values should be stored in the data1 column of the matrix.

outcolumn: a+b*(data0-t0)
→ outcolumn defines that the trend should be stored in the data2 column of the matrix.

outcolumn: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)
→ outcolumn defines that the trend and the annual signal should be stored in the data3 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual))
→ outcolumn defines that the forward modelled equivalent water height values, which are reduced by the trend and the annual signal, should be stored in the data4 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e* sin((data0-t0)*annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the forward modelled equivalent water height values, which are reduced by the trend and the semi-annual signal, should be stored in the data5 column of the matrix.

outcolumn: data1-(c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)* annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the forward modelled equivalent water height values, which are reduced by the annual and the semi-annual, should be stored in the data6 column of the matrix.

Statistics: <none>
→ statistics defines that no statistic columns should be computed.

Result:

The function FunctionsCalculate generates one .txt file for the Alton unit of the Mississippi Basin. This .txt file contains a matrix with the dimensions of 168 x 7. Each row represents one point in time. Thus, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. The second column indicates the trend value. The third column contains the trend values and the annual signal values. Meanwhile, the fourth column contains forward modelled equivalent water height values which were already reduced by the annual signal values and the trend values. The fifth column indicates the forward modelled equivalent water height values which were already reduced by the semi-annual signal values and the trend values. The last column contains the forward modelled equivalent water height values from which the annual signal and the semi-annual signal, were simultaneously removed. The unit of the forward modelled equivalent water height values is metre. Since the time series values were computed by using the forward modelled time spline, the equivalent water height values are also forward modelled.

15.7 FunctionsCalculate

Goal:

The goal is to manipulate the data columns of the GRACE signal matrix in a way, that the annual signal and the semi-annual signal as well as the trend are removed. The focus should be set on the unit Alton of the Mississippi Basin.

Parameters:

outputfile: data/TimeSeries/GRACE_Unit2Alton_TrendSemiAnnualRemoved.txt
→ outputfile defines the path and the filename of the matrix output file for the unit Alton of the Mississippi Basin. This matrix should contain one column in which the annual signal and the semi-annual signal are simultaneously removed from the GRACE signal.

inputfile: data/TimeSeries/GRACE_Unit2Alton.txt
→ inputfile defines the path and the filename of the mean equivalent water height value time series input file for the unit Alton of the Mississippi Basin.

constant: annual=2*pi/365.25
→ constant defines that the annual signal should have an angular frequency of 2*pi/365.25. By introducing the .25, leap years, which occur on average every four years, can be balanced.

constant: t0=54750
→ constant defines that the start point in time should be 11/10/2008.

parameter: a
→ parameter defines that the parameter a should be estimated in a least squares adjustment.

parameter: b
→ parameter defines that the parameter b should be estimated in a least squares adjustment.

parameter: c
→ parameter defines that the parameter c should be estimated in a least squares adjustment.

parameter: d
→ parameter defines that the parameter d should be estimated in a least squares adjustment.

parameter: e
→ parameter defines that the parameter e should be estimated in a least squares adjustment.

parameter: f
→ parameter defines that the parameter f should be estimated in a least squares adjustment.

leastSquares: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)*annual *2)+f*cos((data0-t0)*annual*2)-data1
→ leastSquares defines that the parameters should be adjusted by applying this expression. Hence, the Equation does not only include a description of the trend, but also of the annual signal and the semi-annual signal as well the processed equivalent water height values which were derived from GRACE observations.

outcolumn: data0
→ outcolumn defines that the points in time, which are expressed as modified julian date, should be stored in the data0 column of the matrix.

outcolumn: data1
→ outcolumn defines that the processed equivalent water height values, which were derived from GRACE observations, should be stored in the data1 column of the matrix.

outcolumn: a+b*(data0-t0)
→ outcolumn defines that the trend should be stored in the data2 column of the matrix.

outcolumn: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)
→ outcolumn defines that the trend and the annual signal should be stored in the data3 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual))
→ outcolumn defines that the processed equivalent water height values derived from GRACE observations, which are reduced by the trend and the annual signal, should be stored in the data4 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)*annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that processed equivalent water height values derived from GRACE observations, which are reduced by the trend and the semi-annual signal, should be stored in the data5 column of the matrix.

outcolumn: data1-(c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)*annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the processed equivalent water height values derived from GRACE observations, which are reduced by the annual and the semi-annual, should be stored in the data6 column of the matrix.

Statistics: <none>
→ statistics defines that no statistic columns should be computed.

Result:

The function FunctionsCalculate generates one .txt file for the unit Alton of the Mississippi Basin. This .txt file contains a matrix with the dimensions of 168 x 7. Each row represents one point in time. The first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. The second column indicates the trend value. The third column contains the trend values and the annual signal values. Meanwhile, the fourth column contains equivalent water height values which were already reduced by the annual signal values and the trend values. The fifth column indicates the processed equivalent water height values which were derived from GRACE observations and which were already reduced by the semi-annual signal values and the trend values. The last column contains the GRACE signal in terms of equivalent water height values from which the annual signal and the semi-annual signal, were simultaneously removed. The unit of the processed equivalent water height values is metre. In this case, the processed equivalent water height values were directly derived from the GRACE observations. These observations are already pre-processed. Hence, the data is already interpolated and the effect of the glacial isostatic adjustment is also removed.

15.8 FunctionsCalculate

Goal:

The goal is to manipulate the data columns of the corrected GRACE signal matrix in a way, that the annual signal and the semi-annual signal as well as the trend are removed. The focus should be set on the unit Alton of the Mississippi Basin.

Parameters:

outputfile: data/TimeSeries/GRACE-FM_Unit2Alton_TrendSemiAnnualRemoved.txt
→ outputfile defines the path and the filename of the corrected matrix output file for the unit Alton of the Mississippi Basin. This matrix should contain one column in which the annual signal and the semi-annual signal are simultaneously removed from the corrected GRACE signal.

inputfile: data/TimeSeries/GRACE-FM_Unit2Alton.txt
→ inputfile defines the path and the filename of the corrected mean equivalent water height value time series output file for the unit Alton of the Mississippi Basin.

constant: annual=2*pi/365.25
→ constant defines that the annual signal should have an angular frequency of 2*pi/365.25. By introducing the .25, leap years, which occur on average every four years, can be balanced.

constant: t0=54750
→ constant defines that the start point in time should be 11/10/2008.

parameter: a
→ parameter defines that the parameter a should be estimated in a least squares adjustment.

arameter: b
→ parameter defines that the parameter b should be estimated in a least squares adjustment.

parameter: c
→ parameter defines that the parameter c should be estimated in a least squares adjustment.

parameter: d
→ parameter defines that the parameter d should be estimated in a least squares adjustment.

parameter: e
→ parameter defines that the parameter e should be estimated in a least squares adjustment.

parameter: f
→ parameter defines that the parameter f should be estimated in a least squares adjustment.

leastSquares: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)*annual *2)+f*cos((data0-t0)*annual*2)-data1
→ leastSquares defines that the parameters should be adjusted by applying this expression. Hence, the Equation does not only include a description of the trend, but also of the annual signal and the semi-annual signal as well the corrected equivalent water level value itself.

outcolumn: data0
→ outcolumn defines that the points in time, which are expressed as modified julian date, should be stored in the data0 column of the matrix.

outcolumn: data1
→ outcolumn defines that the corrected equivalent water height values should be stored in the data1 column of the matrix.

outcolumn: a+b*(data0-t0)
→ outcolumn defines that the trend should be stored in the data2 column of the matrix.

outcolumn: a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)
→ outcolumn defines that the trend and the annual signal should be stored in the data3 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual))
→ outcolumn defines that the corrected equivalent water height values, which are further reduced by the trend and the annual signal, should be stored in the data4 column of the matrix.

outcolumn: data1-(a+b*(data0-t0)+c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e* sin((data0-t0)*annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the corrected equivalent water height values, which are further reduced by the trend and the semi-annual signal, should be stored in the data5 column of the matrix.

outcolumn: data1-(c*sin((data0-t0)*annual)+d*cos((data0-t0)*annual)+e*sin((data0-t0)* annual*2)+f*cos((data0-t0)*annual*2))
→ outcolumn defines that the corrected equivalent water height values, which are further reduced by the annual and the semi-annual, should be stored in the data6 column of the matrix.

Statistics: <none>
→ statistics defines that no statistic columns should be computed.

Result:

The function FunctionsCalculate generates one .txt file for the unit Alton of the Mississippi Basin. This .txt file contains a matrix with the dimensions of 168 x 7. Each row represents one point in time. The first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. The second column indicates the corrected equivalent water height values. The third column contains the trend value. The fourth column contains the trend values and the annual signal values. Meanwhile, the fifth column contains the corrected equivalent water height values which are already reduced by the annual signal values and the trend values. The sixth column indicates the corrected equivalent water height values which are already reduced by the semi-annual signal values and the trend values. The seventh and last column contains the corrected equivalent water height values from which the annual signal values and the semi-annual signal values, are removed. The unit of the corrected equivalent water height values is metre. In this case the corrected equivalent water height values refer to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations.

15.9 PlotGraph

Goal:

The goal is to generate a two-dimensional plot which visualizes the temporal variation of the total water height values over the unit Alton of the Mississippi Basin for every month from 01/2003 to 12/2016. Hence, the graph should not only illustrate the forward modelled equivalent water height values from which the annual signal and the semi-annual signal were simultaneously removed, but also the processed equivalent water height values which were derived from GRACE observations and which were also simultaneously reduced by the annual signal and the semi-annual signal. Finally, the graph should also visualize the corrected GRACE signal. Hence, the corrected GRACE signal refers to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations

Parameters:

outputfile: data/Graphs/{listName}/Unit2Alton.png
→ outputfile defines the path and the filename of the generated graph.

title: EWH Delta over Alton subbasin (annual / semiannual signal removed)
→ title defines the title of the graph which should be displayed on the graph.

layer
layer: linesAndPoints → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. inputfileMatrix: data/TimeSeries/FM_Unit2Alton_TrendSemiAnnualRemoved.txt → inputfileMatrix defines the path and the filename of the forward modelled matrix input file for the unit Alton of the Mississippi Basin. This matrix contains one column in which the annual signal and the semi-annual signal were simultaneously removed from the forward modelled signal. valueX: data0 → valueX defines that the x-values should be the monthly modified julian date. valueY: data6 → valueY defines that the y-values should be the forward modelled equivalent water height values from which the annual signal and the semi-annual signal were simultaneously removed. The unit of the equivalent water height value is metre. valueZ: --- → valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar. valueErrorBar: --- → valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar. description: FM signal → description defines that the text of the legend should be "FM signal". line: solid → line defines that the line style of the forward modelled equivalent water height values should be solid. width: 1.5 → width defines that the width of the equivalent water height value line should be 1.5 points. color: red → color defines that the colour of the equivalent water height value line should be red. symbol: <none> → symbol defines that each data point should not be visualized by a symbol such as a circle or a star. plotOnSecondAxis: no

→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

layer
layer: linesAndPoints → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. inputfileMatrix: data/TimeSeries/GRACE_Unit2Alton_TrendSemiAnnualRemoved.txt → inputfileMatrix defines the path and the filename of the matrix input file for the unit Alton of the Mississippi Basin. This matrix contains one column in which the annual signal and the semi-annual signal were simultaneously removed from the GRACE signal. valueX: data0 → valueX defines that the x-values should be the monthly modified julian date. valueY: data6 → valueY defines that the y-values should indicate the processed equivalent water height values which were derived from GRACE observations and from which the semi-annual and the annual signal were simultaneously removed. The unit of the equivalent water height value is metre. valueZ: --- → valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar. valueErrorBar: --- → valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar. description: GRACE signal → description defines that the text of the legend should be “GRACE signal”. line: solid → line defines that the line style of the processed equivalent water height values, which were derived from GRACE observations, should be solid. width: 1.5 → width defines that the width of the equivalent water height value line should be 1.5 points. color: blue → color defines that the colour of the equivalent water height value line should be blue. symbol: <none>

→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.

plotOnSecondAxis: no

→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

layer
layer: linesAndPoints → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. inputfileMatrix: data/TimeSeries/GRACE-FM_Unit2Alton_TrendSemiAnnualRemoved.txt → inputfileMatrix defines the path and the filename of the corrected matrix input file for the unit Alton of the Mississippi Basin. This matrix contains one column in which the annual signal and the semi-annual signal were simultaneously removed from the corrected GRACE signal. valueX: data0 → valueX defines that the x-values should be the monthly modified julian date. valueY: data6 → valueY defines that the y-values should be the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations and which were then further reduced by the annual signal and the semi-annual signal. The unit of this difference is metre. valueZ: --- → valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar. valueErrorBar: --- → valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar. description: Grace minus FM → description defines that the text of the legend should be “Grace minus FM”. line: solid → line defines that the line style of the corrected equivalent water height values should be solid. width: 1.5

→ width defines that the width of the equivalent water height value line should be 1.5 points.

color: green

→ color defines that the colour of the equivalent water height value line should be green.

symbol: <none>

→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.

plotOnSecondAxis: no

→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

axisX
axisX: time → axisX defines the style of the x-axis of the graph. In this case, the input data are interpreted as modified julian date. min: --- → min defines that there is no specified minimum value of the x-axis. Hence, the minimum scale value is set automatically. max: --- → max defines that there is no specified maximum value of the x-axis. Hence, the maximum scale value is set automatically. majorTickSpacing: 2Y → majorTickSpacing defines that the boundary annotation of the x-axis should be set every second year. minorTickSpacing: 2Y → minorTickSpacing defines that the spacing of the frame tick intervals on the x-axis should be set every second year. gridLineSpacing: 1Y → gridLineSpacing defines that that the spacing of the grid lines on the x-axis should be set every year. secondary: <none> → secondary defines that no additional time axis should be established. color: black → color defines that the colour of the x-axis should be black. gridline: solid

→ gridline defines that the style of the grid lines should be solid. width: 0.25 → width defines that the width of the grid lines should be 0.25 points. color: gray → color defines that the colour of the grid lines should be gray. changeDirection: no → changeDirection defines that the direction of the x-axis should not be changed from right / up to left / down. options: FORMAT_DATE_MAP=yyyy-mm-dd → options defines that the output data string should be given in the format year-month-day. options: FORMAT_CLOCK_MAP=hh:mm → options defines that the output clock string should be given in the format hour-minute. options: TIME_EPOCH=1858-11-17T00:00:00 → options defines the value of the calendar and the clock at the origin (0 point) of relative time units. options: TIME_UNIT=d → options defines that the units of the relative time data since the TIME_EPOCH should be daily.

axisY
axisY: standard → axisY defines the style of the y-axis of the graph. In this case, the input data should be interpreted as arbitrary input data. min: --- → min defines that the minimum value of the y-axis should not be further specified. max: --- → max defines that the maximum value of the y-axis should not be further specified. majorTickSpacing: 0.02 → majorTickSpacing defines that the boundary annotation of the y-axis should be set every 0.02. Hence, it is set for every 0.02 m of equivalent water height. minorTickSpacing: 0.002 → minorTickSpacing defines that the spacing of the frame tick intervals on the y-axis should be set every 0.002. Hence, it is set for every 0.002 m of equivalent water height.

gridLineSpacing: ---
→ gridLineSpacing defines that the spacing of the grid lines on the y-axis should not be further specified.
gridline: solid
→ gridline defines that the style of the grid lines should be solid.
width: 0.25
→ width defines that the width of the grid lines should be 0.25 points.
color: gray
→ color defines that the colour of the grid lines should be gray.
unit: ---
→ unit defines that the no unit name should be appended to the y-axis values.
Label: EWH [m]
→ label defines that the description of the y-axis should be "EWH [m]".
logarithmic: no
→ logarithmic defines that no logarithmic scale should be used.
color: black
→ color defines that the colour of the bars and labels of the y-axis should be black.
changeDirection: no
→ changeDirection defines that the direction of the x-axis should not be changed from right / up to left / down.

axisY2: <none>
→ axisY2 defines that no second Y-axis should be plotted.

colorbar: <none>
→ colorbar defines that no colour bar should be plotted.

legend
legend: <enabled>
→ legend defines that a legend with descriptions should be plotted.
width: 10

→ width defines that length of the legend should be 10 cm.

height: ---

→ height defines that the height of the plot given in centimetre should not be further specified.

positionX: 1.05

→ positionX defines that the x-position of the legend should be 1.05.

positionY: 1.0 [= 1]

→ positionY defines that the y-position of the legend should be 1.0.

anchorPoint: TL

→ anchorPoint defines that the anchor point should be located at the top left. Hence, the anchor point is the point where the related edges link to.

columns: 1

→ columns defines that the legend should consist of one column.

textColor: <none>

→ textColor defines that there is no specified colour of the text of the legend.

fillColor: <none>

→ fillColor defines that there is no specified colour with which the box of the legend should be filled.

edgeLine: <none>

→ edgeLine defines that there is no specified style of the edge of the box of the legend.

options
width: 12 → width defines that the width of the plot should be 12 cm. height: 7 → height defines that height of the plot should be 7 cm. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no

→ drawGridOnTop defines that no grid lines should be drawn above all other lines and points.

options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels.

options: MAP_ANNOT_OFFSET_PRIMARY=0.1c

→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.

options: FONT_LABEL=10p

→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.

options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

options: TIME_SYSTEM=MJD

→ options defines that the relative time should refer to the modified julian date.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotGraph generates one graph which illustrates the temporal variation of the equivalent water height values over the unit Alton of the Mississippi Basin. The x-axis indicates the year and reaches from 01/2003 to 12/2016. Meanwhile, the y-axis indicates the equivalent water height values in the unit metre. In total, there are three curves. The first curve represents the forward modelled equivalent water height values from which the annual signal and the semi-annual signal were simultaneously removed. The second curve illustrates the processed equivalent water height values which were derived from GRACE observations and from which the annual signal and the semi-annual signal were also simultaneously removed. The third curve visualizes the corrected GRACE signal. The corrected GRACE signal refers to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations. The forward modelled equivalent water height values express the gravity field and function as removal correction. Hence, the forward modelled signal visualizes the size of the forward modelled equivalent water height values that has to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact, that the prevailing water body has on the processed equivalent water height values, which were derived from GRACE observations, can be removed. By subtracting the removal correction of for instance the Mississippi Basin from the GRACE signal, the influence, that the Mississippi Basin has on the GRACE signal, can be removed. Hence, the GRACE signal can be corrected. This procedure is also denoted as removal approach.

catchErrors: <none>
→ catchErrors defines that no program will be executed when an error occurs.

16 GroupPrograms

Goal:

The goal is to run the individually defined programs in a group.

Parameters:

outputfileLog: ---
→ outpufileLog defines that no additional log file should be created.

silently: no
→ silently defines that the output should be shown.

16.1 Gravityfield2GriddedTimeVariabilityAnalysis

Goal:

The goal is to compute a time series which contains the error root mean square values of the forward modelled equivalent water height values. Since the forward modelled equivalent water height values express the gravity field, the error root mean square values have to be computed with respect to a reference field.

Parameters:

outputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_FM_time-VariabilityRMS.txt
→ outputfileGriddedData defines the path and the filename of the gravity field grid output file. This gravity field grid output file should contain one column in which the error root mean square values of the forward modelled equivalent water height values are stored.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5]

→ deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °.

deltaPhi: {gridSizeCoarse} [= 0.5]

→ deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °.

height: 0.0 [= 0]

→ height defines that the distance of the points above the ellipsoid should be 0 m.

R: 6378137.0 [= 6378137]

→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 166: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 167: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: ---

→ border defines that no regional subset of points should be extracted from the global grid.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 168: Coefficients of the Kernel   Source: Mayer-Gürr et al., n.d.   includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: timeSplines   → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain.   inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2018200204201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2018/timeSplines/old_monthly/timeSpline_ITSG-Grace2018_monthly_n96_deg1_c20_replaced_noGIA_noMean_2002-04_2017-06_interp_ddk3.dat]   → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file.   inputfileTimeSplinesCovariance: ---   → inputfileTimeSplinesCovariance defines that no covariance time spline should be used.   minDegree: {minDegree} [= 0]   → minDegree defines that the minimum degree of the expansion should be 0 °.   maxDegree: {maxDegree} [= 96]   → maxDegree defines that the maximum degree of the expansion should be 96 °.   factor: 1.0 [= 1]   → factor defines that the result should be multiplied by 1. This factor is defined by default.

referencefield
<u>referencefield: timeSplines</u> → referencefield defines that a gravity field should be used for comparison. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. <u>inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2018200204201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2018/timeSplines/old_monthly/timeSpline_ITSG-Grace2018_monthly_n96_deg1_c20_replaced_noGIA_noMean_2002-04_2017-06_interp_ddk3.dat]</u> → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. <u>inputfileTimeSplinesCovariance: ---</u> → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. <u>minDegree: {minDegree} [= 0]</u> → minDegree defines that the minimum degree of the expansion should be 0 °. <u>maxDegree: {maxDegree} [= 96]</u> → maxDegree defines that the maximum degree of the expansion should be 96 °. <u>factor: 0</u> → factor defines that the result should be multiplied by 0.

functional: errorRMS
→ functional defines that each grid point, the error root mean square from the time series with respect to the reference field should be computed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the time series should be computed for every month.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 169: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$ Equation 170: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $\mathrm{f} = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$ $\mathrm{f} = 0.003352810681$ and thus, the inverseFlattening is $\bar{\mathrm{f}} = \frac{1}{0.003352810681}$ $\bar{\mathrm{f}} = 298.2572221.$

Result:

The function Gravityfield2GriddedTimeVariabilityAnalysis generates one .txt file with monthly forward modelled gridded data. This .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded error root mean square values of the forward modelled equivalent water height values. The error root mean square values are given in the unit of metres. Hence, the function Gravityfield2GriddedTimeVariabilityAnalysis performs two steps. In a first step, the deviation between the monthly forward modelled equivalent water height values and the monthly provided equivalent water height values of the reference field in the time frame from 01/2003 to 12/2016, is computed. In order to do so, a reference field which covers the time frame from 04/2002 to 06/2017 and which was computed from GRACE observations, was used. The advantage of this reference field is, that it covers the entire time frame between 01/2003 to 12/2016 for which the forward modelled equivalent water height values were computed. As a result, a time series of monthly difference values is assigned to every grid cell. In a second step, each time series is used to compute an error root mean square value. Hence, the error root mean square values indicate how well the monthly forward modelled equivalent water height values match with the monthly equivalent water height values derived from GRACE observations. Thus, the error root mean square values indicate to which extend the forward modelled gravity field and the gravity field computed from GRACE observations, match. Finally, the error root mean square values are assigned to their respective grid cell and denoted in the column data0.

16.2 Gravityfield2GriddedTimeVariabilityAnalysis

Goal:

The goal is to compute a time series which contains the error root mean square values of the processed equivalent water height values which were derived from GRACE observations. Since the processed equivalent water height values express the gravity field, the error root mean square values have to be computed with respect to a reference field.

Parameters:

outputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_GRACE_ timeVariabilityRMS.txt
→ outputfileGriddedData defines the path and the filename of the gravity field grid output file. This gravity field grid output file should contain one column in which the error root mean square values of the processed equivalent water height values, which were derived from GRACE observations, are stored.

grid
<u>grid: geograph</u> → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude.

deltaLambda: {gridSizeCoarse} [= 0.5]

→ deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °.

deltaPhi: {gridSizeCoarse} [= 0.5]

→ deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °.

height: 0.0 [= 0]

→ height defines that the distance of the points above the ellipsoid should be 0 m.

R: 6378137.0 [= 6378137]

→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 171: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 172: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: ---

→ border defines that no regional subset of points should be extracted from the global grid.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 173: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2018200204201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2018/timeSplines/old_monthly/timeSpline_ITSG-Grace2018_monthly_n96_deg1_c20_replaced_noGIA_noMean_2002-04_2017-06_interp_ddk3.dat] → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

referencefield
<u>referencefield: timeSplines</u> → referencefield defines that a gravity field should be used for comparison. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. <u>inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2018200204201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2018/timeSplines/old_monthly/timeSpline_ITSG-Grace2018_monthly_n96_deg1_c20_replaced_noGIA_noMean_2002-04_2017-06_interp_ddk3.dat]</u> → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. <u>inputfileTimeSplinesCovariance: ---</u> → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. <u>minDegree: {minDegree} [= 0]</u> → minDegree defines that the minimum degree of the expansion should be 0 °. <u>maxDegree: {maxDegree} [= 96]</u> → maxDegree defines that the maximum degree of the expansion should be 96 °. <u>factor: 0</u> → factor defines that the result should be multiplied by 0.

functional: errorRMS
→ functional defines that each grid point, the error root mean square from the time series with respect to the reference field should be computed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the time series should be computed for every month.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 174: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by $\bar{f} = \frac{1}{f}.$ Equation 175: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

Result:

The function Gravityfield2GriddedTimeVariabilityAnalysis generates one .txt file with monthly processed gridded data. This .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded error root mean square values of the processed equivalent water height values which were derived from GRACE observations. The error root mean square values are given in the unit of metres. Hence, the function Gravityfield2GriddedTimeVariabilityAnalysis performs two steps. In a first step, the deviation between the monthly processed equivalent water height values which were derived from GRACE observations and the monthly provided equivalent water height values of the reference field in the time frame from 01/2003 to 12/2016, is computed. In order to do so, a reference field which covers the time frame from 04/2002 to 06/2017 and which was computed from other GRACE observations, was used. The advantage of this reference field is, that it covers the entire time frame between 01/2003 to 12/2016 for which the corrected equivalent water height values were computed. As a result, a time series of monthly difference values is assigned to every grid cell. In a second step, each time series is used to compute an error root mean square value. Hence, the error root mean square values indicate how well the monthly processed equivalent water height values, which were derived from GRACE observations, match with the monthly equivalent water height values which were derived from other GRACE observations. Thus, the error root mean square values indicate to which extend the processed gravity field and the gravity field computed from other GRACE observations, match. Finally, the error root mean square values are assigned to their respective grid cell and denoted in the column data0.

16.3 Gravityfield2GriddedTimeVariabilityAnalysis

Goal:

The goal is to compute a time series which contains the error root mean square values of the corrected equivalent water height values. Hence, the corrected equivalent water height values refer to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations. Since the corrected equivalent water height values express the gravity field, the error root mean square values have to be computed with respect to a reference field.

Parameters:

outputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_GRACE-FM_timeVariabilityRMS.txt
→ outputfileGriddedData defines the path and the filename of the gravity field grid output file. This gravity field grid output file should contain one column in which the error root mean square values of the corrected equivalent water height values are stored.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. deltaPhi: {gridSizeCoarse} [= 0.5] → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. height: 0.0 [= 0] → height defines that the distance of the points above the ellipsoid should be 0 m. R: 6378137.0 [= 6378137] → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. inverseFlattening: 298.2572221010 [= 298.2572221] → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$ Equation 176: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by $$\bar{f} = \frac{1}{f}.$$ Equation 177: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$ $$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: ---

→ border defines that no regional subset of points should be extracted from the global grid.

kernel: Θ kernel [= waterHeight]

→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n

$$k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k_n'}{2n + 1}$$

Equation 178: Coefficients of the Kernel

Source: Mayer-Gürr et al., n.d.

includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield

gravityfield: timeSplines

→ gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain.

inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2018200204201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2018/timeSplines/old_monthly/timeSpline_ITSG-Grace2018_monthly_n96_deg1_c20_replaced_noGIA_noMean_2002-04_2017-06_interp_ddk3.dat]

→ inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file.

inputfileTimeSplinesCovariance: ---

→ inputfileTimeSplinesCovariance defines that no covariance time spline should be used.

minDegree: {minDegree} [= 0]

→ minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc] → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. factor: - 1 → factor defines that the forward modelled equivalent water height values, which represent the gravity field, should be subtracted from the processed equivalent water height values which were derived from GRACE observations.

referencefield
referencefield: timeSplines → referencefield defines that a gravity field should be used for comparison. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2018200204201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2018/timeSplines/old_

monthly/timeSpline_ITSG-Grace2018_monthly_n96_deg1_c20_replaced_noGIA_noMean _2002-04_2017-06_interp_ddk3.dat] → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. factor: 0 → factor defines that the result should be multiplied by 0.

referencefield
referencefield: timeSplines → referencefield defines that a gravity field should be used for comparison. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc] → inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. factor: 0 → factor defines that the result should be multiplied by 0.

functional: errorRMS
→ functional defines that each grid point, the error root mean square from the time series with respect to the reference field should be computed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis } - \text{ semiminor axis})}{\text{semimajor axis}}$ Equation 179: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$ Equation 180: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $\mathrm{f} = \frac{(6378137\text{ m } - \text{ } 6356752.3141\text{ m})}{6378137\text{ m}}$ $\mathrm{f} = 0.003352810681$ and thus, the inverseFlattening is $\bar{\mathrm{f}} = \frac{1}{0.003352810681}$

$\bar{f} = 298.2572221.$

Result:

The function Gravityfield2GriddedTimeVariabilityAnalysis generates one .txt file with monthly corrected gridded data. This .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded error root mean square values of the corrected equivalent water height values. The error root mean square values are given in the unit of metres. Hence, the function Gravityfield2GriddedTimeVariabilityAnalysis performs two steps. In a first step, the deviation between the monthly corrected equivalent water height values and the monthly provided equivalent water height values of the reference field in the time frame from 01/2003 to 12/2016, is computed. In order to do so, a reference field which covers the time frame from 04/2002 to 06/2017 and which was computed from other GRACE observations, was used. The advantage of this reference field is, that it covers the entire time frame between 01/2003 to 12/2016 for which the corrected equivalent water height values were computed. As a result, a time series of monthly difference values is assigned to every grid cell. In a second step, each time series is used to compute an error root mean square value. Hence, the error root mean square values indicate how well the monthly corrected equivalent water height values match with the monthly equivalent water height values which were derived from other GRACE observations. Thus, the error root mean square values indicate to which extend the corrected gravity field and the gravity field computed from other GRACE observations, match. Finally, the error root mean square values are assigned to their respective grid cell and denoted in the column data0.

16.4 PlotMap

Goal:

The goal is to generate a global map which visualizes the error root mean square values of the forward modelled equivalent water height values with respect to a reference field. These forward modelled equivalent water height values express the gravity field and function as removal correction.

Parameters:

outputfile: data/Maps/{listName}/{listName}_FM_TimeVariabilityRMS.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_FM_TimeVariabiltyRMS
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: griddedData → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_FM_timeVariabilityRMS.txt → inputfileGriddedData defines the path and the filename of the forward modelled gridded gravity field output file. This gridded gravity field output file contains one column in which the error root mean square values of the forward modelled equivalent water height values are stored. value: data0 → value defines that data0, which contains the error root mean square values of the forward modelled equivalent water height values, should be displayed. increment: 0.5 → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid. illuminate: no → illuminate defines that the grid should not be brightened. resample: <none> → resample defines that the grid input values should not be resampled. gridlineRegistered: no

→ gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
<u>layer: coast</u> → layer defines the content of the map. Hence, coastlines should be plotted. <u>resolution: medium</u> → resolution defines that the resolution of the coastlines should be medium. <u>line: solid</u> → line defines that the line style of the coastlines should be solid. <u>width: 1</u> → width defines that the width of the coastlines should be 1 point. <u>color: black</u> → color defines that the colour of the coastlines should be black. <u>landColor: <none></u> → landColor defines that there is no specific colour with which the land area should be filled. <u>oceanColor: <none></u> → oceanColor defines that there is no specific colour with which the ocean area should be filled. <u>minArea: 10000</u> → minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 181: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 182: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 60
→ majorTickSpacing defines that the boundary annotation should be set every 60 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 30
→ gridLineSpacing defines that the spacing of the grid lines should be set every 30 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: 0 → min defines that the minimum value of the colour bar should be set to 0. max: 0.05 → max defines that the maximum value of the colour bar should be set to 0.05. annotation: 0.005 → annotation defines that a boundary annotation should be drawn every 0.005 °. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [m] → label defines that the axis description and hence the description of the colour bar should be set to "EWH [m]". logarithmic: no → logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. triangleRight: yes → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. illuminate: no → illuminate defines that the grid should not be brightened. vertical: no

→ vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot.

length: 100

→ length defines that the length of the colour bar should be 100 %.

margin: 0.4

→ margin defines that the space between the colour bar and the figure should be 0.4 cm.

colorTable: /data1/colors/custom_palettes/temperature_cont.cpt

→ colorTable defines that the colour bar with the name “temperature_cont.cpt” should be used. This colour bar ranges from dark blue to dark red.

reverse: no

→ reverse defines that the colour bar should not be reversed.

showColorbar: yes

→ showColorbar defines that the colour bar should be plotted.

projection
projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. centralMeridian: 0 → centralMeridian defines that the central meridian should be set at 0 °.

options
width: 16 → width defines that the width of the plot should be 16 cm. height: --- → height defines that the height of the plot given in centimetre should not be further specified. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4

→ marginTitle defines that the space between the figure title should be 0.4 cm.

drawGridOnTop: no

→ drawGridOnTop defines that no grid lines should be drawn above all other lines and points.

options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels.

options: MAP_ANNOT_OFFSET_PRIMARY=0.1c

→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.

options: FONT_LABEL=10p

→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.

options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one global map which represents the error root mean square values of the forward modelled equivalent water height values with respect to a reference field. Since the error root mean square values are computed from monthly forward modelled equivalent water height value time series, the unit is equivalent water heights given in in metre per month.

16.5 PlotMap

Goal:

The goal is to generate a global map which visualizes the error root mean square values of the processed equivalent water height values, which were derived from GRACE observations, with respect to a reference field.

Parameters:

outputfile: data/Maps/{listName}/{listName}_GRACE_TimeVariabilityRMS.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_GRACE_TimeVariabilityRMS
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
<u>layer: griddedData</u> → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. <u>inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_GRACE_timeVariabilityRMS.txt</u> → inputfileGriddedData defines the path and the filename of the gridded gravity field output file. This gridded gravity field output file contains one column in which the error root mean square values of the processed equivalent water height values, which were derived from GRACE observations, are stored. <u>value: data0</u> → value defines that data0, which contains the error root mean square values of the processed equivalent water height values, which were derived from GRACE observations, should be displayed. <u>increment: 0.5</u>

→ increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid.

illuminate: no

→ illuminate defines that the grid should not be brightened.

resample: <none>

→ resample defines that the grid input values should not be resampled.

gridlineRegistered: no

→ gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer

layer: coast

→ layer defines the content of the map. Hence, coastlines should be plotted.

resolution: medium

→ resolution defines that the resolution of the coastlines should be medium.

line: solid

→ line defines that the line style of the coastlines should be solid.

width: 1

→ width defines that the width of the coastlines should be 1 point.

color: black

→ color defines that the colour of the coastlines should be black.

landColor: <none>

→ landColor defines that there is no specific colour with which the land area should be filled.

oceanColor: <none>

→ oceanColor defines that there is no specific colour with which the ocean area should be filled.

minArea: 10000

→ minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 183: Flattening of the rotation ellipsoid   Source: Mayer-Gürr et al., n.d.   the inverseFlattening value $\bar{f}$ can simply be computed by $\bar{f} = \frac{1}{f}.$ Equation 184: Inverse Flattening of the rotation ellipsoid   Source: Mayer-Gürr et al., n.d.   Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 60
→ majorTickSpacing defines that the boundary annotation should be set every 60 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 30
→ gridLineSpacing defines that the spacing of the grid lines should be set every 30 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: 0 → min defines that the minimum value of the colour bar should be set to 0. max: 0.15 → max defines that the maximum value of the colour bar should be set to 0.15. annotation: 0.01 → annotation defines that a boundary annotation should be drawn every 0.01 °. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [m] → label defines that the axis description and hence the description of the colour bar should be set to “EWH [m]”. logarithmic: no → logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values.

triangleRight: yes
→ triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values.
illuminate: no
→ illuminate defines that the grid should not be brightened.
vertical: no
→ vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot.
length: 100
→ length defines that the length of the colour bar should be 100 %.
margin: 0.4
→ margin defines that the space between the colour bar and the figure should be 0.4 cm.
colorTable: /data1/colors/custom_palettes/temperature_cont.cpt
→ colorTable defines that the colour bar with the name "temperature_cont.cpt" should be used. This colour bar ranges from dark blue to dark red.
reverse: no
→ reverse defines that the colour bar should not be reversed.
showColorbar: yes
→ showColorbar defines that the colour bar should be plotted.

projection
projection: robinson
→ projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions.
centralMeridian: 0
→ centralMeridian defines that the central meridian should be set at 0 °.

options
width: 16
→ width defines that the width of the plot should be 16 cm.

height: ---

→ height defines that the height of the plot given in centimetre should not be further specified.

titleFontSize: 12

→ titleFontSize defines that the fontsize of the title should be 12 points.

marginTitle: 0.4

→ marginTitle defines that the space between the figure title should be 0.4 cm.

drawGridOnTop: no

→ drawGridOnTop defines that no grid lines should be drawn above all other lines and points.

options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels.

options: MAP_ANNOT_OFFSET_PRIMARY=0.1c

→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.

options: FONT_LABEL=10p

→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.

options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one global map which represents the error root mean square values of the processed equivalent water height values, which were derived from GRACE observations, with respect to a reference field. Since the error root mean square values are computed from monthly processed equivalent water height value time series, the unit is equivalent water heights given in in metre per month.

16.6 PlotMap

Goal:

The goal is to generate a global map which visualizes the error root mean square values of the corrected equivalent water height values with respect to a reference field. Hence, the corrected equivalent water height values refer to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations.

Parameters:

outputfile: data/Maps/{listName}/{listName}_GRACE-FM_TimeVariabilityRMS.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_GRACE-FM_TimeVariabilityRMS
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: griddedData → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_GRACE-FM_timeVariabilityRMS.txt

→ inputfileGriddedData defines the path and the filename of the gridded gravity field output file. This gridded gravity field output file contains one column in which the error root mean square values of the corrected equivalent water height values are stored.

value: data0

→ value defines that data0, which contains the error root mean square values of the corrected equivalent water height values, should be displayed.

increment: 0.5

→ increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid.

illuminate: no

→ illuminate defines that the grid should not be brightened.

resample: <none>

→ resample defines that the grid input values should not be resampled.

gridlineRegistered: no

→ gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid. width: 1 → width defines that the width of the coastlines should be 1 point. color: black → color defines that the colour of the coastlines should be black. landColor: <none> → landColor defines that there is no specific colour with which the land area should be filled. oceanColor: <none> → oceanColor defines that there is no specific colour with which the ocean area should be filled.

minArea: 10000
→ minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$ Equation 185: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by $$\bar{f} = \frac{1}{f}.$$ Equation 186: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $$f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$$ $$f = 0.003352810681$$ and thus, the inverseFlattening is $$\bar{f} = \frac{1}{0.003352810681}$$ $$\bar{f} = 298.2572221.$$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 60
→ majorTickSpacing defines that the boundary annotation should be set every 60 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 30
→ gridLineSpacing defines that the spacing of the grid lines should be set every 30 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: 0 → min defines that the minimum value of the colour bar should be set to 0. max: --- → max defines that the maximum value of the colour bar should not be further specified. annotation: 0.01 → annotation defines that a boundary annotation should be drawn every 0.01 °. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [m]

→ label defines that the axis description and hence the description of the colour bar should be set to "EWH [m]". <u>logarithmic: no</u> → logarithmic defines that no logarithmic scale should be used. <u>triangleLeft: yes</u> → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. <u>triangleRight: yes</u> → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. <u>illuminate: no</u> → illuminate defines that the grid should not be brightened. <u>vertical: no</u> → vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. <u>length: 100</u> → length defines that the length of the colour bar should be 100 %. <u>margin: 0.4</u> → margin defines that the space between the colour bar and the figure should be 0.4 cm. <u>colorTable: /data1/colors/custom_palettes/temperature_cont.cpt</u> → colorTable defines that the colour bar with the name "temperature_cont.cpt" should be used. This colour bar ranges from dark blue to dark red. <u>reverse: no</u> → reverse defines that the colour bar should not be reversed. <u>showColorbar: yes</u> → showColorbar defines that the colour bar should be plotted.

projection
<u>projection: robinson</u> → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other

meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. centralMeridian: 0 → centralMeridian defines that the central meridian should be set at 0 °.

options
width: 16 → width defines that the width of the plot should be 16 cm. height: --- → height defines that the height of the plot given in centimetre should not be further specified. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. options: FONT_ANNOT_PRIMARY=10p → options defines that the font which is used for primary annotations should be 10 pixels. options: MAP_ANNOT_OFFSET_PRIMARY=0.1c → options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm. options: FONT_LABEL=10p → options defines that the font, which is used to plot the labels below the annotation, should be 10 points. options: MAP_LABEL_OFFSET=0.1c → options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm. options: FONT_ANNOT_SECONDARY=10p → options defines that the font for a secondary time axis should be 10 points. transparent: no

→ transparent defines that the background of the plot should not be transparent. dpi = 300 → dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch. removeFiles: yes → removeFiles defines that the .gmt and script files should be removed after the computation. viewPlot: yes → viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one global map which represents the error root mean square values of the corrected equivalent water height values with respect to a reference field. Hence, the corrected equivalent water height values refer to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations. Since the error root mean square values are computed from monthly corrected equivalent water height value time series, the unit is equivalent water heights given in in metre per month.

16.7 GriddedDataCalculate

Goal:

The goal is to compute gridded correction ratio values of the time variable global gravity field.

Parameters:

outputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_CorrectionRatio_timeVariabilityRMS.txt
→ outputfileGriddedData defines the path and the filename of the gridded data output file. This grid output file should contain one column in which the correction ratio values are stored.

inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_GRACE_timeVariabilityRMS.txt
→ inputfileGriddedData defines the path and the filename of the gridded gravity field output file. This gridded gravity field output file contains one column in which the error root mean

square values of the processed equivalent water height values, which were derived from GRACE observations, are stored.

inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_GRACE-FM_timeVariabilityRMS.txt
→ inputfileGriddedData defines the path and the filename of the gridded gravity field output file. This gridded gravity field output file contains one column in which the error root mean square values of the corrected equivalent water height values are stored.

constant: ---
→ constant defines that no additional constant should be defined.

parameter: ---
→ parameter defines that no additional parameter is defined.

leastSquares: ---
→ leastSquares defines that the expression should not be minimized by adjusting the parameters.

removalCriteria: ---
→ removalCriteria defines that points should not be removed if one criterion evaluates true.

longitude: longitude
→ longitude is described by the expression longitude.

latitude: latitude
→ latitude is described by the expression latitude.

height: height
→ height is described by the expression height.

area: area
→ area is described by the expression area.

value: (1-(data1/data0))*100
→ value defines that the value of the correction ratio should be computed by calculating the quotient of the forward modelled equivalent water height values and the equivalent water height values derived from GRACE observations. Since data1 and data0 are not identical, the reference value will decrease. Hence, the ratio has to be subtracted from 1. To derive a value in percent, the difference has to be multiplied with 100.

computeArea: no
→ computeArea defines that no automatic area computation of rectangular grids, which will overwrite the area information, should be performed.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 187: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by

$$\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$$

Equation 188: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

statistics: <none>
→ statistics defines that no statistic columns should be computed.

Result:

The function GriddedDataCalculate generates one .txt file with gridded data. This .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded correction ratio values of the time variable gravity field for each grid cell. The unit is percentage.

16.8 PlotMap

Goal:

The goal is to generate a global map which visualizes the correction ratio values of the time variable gravity field for each grid cell.

Parameters:

outputfile: data/Maps/{listName}/{listName}_CorrectionRatio_TimeVariabilityRMS.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_CorrectionRatio_timeVariabilityRMS
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: griddedData → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_CorrectionRatio_timeVariabilityRMS.txt → inputfileGriddedData defines the path and the filename of the gridded gravity field input file. This gridded gravity field input file contains one column in which the correction ratio values are stored. value: data0 → value defines that data0, which contains the correction ratio values, should be displayed. increment: 0.5 → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid. illuminate: no → illuminate defines that the grid should not be brightened. resample: <none> → resample defines that the grid input values should not be resampled. gridlineRegistered: no → gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid.

width: 1

→ width defines that the width of the coastlines should be 1 point.

color: black

→ color defines that the colour of the coastlines should be black.

landColor: <none>

→ landColor defines that there is no specific colour with which the land area should be filled.

oceanColor: gray

→ oceanColor defines that the ocean area should be filled with gray colour.

minArea: 10000

→ minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 189: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 190: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$

$f = 0.003352810681$
and thus, the inverseFlattening is
$\bar{f} = \frac{1}{0.003352810681}$
$\bar{f} = 298.2572221.$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 60
→ majorTickSpacing defines that the boundary annotation should be set every 60 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 30
→ gridLineSpacing defines that the spacing of the grid lines should be set every 30 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: - 30 → min defines that the minimum value of the colour bar should be set to - 30. max: 30 → max defines that the maximum value of the colour bar should be set to 30. annotation: 6 → annotation defines that a boundary annotation should be drawn every 6 °. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: Reduction of temporal RMS variability [%] → label defines that the axis description and hence the description of the colour bar should be set to "Reduction of temporal RMS variability [%]". logarithmic: no → logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. triangleRight: yes → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. illuminate: no → illuminate defines that the grid should not be brightened. vertical: no → vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. length: 100 → length defines that the length of the colour bar should be 100 %. margin: 0.4 → margin defines that the space between the colour bar and the figure should be 0.4 cm. colorTable: /data1/colors/custom_palettes/temperature_cont.cpt

→ colorTable defines that the colour bar with the name "temperature_cont.cpt" should be used. This colour bar ranges from dark blue to dark red.
reverse: no
→ reverse defines that the colour bar should not be reversed.
showColorbar: yes
→ showColorbar defines that the colour bar should be plotted.

projection
projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. centralMeridian: 0 → centralMeridian defines that the central meridian should be set at 0 °.

options
width: 12 → width defines that the width of the plot should be 12 cm. height: --- → height defines that the height of the plot given in centimetre should not be further specified. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. options: FONT_ANNOT_PRIMARY=10p → options defines that the font which is used for primary annotations should be 10 pixels. options: MAP_ANNOT_OFFSET_PRIMARY=0.1c

→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.

options: FONT_LABEL=10p

→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.

options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one global map which represents the correction ratio derived from the relationship between the error root mean square values of the processed equivalent water height values which were derived from GRACE observations and the error root mean square values of the corrected equivalent water height values. The unit of the correction ratio is given in percentage.

17 GroupPrograms

Goal:

The goal is to run the individually defined programs in a group.

Parameters:

outputfileLog: ---
→ outpufileLog defines that no additional log file should be created.

silently: no
→ silently defines that the output should be shown.

17.1 Gravityfield2GriddedData

Goal:

The goal is to process equivalent water height values, which were derived from GRACE observations and which express the time variable gravity field values, on a given grid for May 2010.

Parameters:

outputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_GRACE_ may2010.txt
→ outputfileGriddedData defines the path and the filename of the processed equivalent water height value grid output file for 05/2010.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. deltaPhi: {gridSizeCoarse} [= 0.5]

→ deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °.

height: 0.0 [= 0]

→ height defines that the distance of the points above the ellipsoid should be 0 m.

R: 6378137.0 [= 6378137]

→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 191: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 192: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: Θ gridBorder [= rectangle]

→ border allows to extract a regional subset of points from the global grid. In this case the rectangle defines a global grid.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $$k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$$ Equation 193: Coefficients of the Kernel Source: Mayer-Gürr et al., n.d. includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2018200204201706 [= /data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2018/timeSplines/old_monthly/timeSpline_ITSG-Grace2018_monthly_n96_deg1_c20_replaced_noGIA_noMean_2002-04_2017-06_interp_ddk3.dat] → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc] → inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: - 1 → factor defines that the forward modelled equivalent water height values, which represent the gravity field, should be subtracted from the processed equivalent water height values which were derived from GRACE observations.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

time: 55317 [= 2010-05-01]
→ time defines that the gravity field should be evaluated on the 01/05/2010.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$ Equation 194: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{f}$ can simply be computed by $$\bar{f} = \frac{1}{f}.$$ Equation 195: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$ $$f = 0.003352810681$$ and thus, the inverseFlattening is $$\bar{f} = \frac{1}{0.003352810681}$$ $$\bar{f} = 298.2572221.$$

Result:

The function Gravityfield2GriddedData generates one .txt file with gridded data for each month. This .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the processed equivalent water height values, which were derived from GRACE observations in 05/2010 and which express the time variable gravity field for this respective month. The unit of the processed equivalent water height values is metre.

17.2 Gravityfield2GriddedData

Goal:

The goal is to process corrected equivalent water height values, which express the time variable gravity field values, on a given grid for May 2010. Hence, the corrected equivalent water height values refer to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations.

Parameters:

outputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_GRACE-FM_may2010.txt
→ outputfileGriddedData defines the path and the filename of the corrected equivalent water height value grid output file for 05/2010.

grid
grid: geograph → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. deltaLambda: {gridSizeCoarse} [= 0.5] → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. deltaPhi: {gridSizeCoarse} [= 0.5] → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. height: 0.0 [= 0] → height defines that the distance of the points above the ellipsoid should be 0 m. R: 6378137.0 [= 6378137] → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. inverseFlattening: 298.2572221010 [= 298.2572221] → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 196: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 197: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

border: Θ gridBorder [= rectangle]

→ border allows to extract a regional subset of points from the global grid. In this case the rectangle defines a global grid.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 198: Coefficients of the Kernel   Source: Mayer-Gürr et al., n.d.   includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSplineGrace2018200204201608 [=/data2/backup_poessneck_2023_01_23/groopsData/potential/ITSG-Grace2018/timeSplines/old_monthly/timeSpline_ITSG-Grace2018_monthly_n96_deg1_c20_replaced_noGIA_noMean_2002-04_2016-08_interp_ddk3.dat] → inputfileTimeSplinesGravityfield defines the path and the filename of the time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: 60 → maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default.

gravityfield
gravityfield: timeSplines → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc] → inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file. inputfileTimeSplinesCovariance: --- → inputfileTimeSplinesCovariance defines that no covariance time spline should be used.

<u>minDegree: {minDegree} [= 0]</u>
→ minDegree defines that the minimum degree of the expansion should be 0 °.
<u>maxDegree: 60</u>
→ maxDegree defines that the maximum degree of the expansion should be 60 °. Although a reduced maximum degree decreases the resolution, meaning that less detailed structures are visible, it is still sufficient. Meanwhile, a smaller degree also decreases the computation time.
<u>factor: - 1</u>
→ factor defines that the forward modelled equivalent water height values, which represent the gravity field, should be subtracted from the processed equivalent water height values which were derived from GRACE observations.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

time: 55317 [= 2010-05-01]
→ time defines that the gravity field should be evaluated on the 01/05/2010.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 199: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$

Equation 200: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

Result:

The function Gravityfield2GriddedData generates one .txt file with gridded data for each month. This .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the corrected equivalent water height values, which express the gravity field, for 05/2010. The unit of the corrected equivalent water height values is metre. Hence, the corrected equivalent water height values refer to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations.

17.3 PlotMap

Goal:

The goal is to generate a global map which visualizes the processed equivalent water height values, which were derived from GRACE observations, in 05/2010. These processed equivalent water height values express the gravity field.

Parameters:

outputfile: data/Maps/{listName}/{listName}_May2010_GRACE.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_GRACE_May2010
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: griddedData → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_GRACE_may2010.txt → inputfileGriddedData defines the path and the filename of the gridded gravity field input file for 05/2010. value: data0 → value defines that data0, which contains the processed equivalent water height values which were derived from GRACE observations and which express the gravity field in 05/2010, should be displayed. increment: 0.5 → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid. illuminate: no → illuminate defines that the grid should not be brightened. resample: <none> → resample defines that the grid input values should not be resampled. gridlineRegistered: no → gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid. width: 1 → width defines that the width of the coastlines should be 1 point. color: black → color defines that the colour of the coastlines should be black. landColor: <none> → landColor defines that there is no specific colour with which the land area should be filled. oceanColor: gray → oceanColor defines that the ocean area should be filled with gray colour. minArea: 10000 → minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis } - \text{ semiminor axis})}{\text{semimajor axis}}$ Equation 201: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}$.

Equation 202: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 60
→ majorTickSpacing defines that the boundary annotation should be set every 60 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 30
→ gridLineSpacing defines that the spacing of the grid lines should be set every 30 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: - 0.1 → min defines that the minimum value of the colour bar should be set to - 0.1. max: 0.1 → max defines that the maximum value of the colour bar should be set to 0.1. annotation: 0.02 → annotation defines that a boundary annotation should be drawn every 0.02 °. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [m] → label defines that the axis description and hence the description of the colour bar should be set to “EWH [m]”. logarithmic: no → logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. triangleRight: yes → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. illuminate: no → illuminate defines that the grid should not be brightened. vertical: no → vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. length: 100 → length defines that the length of the colour bar should be 100 %. margin: 0.4

→ margin defines that the space between the colour bar and the figure should be 0.4 cm.
colorTable: haxby
→ colorTable defines that the colour bar with the name "haxby" should be used. This colour bar ranges from dark blue to light red.
reverse: yes
→ reverse defines that the colour bar should be reversed. Hence, the colour bar ranges from light red to dark blue.
showColorbar: yes
→ showColorbar defines that the colour bar should be plotted.

projection
projection: robinson
→ projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions.
centralMeridian: 0
→ centralMeridian defines that the central meridian should be set at 0 °.

options
width: 12
→ width defines that the width of the plot should be 12 cm.
height: ---
→ height defines that the height of the plot given in centimetre should not be further specified.
titleFontSize: 12
→ titleFontSize defines that the fontsize of the title should be 12 points.
marginTitle: 0.4
→ marginTitle defines that the space between the figure title should be 0.4 cm.
drawGridOnTop: no

→ drawGridOnTop defines that no grid lines should be drawn above all other lines and points.

options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels.

options: MAP_ANNOT_OFFSET_PRIMARY=0.1c

→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.

options: FONT_LABEL=10p

→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.

options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one global map which represents the processed equivalent water height values which were derived from GRACE observations in 05/2010 and which express the time variable gravity field for this respective month. The unit of the equivalent water height values is metre.

17.4 PlotMap

Goal:

The goal is to generate a global map which visualizes the corrected equivalent water height values, in 05/2010. These processed equivalent water height values express the gravity field.

Hence, the corrected equivalent water height values refer to the difference between the forward modelled equivalent water height values and the processed equivalent water height values which were derived from GRACE observations.

Parameters:

outputfile: data/Maps/{listName}/{listName}_May2010_GRACE-FM.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_GRACE-FM_May2010
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: griddedData → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_GRACE-FM_may2010.txt → inputfileGriddedData defines the path and the filename of the gridded gravity field input file for 05/2010. value: data0 → value defines that data0, which contains the corrected equivalent water height values and which express the gravity field in 05/2010, should be displayed. increment: 0.5 → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid. illuminate: no → illuminate defines that the grid should not be brightened. resample: <none> → resample defines that the grid input values should not be resampled.

gridlineRegistered: no

→ gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer

layer: coast

→ layer defines the content of the map. Hence, coastlines should be plotted.

resolution: medium

→ resolution defines that the resolution of the coastlines should be medium.

line: solid

→ line defines that the line style of the coastlines should be solid.

width: 1

→ width defines that the width of the coastlines should be 1 point.

color: black

→ color defines that the colour of the coastlines should be black.

landColor: <none>

→ landColor defines that there is no specific colour with which the land area should be filled.

oceanColor: gray

→ oceanColor defines that the ocean area should be filled with gray colour.

minArea: 10000

→ minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]

→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 203: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$ Equation 204: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $\mathrm{f} = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$ $\mathrm{f} = 0.003352810681$ and thus, the inverseFlattening is $\bar{\mathrm{f}} = \frac{1}{0.003352810681}$ $\bar{\mathrm{f}} = 298.2572221.$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 60
→ majorTickSpacing defines that the boundary annotation should be set every 60 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 30
→ gridLineSpacing defines that the spacing of the grid lines should be set every 30 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: - 0.1 → min defines that the minimum value of the colour bar should be set to - 0.1. max: 0.1 → max defines that the maximum value of the colour bar should be set to 0.1. annotation: 0.02 → annotation defines that a boundary annotation should be drawn every 0.02 °. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [m] → label defines that the axis description and hence the description of the colour bar should be set to “EWH [m]”. logarithmic: no → logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. triangleRight: yes → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. illuminate: no → illuminate defines that the grid should not be brightened. vertical: no

→ vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. length: 100 → length defines that the length of the colour bar should be 100 %. margin: 0.4 → margin defines that the space between the colour bar and the figure should be 0.4 cm. colorTable: haxby → colorTable defines that the colour bar with the name "haxby" should be used. This colour bar ranges from dark blue to light red. reverse: yes → reverse defines that the colour bar should be reversed. Hence, the colour bar ranges from light red to dark blue. showColorbar: yes → showColorbar defines that the colour bar should be plotted.

projection
projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. centralMeridian: 0 → centralMeridian defines that the central meridian should be set at 0 °.

options
width: 16 → width defines that the width of the plot should be 16 cm. height: --- → height defines that the height of the plot given in centimetre should not be further specified. titleFontSize: 12

→ titleFontSize defines that the fontsize of the title should be 12 points.

marginTitle: 0.4

→ marginTitle defines that the space between the figure title should be 0.4 cm.

drawGridOnTop: no

→ drawGridOnTop defines that no grid lines should be drawn above all other lines and points.

options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels.

options: MAP_ANNOT_OFFSET_PRIMARY=0.1c

→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.

options: FONT_LABEL=10p

→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.

options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates one global map which represents the corrected equivalent water height values in 05/2010 and which express the time variable gravity field for this respective month. The unit of the equivalent water height values is metre.

17.5 GriddedDataCalculate

Goal:

The goal is to compute gridded correction ratio values of the time variable gravity field for May 2010

Parameters:

outputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_May2010_CorrectionSignalRatio.txt
→ outputfileGriddedData defines the path and the filename of the gridded correction ratio output file in 05/2010.

inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_GRACE_may2010.txt
→ inputfileGriddedData defines the path and the filename of the gridded gravity field input file for 05/2010.

inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_GRACE-FM_may2010.txt
→ inputfileGriddedData defines the path and the filename of the gridded gravity field input file for 05/2010.

constant: ---
→ constant defines that no additional constant should be defined.

parameter: ---
→ parameter defines that no additional parameter is defined.

leastSquares: ---
→ leastSquares defines that the expression should not be minimized by adjusting the parameters.

removalCriteria: ---
→ removalCriteria defines that points should not be removed if one criterion evaluates true.

longitude: longitude
→ longitude is described by the expression longitude.

latitude: latitude
→ latitude is described by the expression latitude.

height: height
→ height is described by the expression height.

area: area
→ area is described by the expression area.

value: (1-(data1/data0))*100
→ value defines that the value of the correction ratio should be computed by calculating the quotient of the corrected equivalent water height values and the equivalent water height observed by GRACE. To convert the ratio to percentage, the ratio has to be multiplied with 100. Since data1 and data0 are not identical, the reference value will decrease. Hence, the ratio has to be subtracted from 1. To derive a value in percent, the difference has to be multiplied with 100.

computeArea: no
→ computeArea defines that no automatic area computation of rectangular grids, which will overwrite the area information, should be performed.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 205: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by

$$\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$$

Equation 206: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$\mathrm{f} = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$$

$$\mathrm{f} = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{\mathrm{f}} = \frac{1}{0.003352810681}$$

$$\bar{\mathrm{f}} = 298.2572221.$$

statistics: <none>

→ statistics defines that no statistic columns should be computed.

Result:

The function GriddedDataCalculate generates one .txt file with gridded data. This .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the gridded correction ratio values of the correction signal to the initial GRACE signal in 05/2010. The unit is percentage.

17.6 PlotMap

Goal:

The goal is to generate a global map which visualizes the ratio of the correction signal to the initial GRACE signal in 05/2010.

Parameters:

outputfile: data/Maps/{listName}/{listName}_May2010_CorrectionSignalRatio.png
→ outputfile defines the path and the filename of the generated map.

title: {listName}_May2010_CorrectionSignalRatio
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
<u>layer: griddedData</u> → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. <u>inputfileGriddedData: data/Grids/GriddedGravityfield/{listName}/{listName}_May2010_CorrectionSignalRatio.txt</u> → inputfileGriddedData defines the path and the filename of the gridded correction ratio input file in 05/2010. <u>value: data0</u> → value defines that data0, which contains the ratio of the correction signal to the initial GRACE signal, should be displayed. <u>increment: 0.5</u> → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid.

illuminate: no

→ illuminate defines that the grid should not be brightened.

resample: <none>

→ resample defines that the grid input values should not be resampled.

gridlineRegistered: no

→ gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer

layer: coast

→ layer defines the content of the map. Hence, coastlines should be plotted.

resolution: medium

→ resolution defines that the resolution of the coastlines should be medium.

line: solid

→ line defines that the line style of the coastlines should be solid.

width: 1

→ width defines that the width of the coastlines should be 1 point.

color: black

→ color defines that the colour of the coastlines should be black.

landColor: <none>

→ landColor defines that there is no specific colour with which the land area should be filled.

oceanColor: gray

→ oceanColor defines that the ocean area should be filled with gray colour.

minArea: 10000

→ minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

layer

layer: polygon

→ layer defines the content of the map. Hence, a polygon around the Mississippi Basin should be drawn.

inputfilePolygon: /data1/border/riverbasins/GlobalCDA/Polygon_MississippiBasin.txt

→ inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the Mississippi Basin.

line: solid

→ line defines that the line style of the polygon should be solid.

width: 1.5

→ width defines that the width of the coastlines should be 1.5 points.

color: red

→ color defines that the colour of the polygon should be red.

fillColor: <none>

→ fillColor defines that there is no specified colour with which the box of the legend should be filled.

value: ---

→ value defines that the fillColor should not have a specified value. This can be traced back to the fact that no fillColor is used anyway.

drawLineAsGreatCircle: yes

→ drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 207: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 208: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 60
→ majorTickSpacing defines that the boundary annotation should be set every 60 °.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 30
→ gridLineSpacing defines that the spacing of the grid lines should be set every 30 °.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: --- → min defines that the minimum value of the colour bar should not be further specified. max: --- → max defines that the maximum value of the colour bar should not be further specified. annotation: 40 → annotation defines that a boundary annotation should be drawn every 40 °. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: Change of GRACE signal [%] → label defines that the axis description and hence the description of the colour bar should be set to "Change of GRACE signal [%]". logarithmic: no → logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. triangleRight: yes → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. illuminate: no → illuminate defines that the grid should not be brightened. vertical: no → vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. length: 100 → length defines that the length of the colour bar should be 100 %. margin: 0.4

→ margin defines that the space between the colour bar and the figure should be 0.4 cm. colorTable: haxby → colorTable defines that the colour bar with the name “haxby” should be used. This colour bar ranges from dark blue to light red. reverse: no → reverse defines that the colour bar should not be reversed. showColorbar: yes → showColorbar defines that the colour bar should be plotted.

projection
projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. centralMeridian: 0 → centralMeridian defines that the central meridian should be set at 0 °.

options
width: 16 → width defines that the width of the plot should be 16 cm. height: --- → height defines that the height of the plot given in centimetre should not be further specified. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels. <u>options: MAP_ANNOT_OFFSET_PRIMARY=0.1c</u> → options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm. <u>options: FONT_LABEL=10p</u> → options defines that the font, which is used to plot the labels below the annotation, should be 10 points. <u>options: MAP_LABEL_OFFSET=0.1c</u> → options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm. <u>options: FONT_ANNOT_SECONDARY=10p</u> → options defines that the font for a secondary time axis should be 10 points. <u>transparent: no</u> → transparent defines that the background of the plot should not be transparent. <u>dpi = 300</u> → dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch. <u>removeFiles: yes</u> → removeFiles defines that the .gmt and script files should be removed after the computation. <u>viewPlot: yes</u> → viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates a global map which visualizes the ratio of the correction signal to the initial GRACE signal in 05/2010. Hence, the map shows how the ratio changes and where these changes are stronger and less strong. The ratio is given in the unit of metres.

catchErrors: <none>
→ catchErrors defines that no program will be executed when an error occurs.

18 GroupPrograms

Goal:

The goal is to run the individually defined programs in a group.

Parameters:

outputfileLog: ---
→ outpufileLog defines that no additional log file should be created.

silently: no
→ silently defines that the output should be shown.

18.1 GridRectangular2NetCdf

Goal:

The goal is to convert a sequence of GridRectangular files, in this case the monthly removed NetCdf files which express the gravity field values through equivalent water height values, to one NetCdf file.

Parameters:

outputfileNetCdf: data/Grids/RemovedNetCDF/{listName}_RemovedNetCDF.nc
→ outputfileNetCdf defines the path and the filename of the NetCdf output file.

inputfileGridRectangular [loop= LocationRemoved2NetCDF]: data/Grids/Removed-NetCDF/{listName}_txt/{InputRemoved2NetCDF}
→ inputfileGridRectangular defines the path and the filename of the gridded gravity field input file over which should be looped.

times: Θ timeFrame [= monthly]
→ times defines that the values for the time axis should be monthly dates within the time frame of 01/2003 to 12/2016.

dataVariable
<u>selectDataField: ---</u> → selectDataField defines that the input data column should not be further specified. <u>name: EWH</u> → name defines that the variable within the NetCdf file should be named "EWH". <u>datatype: float</u> → datatype defines that the EWH values should be of type float. <u>attribute: ---</u> → attribute defines that no further attributes should be written into the NetCdf file.

globalAttribute: --- → globalAttribute defines that no further meta data should be written into the NetCdf file.

Result:

The function GridRectangular2NetCdf generates one NetCdf file which combines all monthly NetCdf files. The NetCdf file contains the respective modified julian date, the longitudes and the latitudes for each 0.5 ° and a matrix which contains the equivalent water height value for each grid cell.

18.2 GridRectangular2NetCdf

Goal:

The goal is to convert a sequence of GridRectangular files, in this case the monthly restored NetCdf files which describe the gravity field values through water level values, to one NetCdf file.

Parameters:

outputfileNetCdf: data/Grids/RestoredNetCDF/{listName}_RestoredNetCDF.nc
→ outputfileNetCdf defines the path and the filename of the NetCdf output file.

inputfileGridRectangular: data/Grids/RestoredNetCDF/{listName}_txt/{InputRemoved2 NetCDF}
→ inputfileGridRectangular defines the path and the filename of the gridded input file.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

dataVariable
selectDataField: 0 → selectDataField defines that the first data field, which refers to data0 and which contains the water level values, should be selected. name: data0 → name defines that the variable within the NetCdf file should be named "data0". datatype: float → datatype defines that the data0 values should be of type float. attribute: --- → attribute defines that no further attributes should be written into the NetCdf file.

globalAttribute: --- → globalAttribute defines that no further meta data should be written into the NetCdf file.

Result:

The function GridRectangular2NetCdf generates one NetCdf file which combines all monthly NetCdf files. The NetCdf file contains the respective modified julian date, the longitudes and the latitudes for each 0.5 ° and a matrix which contains the water level values for each grid cell.

18.3 NetCdfInfo

Goal:

The goal is to retrieve information of the generated NetCdf file.

Parameters:

inputfileNetCdf: data/Grids/RemovedNetCDF/{listName}_RemovedNetCDF.nc
→ inputfileNetCdf defines the path and the filename of the NetCdf input file from which information such as dimensions and variables should be derived.

Result:

The function NetCdfInfo displays the information of the NetCdf file in the console. This information includes the variables time, latitude, longitude, EWH as well as the dimension of the file and, if available, global attributes.

18.4 NetCdfInfo

Goal:

The goal is to retrieve information of the generated NetCdf file.

Parameters:

inputfileNetCdf: data/Grids/RemovedNetCDF/{listName}_RemovedNetCDF.nc
→ inputfileNetCdf defines the path and the filename of the NetCdf input file from which information such as dimensions and variables should be derived.

Result:

The function NetCdfInfo displays the information of the NetCdf file in the console. This information includes the variables time, latitude, longitude, data0 as well as the dimension of the file and, if available, global attributes.

catchErrors: <none>
→ catchErrors defines that no program will be executed when an error occurs.

19 LoopPrograms

Goal:

The goal is to repeat the programs which are defined inside the loop.

Parameters:

loop
loop: timeSeries → loop loops over points in time and generates a series in ascending order. timeSeries: Θ timeFrame [= monthly] → timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016. variableLoopTime: mjd → variableLoopTime defines that monthly iterations should be performed. variableLoopIndex: --- → variableLoopIndex defines that the variable with the index of the current iteration should not be further specified. variableLoopCount: --- → variableLoopCount defines that the total number of iterations should not be counted.

continueAfterError: no
→ continueAfterError defines that the program should not continue with the next iteration when an error occurs.

processCountPerIteration: 0
→ processCountPerIteration defines that all processes should be used within each iteration.

parallelLog: yes
→ parallelLog defines that all processing nodes should be executed in parallelized loops.

19.1 Gravityfield2PotentialCoefficients

Goal:

The goal is to evaluate the forward modelled equivalent water height values, which express the time variable gravity field, each month in the time frame of 01/2003 to 12/2016 and to write the respective potential coefficients to a file.

Parameters:

outputfileTimeSeries: data/PotentialCoefficients/ForwardModelled/{listName}/RECOG-LR_RL01_removal_SH_{mjd:%y-%m}.txt
→ outputfileTimeSeries defines the path and the filename of the forward modelled removal correction time series output file.

gravityfield
<u>gravityfield: timeSplines</u> → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of a time spline, the time dependent gravity field is represented by a spherical harmonics expansion in the spatial domain and spline functions in the time domain. <u>inputfileTimeSplinesGravityfield: Θ inputTimeSpline [= data/PotentialCoefficients/TimeSplines/{listName}_ForModTimeSplines.gfc]</u> → inputfileTimeSplinesGravityfield defines the path and the filename of the forward modelled time spline input file. <u>inputfileTimeSplinesCovariance: ---</u> → inputfileTimeSplinesCovariance defines that no covariance time spline should be used. <u>minDegree: {minDegree} [= 0]</u> → minDegree defines that the minimum degree of the expansion should be 0 °. <u>maxDegree: {minDegree} [= 96]</u> → maxDegree defines that the maximum degree of the expansion should be 96 °. <u>factor: 1.0 [= 1]</u> → factor defines that the result should be multiplied by 1. This factor is defined by default.

minDegree: {minDegree} [= 0]
→ minDegree defines that the minimum degree of the expansion should be 0 °.

maxDegree: {maxDegree} [= 96]
→ maxDegree defines that the maximum degree of the expansion should be 96 °.

GM: 3.986004415e+14 [= 398600441500000]
→ GM defines that the geocentric gravitational constant of the Earth should be 398600441500000 $\frac{m^2}{s^2}$.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

time: {mjd} [= 00:00:00]
→ time defines that the gravity field should be evaluated once a month.

Result:

The function Gravityfield2PotentialCoefficients generates one .txt file for each month in the time frame 01/2003 to 12/2016. Hence, 168 .txt files are generated. Each .txt file contains the respective potential coefficients which were derived from the forward modelled equivalent water height values which express the gravity field.

20 Gravityfield2GriddedData

Goal:

The goal is to compute forward modelled equivalent water height values which express the time variable gravity field on a given grid for July 2010.

Parameters:

outputfileGriddedData: data/PotentialCoefficients/ForwardModelled/{listName}/ SH2Grid_201007.txt
→ outputfileGriddedData defines the path and the filename of the gravity field grid output grid in 07/2010.

grid
<u>grid: geograph</u> → grid generates a set of points. In respect of a geographical grid, the points follow an equal-angular distribution in which the points are located along the meridians and along the circles of latitude. <u>deltaLambda: {gridSizeCoarse} [= 0.5]</u> → deltaLambda defines that the angular difference between the adjacent points along the meridians should be 0.5 °. <u>deltaPhi: {gridSizeCoarse} [= 0.5]</u> → deltaPhi defines that the angular difference between the adjacent points along the circles of latitude should be 0.5 °. <u>height: 0.0 [= 0]</u> → height defines that the distance of the points above the ellipsoid should be 0 m. <u>R: 6378137.0 [= 6378137]</u> → R defines that the major axis of the ellipsoid / sphere should be 6378137 m. <u>inverseFlattening: 298.2572221010 [= 298.2572221]</u> → inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$

Equation 209: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 210: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137 \text{ m} - 6356752.3141 \text{ m})}{6378137 \text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{f} = \frac{1}{0.003352810681}$$

$$\bar{f} = 298.2572221.$$

<u>border: ---</u>

→ border defines that no regional subset of points should be extracted from the global grid.

kernel: Θ kernel [= waterHeight]
→ kernel defines harmonic isotropic integral kernels K. The kernel function can be used as a basis function to represent the gravity field. In this case the gravity field is represented as water height. Water height refers to the height of an equivalent water column which takes the effect of loading into account. Hence the Equation to compute the coefficients of the kernel k_n $k_n = 4 \cdot \pi \cdot G \cdot \rho \cdot R \cdot \frac{1 + k'_n}{2n + 1}$ Equation 211: Coefficients of the Kernel   Source: Mayer-Gürr et al., n.d.   includes the gravitational constant G, the density of the water ρ, the reference radius R, the load Love numbers k'_n and the respective degree n.

gravityfield
gravityfield: potentialCoefficients → gravityfield defines that functionals of the time dependent gravity field are computed. In respect of potentialCoefficients, the potential is given by $V(\lambda, \vartheta, r) = \frac{GM}{R}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\left(\frac{R}{r}\right)^{n+1}(c_{nm}C_{nm}(\lambda, \vartheta) + s_{nm}S_{nm}(\lambda, \vartheta))$ Equation 212: Spherical Harmonic Expansion Equation Source: Mayer-Gürr et al., n.d. with G = gravity constant, M = mass of the Earth, R = radius of the Earth, n = degree, m = order and the potential coefficients c_{nm} and s_{nm}, which depend on longitude and latitude. inputfilePotentialCoefficients: data/PotentialCoefficients/ForwardModelled/{listName}/ RECOG-LR_RL01_removal_SH_2010-07.txt → inputfilePotentialCoefficients defines the path and the filename of the forward modelled potential coefficient input file. minDegree: {minDegree} [= 0] → minDegree defines that the minimum degree of the expansion should be 0 °. maxDegree: {maxDegree} [= 96] → maxDegree defines that the maximum degree of the expansion should be 96 °. factor: 1.0 [= 1] → factor defines that the result should be multiplied by 1. This factor is defined by default. setSigmasToZero: no → setSigmasToZero defines that the variance should not be set to 0.

convertToHarmonics: yes
→ convertToHarmonics defines that the gravity field should be converted to spherical harmonics before it is evaluated. This may accelerate the computation.

time: 55378 [= 2010-07-01]
→ time defines that the gravity field should be evaluated in 07/2010.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
$\rightarrow$ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 213: Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by $\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$ Equation 214: Inverse Flattening of the rotation ellipsoid Source: Mayer-Gürr et al., n.d. Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $\mathrm{f} = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$ $\mathrm{f} = 0.003352810681$ and thus, the inverseFlattening is $\bar{\mathrm{f}} = \frac{1}{0.003352810681}$ $\bar{\mathrm{f}} = 298.2572221.$

Result:

The function Gravityfield2GriddedData generates one .txt file with gridded data for each month. This .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the forward modelled equivalent water height values in 07/2010 which express the time variable gravity field for this respective month. The unit of the forward modelled equivalent water height values is metre.

21 PlotMap

Goal:

The goal is to generate a global map which visualizes the forward modelled equivalent water height values in 07/2010. These forward modelled equivalent water height values express the gravity field and function as removal correction.

Parameters:

outputfile: data/Maps/{listName}/{listName}_SH2Grid_201007.png
→ outputfile defines the path and the filename of the generated map.

title: RECOG-LR RL01 (removal correction) {mjd:%y-%m}
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid. width: 0.5 → width defines that the width of the coastlines should be 0.5 points. color: black → color defines that the colour of the coastlines should be black. landColor: rgb → landColor defines that the land area should be filled with rgb values. red: 218

→ red defines that the intensity of the red color should be 218.

green: 214

→ green defines that the intensity of the green color should be 214.

blue: 211

→ blue defines that the intensity of the blue color should be 211.

oceanColor: gray

→ oceanColor defines that the ocean area should be filled with gray colour.

minArea: 10000

→ minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

layer
layer: griddedData → layer defines the content of the map. Hence, a regular grid of yxz values should be plotted. inputfileGriddedData: data/PotentialCoefficients/ForwardModelled/{listName}/SH2Grid_201007.txt → inputfileGriddedData defines the path and the filename of the forward modelled gridded gravity field input file. value: data0*100 → value defines that data0, which contains the forward modelled gridded equivalent water height values, which express the gravity field in 07/2010, should be displayed. To change the unit of the forward modelled equivalent water height values from metre to centimetre, data0 is multiplied with 100. increment: 0.5 → increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid. illuminate: no → illuminate defines that the grid should not be brightened. resample: <none> → resample defines that the grid input values should not be resampled. gridlineRegistered: no → gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
<u>layer: polygon</u> → layer defines the content of the map. Hence, a polygon around the Black Sea is drawn. <u>inputfilePolygon: /data1/border/specialBorders/blackSea_poly.txt</u> → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the Black Sea. <u>line: solid</u> → line defines that the line style of the polygon should be solid. <u>width: 0</u> → width defines that the width of the polygon should be 0 points. Since the layer coast is activated, the polygon can be seen anyways. <u>color: black</u> → color defines that the colour of the polygon should be black. <u>fillColor: gray</u> → fillColor defines that the box of the legend should be filled with gray colour. <u>value: ---</u> → value defines that the fillColor should not have a specified gray value. <u>drawLineAsGreatCircle: yes</u> → drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

layer
<u>layer: coast</u> → layer defines the content of the map. Hence, coastlines should be plotted. <u>resolution: medium</u> → resolution defines that the resolution of the coastlines should be medium. <u>line: solid</u> → line defines that the line style of the coastlines should be solid. <u>width: 0.5</u> → width defines that the width of the coastlines should be 0.5 points. <u>color: black</u> → color defines that the colour of the coastlines should be black. <u>landColor: <none></u>

→ landColor defines that there is no specific colour with which the land area should be filled.   oceanColor: <none>   → oceanColor defines that there is no specific colour with which the ocean area should be filled.   minArea: 10000   → minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]
→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying $f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$ Equation 215: Flattening of the rotation ellipsoid   Source: Mayer-Gürr et al., n.d.   the inverseFlattening value $\bar{f}$ can simply be computed by $\bar{f} = \frac{1}{f}.$ Equation 216: Inverse Flattening of the rotation ellipsoid   Source: Mayer-Gürr et al., n.d.   Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is $f = \frac{(6378137\ \text{m} - 6356752.3141\ \text{m})}{6378137\ \text{m}}$ $f = 0.003352810681$ and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 0
→ majorTickSpacing defines that the boundary annotation should be set every 0 °. Hence, no boundary annotation is given at all.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 0
→ gridLineSpacing defines that the spacing of the grid lines should be set every 0 °. Hence, no grid spacing is given at all.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: - 5 → min defines that the minimum value of the colour bar should be set to - 5. max: 5

→ max defines that the maximum value of the colour bar should be set to 5.

annotation: ---

→ annotation defines that no boundary annotation should be drawn.

unit: ---

→ unit defines that no unit information should be appended to the values of the axis.

label: EWH [cm]

→ label defines that the axis description and hence the description of the colour bar should be set to “EWH [cm]”.

logarithmic: no

→ logarithmic defines that no logarithmic scale should be used.

triangleLeft: yes

→ triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values.

triangleRight: yes

→ triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values.

illuminate: no

→ illuminate defines that the grid should not be brightened.

vertical: no

→ vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot.

length: 100

→ length defines that the length of the colour bar should be 100 %.

margin: 0.4

→ margin defines that the space between the colour bar and the figure should be 0.4 cm.

colorTable: haxby

→ colorTable defines that the colour bar with the name “haxby” should be used. This colour bar ranges from dark blue to light red.

reverse: yes

→ reverse defines that the colour bar should be reversed. Hence, the colour bar ranges from light red to dark blue.

showColorbar: yes

→ showColorbar defines that the colour bar should be plotted.

projection
projection: robinson → projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions. centralMeridian: 0 → centralMeridian defines that the central meridian should be set at 0 °.

options
width: 16 → width defines that the width of the plot should be 16 cm. height: --- → height defines that the height of the plot given in centimetre should not be further specified. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. options: FONT_ANNOT_PRIMARY=10p → options defines that the font which is used for primary annotations should be 10 pixels. options: MAP_ANNOT_OFFSET_PRIMARY=0.1c → options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm. options: FONT_LABEL=10p → options defines that the font, which is used to plot the labels below the annotation, should be 10 points. options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates a global map for July 2010. This map represents the first release of the monthly computed removal correction. The removal correction is expressed in terms of equivalent water height values, which are indicated in the unit of centimetre. Hence, the map visualizes the size of the forward modelled equivalent water height values that has to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact, that the prevailing water body has on the processed equivalent water height values, which were derived from GRACE observations, can be removed. Hence, the GRACE signal can be corrected. Consequently, this map functions as an indicator which shows how strong each water body actually influences the mass change observed by GRACE in 07/2010. This information is extremely helpful to make the estimates of GRACE more consistent with the output from hydrological models for this respective month.

22 NetCdf2GridRectangular

Goal:

The goal is to convert the merged removed NetCdf file, which contains equivalent water level values that express the gravity field, to a gridded format.

Parameters:

outputfileGridRectangular: data/Grids/RemovedNetCDF/{listName}_NetCDF/NetCDF_{number}.txt
→ outputfileGridRectangular defines the path and the filename of the gridded water level output file.

loopTimeVariable: number
→ loopTimeVariable defines that number should the local variable over which should be looped. Here, number is identical to mjd.

inputfileNetCdf: data/Grids/RemovedNetCDF/{listName}_RemovedNetCDF.nc
→ inputfileNetCdf defines the path and the filename of the NetCdf input file.

variableNameLongitude: lon
→ variableNameLongitude defines that the NetCdf variable for Longitude is lon.

variableNameLatitude: lat
→ variableNameLongitude defines that the NetCdf variable for Latitude is lat.

variableNameTime: time
→ variableNameLongitude defines that the NetCdf variable for Time is time.

variableNameData: EWH
→ variableNameLongitude defines that the NetCdf variable for Data is EWH.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$\mathrm{f} = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 217: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{\mathrm{f}}$ can simply be computed by

$$\bar{\mathrm{f}} = \frac{1}{\mathrm{f}}.$$

Equation 218: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$\mathrm{f} = \frac{(6378137\ \mathrm{m} - 6356752.3141\ \mathrm{m})}{6378137\ \mathrm{m}}$$

$$\mathrm{f} = 0.003352810681$$

and thus, the inverseFlattening is

$$\bar{\mathrm{f}} = \frac{1}{0.003352810681}$$

$$\bar{\mathrm{f}} = 298.2572221.$$

Result:

The function Netcdf2GridRectangular generates one .txt file with gridded data for each month. Each .txt file contains five columns, being longitude [deg], latitude [deg], height [m], unit areas [-] and data0. The grid has a resolution of 0.5 ° x 0.5 °. Hence, each point is defined by geographic coordinates and an ellipsoidal height. Furthermore, each point also has an associated area. This area value refers to a projection of the area defined by the point coordinates on a unit sphere which itself has a total area of 4π. The data0 column represents the forward modelled equivalent water height values which express the time variable gravity field for this respective month. The unit of the forward modelled equivalent water height values is metre.

23 PlotMap

Goal:

The goal is to generate a global map which visualizes the forward modelled equivalent water height values in 07/2010. These forward modelled equivalent water height values express the gravity field and function as removal correction. The difference to 21 PlotMap is, that the global map is generated from the NetCdf file which contains the equivalent water height values and not from the forward modelled potential coefficients.

Parameters:

outputfile: data/Maps/{listName}/NetCDF_20100701.png
→ outputfile defines the path and the filename of the generated map.

title: RECOG-LR RL01 (removal correction) {mjd:%y-%m}
→ title defines the title of the plot which should be displayed on each map.

statisticInfos: yes
→ statisticInfos defines that statistical information including the minimum value, the maximum value, the mean value and the root mean square value should be displayed on top of each map underneath the title.

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid. width: 0.5 → width defines that the width of the coastlines should be 0.5 points. color: black → color defines that the colour of the coastlines should be black. landColor: rgb

→ landColor defines that the land area should be filled with rgb values.

red: 218

→ red defines that the intensity of the red color should be 218.

green: 214

→ green defines that the intensity of the green color should be 214.

blue: 211

→ blue defines that the intensity of the blue color should be 211.

oceanColor: gray

→ oceanColor defines that the ocean area should be filled with gray colour.

minArea: 5000

→ minArea defines that features, which have an area size that is smaller than 5000 km^2, should be dropped.

layer

layer: griddedData

→ layer defines the content of the map. Hence, a regular grid of yxz values should be plotted.

inputfileGriddedData: data/Grids/RemovedNetCDF/{listName}_NetCDF/NetCDF_55378 .txt

→ inputfileGriddedData defines the path and the filename of the gridded gravity field input file.

value: data0*100

→ value defines that data0, which contains the forward modelled gridded equivalent water height values, which express the gravity field in 07/2010, should be displayed. To change the unit of the forward modelled equivalent water height values from metre to centimetre, data0 is multiplied with 100.

increment: 0.5

→ increment defines that the grid spacing should be 0.5 °. Hence, it matches the size of the coarse grid.

illuminate: no

→ illuminate defines that the grid should not be brightened.

resample: <none>

→ resample defines that the grid input values should not be resampled.

gridlineRegistered: no

→ gridlineRegistered defines that the input should be treated as cell means and not as point values.

layer
layer: polygon → layer defines the content of the map. Hence, a polygon around the Black Sea is drawn. inputfilePolygon: /data1/border/specialBorders/blackSea_poly.txt → inputfilePolygon defines the path and the filename of the polygon file which contains the border coordinates for the Black Sea. line: solid → line defines that the line style of the polygon should be solid. width: 0 → width defines that the width of the polygon should be 0 points. Since the layer coast is activated, the polygon can be seen anyways. color: black → color defines that the colour of the polygon should be black. fillColor: gray → fillColor defines that the box of the legend should be filled with gray colour. value: --- → value defines that the fillColor should not have a specified gray value. drawLineAsGreatCircle: yes → drawLineAsGreatCircle defines that connecting lines should be drawn as great circles and not as straight lines.

layer
layer: coast → layer defines the content of the map. Hence, coastlines should be plotted. resolution: medium → resolution defines that the resolution of the coastlines should be medium. line: solid → line defines that the line style of the coastlines should be solid. width: 0.5 → width defines that the width of the coastlines should be 0.5 points.

color: black → color defines that the colour of the coastlines should be black. landColor: <none> → landColor defines that there is no specific colour with which the land area should be filled. oceanColor: <none> → oceanColor defines that there is no specific colour with which the ocean area should be filled. minArea: 10000 → minArea defines that features, which have an area size that is smaller than 10000 km^2, should be dropped.

R: 6378137.0 [= 6378137]
→ R defines that the major axis of the ellipsoid / sphere should be 6378137 m.

inverseFlattening: 298.2572221010 [= 298.2572221]

→ inverseFlattening defines the compression of a circle or a sphere along a diameter to form an ellipse or an ellipsoid. It refers to a scale factor, which can be computed by taking the inverse of the flattening parameter f. While the flattening parameter can be computed by applying

$$f = \frac{(\text{Semimajor axis} - \text{semiminor axis})}{\text{semimajor axis}}$$

Equation 219: Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

the inverseFlattening value $\bar{f}$ can simply be computed by

$$\bar{f} = \frac{1}{f}.$$

Equation 220: Inverse Flattening of the rotation ellipsoid

Source: Mayer-Gürr et al., n.d.

Hence, the inverseFlattening, which is also known as flattening ratio, depends on the chosen reference ellipsoid. In this case the geodetic reference system from 1980 was selected. Hence, the flattening is

$$f = \frac{(6378137\text{ m} - 6356752.3141\text{ m})}{6378137\text{ m}}$$

$$f = 0.003352810681$$

and thus, the inverseFlattening is $\bar{f} = \frac{1}{0.003352810681}$ $\bar{f} = 298.2572221.$

minLambda: - 180
→ minLambda defines that the minimum degree of longitude should be - 180 °.

maxLambda: 180
→ maxLambda defines that the maximum degree of longitude should be 180 °.

minPhi: - 90
→ minPhi defines that the minimum degree of latitude should be - 90 °.

maxPhi: 90
→ maxPhi defines that the maximum degree of latitude should be 90 °.

majorTickSpacing: 0
→ majorTickSpacing defines that the boundary annotation should be set every 0 °. Hence, no boundary annotation is given at all.

minorTickSpacing: 0
→ minorTickSpacing defines that the frame tick spacing should be set every 0 °. Hence, no frame tick spacing is given at all.

gridLineSpacing: 0
→ gridLineSpacing defines that the spacing of the grid lines should be set every 0 °. Hence, no grid spacing is given at all.

colorbar
colorbar: <enabled> → colorbar defines that a colour bar should be plotted. min: - 5 → min defines that the minimum value of the colour bar should be set to - 5. max: 5 → max defines that the maximum value of the colour bar should be set to 5. annotation: --- → annotation defines that no boundary annotation should be drawn. unit: --- → unit defines that no unit information should be appended to the values of the axis. label: EWH [cm] → label defines that the axis description and hence the description of the colour bar should be set to “EWH [cm]”. logarithmic: no → logarithmic defines that no logarithmic scale should be used. triangleLeft: yes → triangleLeft defines that the left edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. triangleRight: yes → triangleRight defines that the right edge of the colour bar should be indicated by a triangle. This triangle indicates out-of-bound values. illuminate: no → illuminate defines that the grid should not be brightened. vertical: no → vertical defines that the colour bar should not be plotted vertically on the right side of the plot. Hence, the colour bar should be plotted horizontally beneath the plot. length: 100 → length defines that the length of the colour bar should be 100 %. margin: 0.4 → margin defines that the space between the colour bar and the figure should be 0.4 cm. colorTable: haxby

→ colorTable defines that the colour bar with the name “haxby” should be used. This colour bar ranges from dark blue to light red.
reverse: yes
→ reverse defines that the colour bar should be reversed. Hence, the colour bar ranges from light red to dark blue.
showColorbar: yes
→ showColorbar defines that the colour bar should be plotted.

projection
projection: robinson
→ projection defines the projection of the map. Hence, the robinson projection was presented by Arthur H. Robinson in 1963. It is a modified cylindrical projection which is neither conformal nor equal-area. While the central meridian and all parallels are straight lines, the other meridians are curved. To ensure that the resulting map looks correct, it uses lookup tables rather than analytical expressions.
centralMeridian: 0
→ centralMeridian defines that the central meridian should be set at 0 °.

options
width: 16
→ width defines that the width of the plot should be 16 cm.
height: ---
→ height defines that the height of the plot given in centimetre should not be further specified.
titleFontSize: 12
→ titleFontSize defines that the fontsize of the title should be 12 points.
marginTitle: 0.4
→ marginTitle defines that the space between the figure title should be 0.4 cm.
drawGridOnTop: no
→ drawGridOnTop defines that no grid lines should be drawn above all other lines and points.
options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels.
options: MAP_ANNOT_OFFSET_PRIMARY=0.1c
→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.
options: FONT_LABEL=10p
→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.
options: MAP_LABEL_OFFSET=0.1c
→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.
options: FONT_ANNOT_SECONDARY=10p
→ options defines that the font for a secondary time axis should be 10 points.
transparent: no
→ transparent defines that the background of the plot should not be transparent.
dpi = 300
→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.
removeFiles: yes
→ removeFiles defines that the .gmt and script files should be removed after the computation.
viewPlot: yes
→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotMap generates a global map for July 2010. This map represents the first release of the monthly computed removal correction. The removal correction is expressed in terms of equivalent water height values, which are indicated in the unit of centimetre. Hence, the map visualizes the size of the forward modelled equivalent water height values that has to be removed from the GRACE signal. By subtracting the respective size from the GRACE signal, the impact, that the prevailing water body has on the processed equivalent water height values, which were derived from GRACE observations, can be removed. Hence, the GRACE signal can be corrected. Consequently, this map functions as an indicator which shows how strong each water body actually influences the mass change observed by GRACE in 07/2010. This information is extremely helpful to make the estimates of GRACE more consistent with the output from hydrological models for this respective month.

24 GroupPrograms

Goal:

The goal is to run the individually defined programs in a group.

Parameters:

outputfileLog: ---
→ outpufileLog defines that no additional log file should be created.

silently: no
→ silently defines that the output should be shown.

24.1 GriddedData2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of area mean values from a series of grid files for an area which is located on the north eastern border of lake Huron and thus close to the Great Lakes.

Parameters:

outputfileTimeSeries: data/TimeSeries/RECOG-LR_TimeSeries_GreatLakes_45N_-84E.txt
→ outputfileTimeSeries defines the path and the filename of the time series removal correction output file with focus on an area close to the Great Lakes.

inputfileGriddedData [loop= loopTime]: data/Grids/GriddedGravityfield/{listName}/{listName}_FM_{loopTime}_masked.txt
→ inputfileGriddedData defines the path and the filename of the forward modelled gridded gravity input file over which should be looped.

border
<u>border: rectangle</u> → border defines that a rectangular region should be extracted from the global grid. Hence, the rectangular region is restricted along the lines of geographical coordinates. <u>minLambda: - 84.5</u> → minLambda defines that the minimum degree of longitude should be - 84.5 °.

<u>maxLambda: - 83.5</u>
→ maxLambda defines that the maximum degree of longitude should be - 83.5 °.
<u>minPhi: 44.5</u>
→ minPhi defines that the minimum degree of latitude should be 44.5 °.
<u>maxPhi: 45.5</u>
→ maxPhi defines that the maximum degree of longitude should be 45.5 °.
<u>exclude: no</u>
→ exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: no
→ removeMean defines that the temporal mean of the time series should not be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

Result:

The function GriddedData2AreaMeanTimeSeries generates one .txt file for an area which is located on the north eastern border of lake Huron and thus close to the Great Lakes. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the gravity field is expressed in terms of an averaged and forward modelled equivalent water height value. The unit of this equivalent water height value is metre.

24.2 GriddedData2AreaMeanTimeSeries

Goal:

The goal is to compute a time series of area mean values from a series of grid files for an area which is located on the south western border of the Caspian Sea.

Parameters:

outputfileTimeSeries: data/TimeSeries/RECOG-LR_TimeSeries_CaspianSea_41N_49E.txt
→ outputfileTimeSeries defines the path and the filename of the time series removal correction output file with focus on an area close to the Caspian Sea.

inputfileGriddedData [loop= loopTime]: data/Grids/GriddedGravityfield/{listName}/{listName}_FM_{loopTime}_masked.txt
→ inputfileGriddedData defines the path and the filename of the forward modelled gridded gravity input file over which should be looped.

border
border: rectangle → border defines that a rectangular region should be extracted from the global grid. Hence, the rectangular region is restricted along the lines of geographical coordinates. minLambda: 48.5 → minLambda defines that the minimum degree of longitude should be 48.5 °. maxLambda: 49.5 → maxLambda defines that the maximum degree of longitude should be 49.5 °. minPhi: 40.5 → minPhi defines that the minimum degree of latitude should be 40.5 °. maxPhi: 41.5 → maxPhi defines that the maximum degree of longitude should be 41.5 °. exclude: no → exclude defines that no points within the polygon should be dismissed.

timeSeries: Θ timeFrame [= monthly]
→ timeSeries defines that the loop should be called for every month within the time frame of 01/2003 to 12/2016.

multiplyWithArea: no
→ multiplyWithArea defines that the time series should not be multiplied with the total area.

removeMean: no
→ removeMean defines that the temporal mean of the time series should not be removed. To remove the mean values does not only create uniformity, but it also allows to easily determine the relative changes.

computeRms: no
→ computeRms defines that no additional root mean square should not be computed at each time step.

Result:

The function GriddedData2AreaMeanTimeSeries generates one .txt file for an area which is located on the south western border of the Caspian Sea. This .txt file contains two columns, being time [mjd] and data0. Hence, the first column contains one modified julian date for each month within the time span from 01/2003 to 12/2016. Thus, there are 168 rows in total. For each month, the value of the gravity field is expressed in terms of an averaged and forward modelled equivalent water height value. The unit of this equivalent water height value is metre.

24.3 PlotGraph

Goal:

The goal is to generate a two-dimensional plot which visualizes the influence of the Leakage effect on two selected areas which are located close to the Great Lakes and the Caspian Sea in the time frame from 01/2003 to 12/2016.

Parameters:

outputfile: data/Graphs/{listName}/GreatLakes_CaspianSea.png
→ outputfile defines the path and the filename of the generated graph.

title: Removal correction time series for areas close to Great Lakes and Caspian Sea
→ title defines the title of the graph which should be displayed on the graph.

layer
layer: linesAndPoints → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. inputfileMatrix: data/TimeSeries/RECOG-LR_TimeSeries_GreatLakes_45N_-84E.txt → inputfileMatrix defines the path and the filename of the time series removal correction input file with focus on an area close to the Great Lakes. valueX: data0 → valueX defines that the x-values should be the monthly modified julian date. valueY: data1*100 → valueY defines that data1, which contains the forward modelled gridded equivalent water height values, which express the gravity field close to the Great Lakes, should be displayed on the y-axis. To change the unit of the forward modelled equivalent water height values from metre to centimetre, data1 is multiplied with 100. valueZ: --- → valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar. valueErrorBar: --- → valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar. description: Great Lakes (45N, -84E) → description defines that the text of the legend should be "Great Lakes (45N, -84E)". line: solid → line defines that the line style of the corrected equivalent water height values should be solid.

width: 1
→ width defines that the width of the equivalent water height value line should be 1 point.
color: red
→ color defines that the colour of the equivalent water height value line should be red.
symbol: <none>
→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.
plotOnSecondAxis: no
→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

layer
layer: linesAndPoints
→ layer defines the content of the map. Hence, a line and / or points of xy data should be plotted.
inputfileMatrix: data/TimeSeries/RECOG-LR_TimeSeries_CaspianSea_41N_49E.txt
→ inputfileMatrix defines the path and the filename of the time series removal correction input file with focus on an area close to the Caspian Sea.
valueX: data0
→ valueX defines that the x-values should be the monthly modified julian date.
valueY: data1*100
→ valueY defines that data1, which contains the forward modelled gridded equivalent water height values, which express the gravity field close to the Great Lakes, should be displayed on the y-axis. To change the unit of the forward modelled equivalent water height values from metre to centimetre, data1 is multiplied with 100.
valueZ: ---
→ valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar.
valueErrorBar: ---
→ valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar.
description: Caspian Sea (41N, 49E)
→ description defines that the text of the legend should be "Caspian Sea (41N, 49E)".
line: solid

→ line defines that the line style of the corrected equivalent water height values should be solid.
width: 1
→ width defines that the width of the equivalent water height value line should be 1 point.
color: black
→ color defines that the colour of the equivalent water height value line should be black.
symbol: <none>
→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.
plotOnSecondAxis: no
→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

axisX
axisX: time
→ axisX defines the style of the x-axis of the graph. In this case, the input data are interpreted as modified julian date.
min: ---
→ min defines that there is no specified minimum value of the x-axis. Hence, the minimum scale value is set automatically.
max: ---
→ max defines that there is no specified maximum value of the x-axis. Hence, the maximum scale value is set automatically.
majorTickSpacing: 2Y
→ majorTickSpacing defines that the boundary annotation of the x-axis should be set every second year.
minorTickSpacing: 1Y
→ minorTickSpacing defines that the spacing of the frame tick intervals on the x-axis should be set every year.
gridLineSpacing: 1Y
→ gridLineSpacing defines that that the spacing of the grid lines on the x-axis should be set every year.
secondary: <none>
→ secondary defines that no additional time axis should be established.

color: black

→ color defines that the colour of the x-axis should be black.

gridline: solid

→ gridline defines that the style of the grid lines should be solid.

width: 0.25

→ width defines that the width of the grid lines should be 0.25 points.

color: black

→ color defines that the colour of the grid lines should be black.

changeDirection: no

→ changeDirection defines that the direction of the x-axis should not be changed from right / up to left / down.

options: FORMAT_DATE_MAP=yyyy-mm-dd

→ options defines that the output data string should be given in the format year-month-day.

options: FORMAT_CLOCK_MAP=hh:mm

→ options defines that the output clock string should be given in the format hour-minute.

options: TIME_EPOCH=1858-11-17T00:00:00

→ options defines the value of the calendar and the clock at the origin (0 point) of relative time units.

options: TIME_UNIT=d

→ options defines that the units of the relative time data since the TIME_EPOCH should be daily.

axisY

axisY: standard

→ axisY defines the style of the y-axis of the graph. In this case, the input data should be interpreted as arbitrary input data.

min: - 40

→ min defines that the minimum value of the y-axis should be set to - 40.

max: 35

→ max defines that the maximum value of the y-axis should be set to 35.

majorTickSpacing: 8

→ majorTickSpacing defines that the boundary annotation of the y-axis should be set every 8. Hence, it is set for every 8 m of equivalent water height.

minorTickSpacing: 1 → minorTickSpacing defines that the spacing of the frame tick intervals on the y-axis should be set every 1. Hence, it is set for every 1 m of equivalent water height. gridLineSpacing: --- → gridLineSpacing defines that the spacing of the grid lines on the y-axis should not be further specified. gridline: solid → gridline defines that the style of the grid lines should be solid. width: 0.25 → width defines that the width of the grid lines should be 0.25 points. color: gray → color defines that the colour of the grid lines should be gray. unit: --- → unit defines that the no unit name should be appended to the y-axis values. Label: EWH [m] → label defines that the description of the y-axis should be "EWH [cm]". logarithmic: no → logarithmic defines that no logarithmic scale should be used. color: black → color defines that the colour of the bars and labels of the y-axis should be black. changeDirection: no → changeDirection defines that the direction of the x-axis should not be changed from right / up to left / down.

axisY2: <none>
→ axisY2 defines that no second Y-axis should be plotted.

colorbar: <none>
→ colorbar defines that no colour bar should be plotted.

legend
legend: <enabled>

→ legend defines that a legend with descriptions should be plotted.
width: 10
→ width defines that length of the legend should be 10 cm.
height: ---
→ height defines that the height of the plot given in centimetre should not be further specified.
positionX: 1.05
→ positionX defines that the x-position of the legend should be 1.05.
positionY: 1.0 [= 1]
→ positionY defines that the y-position of the legend should be 1.0.
anchorPoint: TL
→ anchorPoint defines that the anchor point should be located at the top left. Hence, the anchor point is the point where the related edges link to.
columns: 1
→ columns defines that the legend should consist of one column.
textColor: <none>
→ textColor defines that there is no specified colour of the text of the legend.
fillColor: <none>
→ fillColor defines that there is no specified colour with which the box of the legend should be filled.
edgeLine: <none>
→ edgeLine defines that there is no specified style of the edge of the box of the legend.

options
width: 12
→ width defines that the width of the plot should be 12 cm.
height: 7
→ height defines that height of the plot should be 7 cm.
titleFontSize: 12
→ titleFontSize defines that the fontsize of the title should be 12 points.
marginTitle: 0.4
→ marginTitle defines that the space between the figure title should be 0.4 cm.
drawGridOnTop: no

→ drawGridOnTop defines that no grid lines should be drawn above all other lines and points.

options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels.

options: MAP_ANNOT_OFFSET_PRIMARY=0.1c

→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.

options: FONT_LABEL=10p

→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.

options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

options: TIME_SYSTEM=MJD

→ options defines that the relative time should refer to the modified julian date.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotGraph generates one graph which illustrates the temporal variation of the equivalent water height values of an area which is located close to the Great Lakes and another area which is located close to the Caspian Sea. The x-axis indicates the year and reaches from 01/2003 to 12/2016. Meanwhile, the y-axis indicates the equivalent water height values in the unit of centimetre. In total, there are two curves. The first curve represents the forward modelled equivalent water height values for the area which is located close to the Great Lakes. The second curve illustrates the forward modelled equivalent water height values for the area which is located close to the Caspian Sea. These forward modelled equivalent water height values express the gravity field and function as removal correction. Since both selected areas are located close to the respective water body, they are situated on the landside and hence, they are also effected by the Leakage effect. The Leakage effect occurs whenever the signal is filtered. By means of that, filtering always implies a spatial averaging of the signal which then leads to a smearing effect and thus also to a loss of signal information. Consequently, the spatial resolution decreases (Tripathi et al., 2022). Thus, the signal from the Great Lakes and from the Caspian Sea is also smeared out and hence, it also effects the neighbouring grid cells on the landside. Consequently, the equivalent water height values within those neighbouring grid cells and thus also the estimated mass change, are falsified. Since the graph refers to the forward modelled equivalent water height values, which were only computed for the prevailing water bodies, an area outside a water body, should technique indicate equivalent water height values of zero. However, due to the Leakage effect, the equivalent water height values are not zero for areas close to a water body. How strong the influence of the Leakage effect is and with what magnitude this effect is associated, is represented by the two curves which are illustrated in this graph.

24.4 PlotGraph

Goal:

The goal is to generate a two-dimensional plot which visualizes the influence of the Leakage effect on a selected area located close to the Great Lakes in the time frame from 01/2003 to 12/2016.

Parameters:

outputfile: data/Graphs/{listName}/RemovalTimeSeriesGreatLakes.png
→ outputfile defines the path and the filename of the generated graph.

title: Removal correction time series for areas close to Great Lakes
→ title defines the title of the graph which should be displayed on the graph.

layer
<u>layer: linesAndPoints</u> → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. <u>inputfileMatrix: data/TimeSeries/RECOG-LR_TimeSeries_GreatLakes_45N_-84E.txt</u>

→ inputfileMatrix defines the path and the filename of the time series removal correction input file with focus on an area close to the Great Lakes.

valueX: data0

→ valueX defines that the x-values should be the monthly modified julian date.

valueY: data1*100

→ valueY defines that data1, which contains the forward modelled gridded equivalent water height values, which express the gravity field close to the Great Lakes, should be displayed on the y-axis. To change the unit of the forward modelled equivalent water height values from metre to centimetre, data1 is multiplied with 100.

valueZ: ---

→ valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar.

valueErrorBar: ---

→ valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar.

description: Great Lakes (45N, -84E)

→ description defines that the text of the legend should be "Great Lakes (45N, -84E)".

line: solid

→ line defines that the line style of the corrected equivalent water height values should be solid.

width: 1

→ width defines that the width of the equivalent water height value line should be 1 point.

color: black

→ color defines that the colour of the equivalent water height value line should be black.

symbol: <none>

→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.

plotOnSecondAxis: no

→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

axisX
<u>axisX: time</u> → axisX defines the style of the x-axis of the graph. In this case, the input data are interpreted as modified julian date. <u>min: ---</u> → min defines that there is no specified minimum value of the x-axis. Hence, the minimum scale value is set automatically. <u>max: ---</u> → max defines that there is no specified maximum value of the x-axis. Hence, the maximum scale value is set automatically. <u>majorTickSpacing: 2Y</u> → majorTickSpacing defines that the boundary annotation of the x-axis should be set every second year. <u>minorTickSpacing: 1Y</u> → minorTickSpacing defines that the spacing of the frame tick intervals on the x-axis should be set every year. <u>gridLineSpacing: 1Y</u> → gridLineSpacing defines that that the spacing of the grid lines on the x-axis should be set every year. <u>secondary: <none></u> → secondary defines that no additional time axis should be established. <u>color: black</u> → color defines that the colour of the x-axis should be black. <u>gridline: solid</u> → gridline defines that the style of the grid lines should be solid. <u>width: 0.25</u> → width defines that the width of the grid lines should be 0.25 points. <u>color: gray</u> → color defines that the colour of the grid lines should be gray. <u>changeDirection: no</u> → changeDirection defines that the direction of the x-axis should not be changed from right / up to left / down. <u>options: FORMAT_DATE_MAP=yyyy-mm-dd</u>

→ options defines that the output data string should be given in the format year-month-day. options: FORMAT_CLOCK_MAP=hh:mm → options defines that the output clock string should be given in the format hour-minute. options: TIME_EPOCH=1858-11-17T00:00:00 → options defines the value of the calendar and the clock at the origin (0 point) of relative time units. options: TIME_UNIT=d → options defines that the units of the relative time data since the TIME_EPOCH should be daily.

axisY
axisY: standard → axisY defines the style of the y-axis of the graph. In this case, the input data should be interpreted as arbitrary input data. min: - 40 → min defines that the minimum value of the y-axis should be set to - 40. max: 35 → max defines that the maximum value of the y-axis should be set to 35. majorTickSpacing: 8 → majorTickSpacing defines that the boundary annotation of the y-axis should be set every 8. Hence, it is set for every 8 m of equivalent water height. minorTickSpacing: 1 → minorTickSpacing defines that the spacing of the frame tick intervals on the y-axis should be set every 1. Hence, it is set for every 1 m of equivalent water height. gridLineSpacing: --- → gridLineSpacing defines that the spacing of the grid lines on the y-axis should not be further specified. gridline: solid → gridline defines that the style of the grid lines should be solid. width: 0.25 → width defines that the width of the grid lines should be 0.25 points. color: gray → color defines that the colour of the grid lines should be gray.

unit: ---

→ unit defines that the no unit name should be appended to the y-axis values.

Label: EWH [cm]

→ label defines that the description of the y-axis should be “EWH [cm]”.

logarithmic: no

→ logarithmic defines that no logarithmic scale should be used.

color: black

→ color defines that the colour of the bars and labels of the y-axis should be black.

changeDirection: no

→ changeDirection defines that the direction of the x-axis should not be changed from right / up to left / down.

axisY2: <none>

→ axisY2 defines that no second Y-axis should be plotted.

colorbar: <none>

→ colorbar defines that no colour bar should be plotted.

legend

legend: <enabled>

→ legend defines that a legend with descriptions should be plotted.

width: 10

→ width defines that length of the legend should be 10 cm.

height: ---

→ height defines that the height of the plot given in centimetre should not be further specified.

positionX: 1.05

→ positionX defines that the x-position of the legend should be 1.05.

positionY: 1.0 [= 1]

→ positionY defines that the y-position of the legend should be 1.0.

anchorPoint: TL

→ anchorPoint defines that the anchor point should be located at the top left. Hence, the anchor point is the point where the related edges link to.

columns: 1

→ columns defines that the legend should consist of one column.

textColor: <none>

→ textColor defines that there is no specified colour of the text of the legend.

fillColor: <none>

→ fillColor defines that there is no specified colour with which the box of the legend should be filled.

edgeLine: <none>

→ edgeLine defines that there is no specified style of the edge of the box of the legend.

options

width: 12

→ width defines that the width of the plot should be 12 cm.

height: 7

→ height defines that height of the plot should be 7 cm.

titleFontSize: 12

→ titleFontSize defines that the fontsize of the title should be 12 points.

marginTitle: 0.4

→ marginTitle defines that the space between the figure title should be 0.4 cm.

drawGridOnTop: no

→ drawGridOnTop defines that no grid lines should be drawn above all other lines and points.

options: FONT_ANNOT_PRIMARY=10p

→ options defines that the font which is used for primary annotations should be 10 pixels.

options: MAP_ANNOT_OFFSET_PRIMARY=0.1c

→ options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm.

options: FONT_LABEL=10p

→ options defines that the font, which is used to plot the labels below the annotation, should be 10 points.

options: MAP_LABEL_OFFSET=0.1c

→ options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm.

options: FONT_ANNOT_SECONDARY=10p

→ options defines that the font for a secondary time axis should be 10 points.

options: TIME_SYSTEM=MJD

→ options defines that the relative time should refer to the modified julian date.

transparent: no

→ transparent defines that the background of the plot should not be transparent.

dpi = 300

→ dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

removeFiles: yes

→ removeFiles defines that the .gmt and script files should be removed after the computation.

viewPlot: yes

→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotGraph generates one graph which illustrates the temporal variation of the equivalent water height values of an area which is located close to the Great Lakes. The x-axis indicates the year and reaches from 01/2003 to 12/2016. Meanwhile, the y-axis indicates the equivalent water height values in the unit of centimetre. The curve represents the forward modelled equivalent water height values for an area which is located close to the Great Lakes. These forward modelled equivalent water height values express the gravity field and function as removal correction. Since the selected area is located close to the respective water body, it is situated on the landside and hence, it is also effected by the Leakage effect. The Leakage effect occurs whenever the signal is filtered. By means of that, filtering always implies a spatial averaging of the signal which then leads to a smearing effect and thus also to a loss of signal information. Consequently, the spatial resolution decreases (Tripathi et al., 2022). Thus, the signal from the Great Lakes is also smeared out and hence, it also effects the neighbouring grid cells on the landside. Consequently, the equivalent water height values within those neighbouring grid cells and thus also the estimated mass change, are falsified. Since the graph refers to the forward modelled equivalent water height values, which were only computed for the prevailing water bodies, an area outside a water body, should technique indicate equivalent water height values of zero. However, due to the Leakage effect, the equivalent water height values are not zero for an area close to a water body. How strong the influence of the Leakage effect is close to the Great Lakes and with what magnitude this effect is associated, is represented by the curve which is illustrated in this graph.

24.5 PlotGraph

Goal:

The goal is to generate a two-dimensional plot which visualizes the influence of the Leakage effect on a selected area located close to the Caspian Sea in the time frame from 01/2003 to 12/2016.

Parameters:

outputfile: data/Graphs/{listName}/RemovalTimeSeriesCaspianSea.png
→ outputfile defines the path and the filename of the generated graph.

title: Removal correction time series for areas close to Caspian Sea
→ title defines the title of the graph which should be displayed on the graph.

layer
<u>layer: linesAndPoints</u> → layer defines the content of the map. Hence, a line and / or points of xy data should be plotted. <u>inputfileMatrix: data/TimeSeries/RECOG-LR_TimeSeries_CaspianSea_41N_49E.txt</u> → inputfileMatrix defines the path and the filename of the time series removal correction input file with focus on an area close to the Caspian Sea. <u>valueX: data0</u> → valueX defines that the x-values should be the monthly modified julian date. <u>valueY: data1*100</u> → valueY defines that data1, which contains the forward modelled gridded equivalent water height values, which express the gravity field close to the Caspian Sea, should be displayed on the y-axis. To change the unit of the forward modelled equivalent water height values from metre to centimetre, data1 is multiplied with 100. <u>valueZ: ---</u> → valueZ defines that there should be no expression for the colour bar. This can be related to the fact that the graph does not contain any colour bar.

valueErrorBar: ---
→ valueErrorBar defines that there should be no expression for the error bars. This can be related to the fact that the graph does not contain any valueErrorBar.
description: Caspian Sea (41N, 49E)
→ description defines that the text of the legend should be "Caspian Sea (41N, 49E)".
line: solid
→ line defines that the line style of the corrected equivalent water height values should be solid.
width: 1
→ width defines that the width of the equivalent water height value line should be 1 point.
color: black
→ color defines that the colour of the equivalent water height value line should be black.
symbol: <none>
→ symbol defines that each data point should not be visualized by a symbol such as a circle or a star.
plotOnSecondAxis: no
→ plotOnSecondAxis defines that no additional dataset should be drawn on a second Y-axis.

axisX
axisX: time
→ axisX defines the style of the x-axis of the graph. In this case, the input data are interpreted as modified julian date.
min: ---
→ min defines that there is no specified minimum value of the x-axis. Hence, the minimum scale value is set automatically.
max: ---
→ max defines that there is no specified maximum value of the x-axis. Hence, the maximum scale value is set automatically.
majorTickSpacing: 2Y
→ majorTickSpacing defines that the boundary annotation of the x-axis should be set every second year.
minorTickSpacing: 1Y

→ minorTickSpacing defines that the spacing of the frame tick intervals on the x-axis should be set every year.

gridLineSpacing: 1Y

→ gridLineSpacing defines that that the spacing of the grid lines on the x-axis should be set every year.

secondary: <none>

→ secondary defines that no additional time axis should be established.

color: black

→ color defines that the colour of the x-axis should be black.

gridline: solid

→ gridline defines that the style of the grid lines should be solid.

width: 0.25

→ width defines that the width of the grid lines should be 0.25 points.

color: gray

→ color defines that the colour of the grid lines should be gray.

changeDirection: no

→ changeDirection defines that the direction of the x-axis should not be changed from right / up to left / down.

options: FORMAT_DATE_MAP=yyyy-mm-dd

→ options defines that the output data string should be given in the format year-month-day.

options: FORMAT_CLOCK_MAP=hh:mm

→ options defines that the output clock string should be given in the format hour-minute.

options: TIME_EPOCH=1858-11-17T00:00:00

→ options defines the value of the calendar and the clock at the origin (0 point) of relative time units.

options: TIME_UNIT=d

→ options defines that the units of the relative time data since the TIME_EPOCH should be daily.

axisY
<u>axisY: standard</u> → axisY defines the style of the y-axis of the graph. In this case, the input data should be interpreted as arbitrary input data. <u>min: - 40</u> → min defines that the minimum value of the y-axis should be set to - 40. <u>max: 35</u> → max defines that the maximum value of the y-axis should be set to 35. <u>majorTickSpacing: 8</u> → majorTickSpacing defines that the boundary annotation of the y-axis should be set every 8. Hence, it is set for every 8 m of equivalent water height. <u>minorTickSpacing: 1</u> → minorTickSpacing defines that the spacing of the frame tick intervals on the y-axis should be set every 1. Hence, it is set for every 1 m of equivalent water height. <u>gridLineSpacing: ---</u> → gridLineSpacing defines that the spacing of the grid lines on the y-axis should not be further specified. <u>gridline: solid</u> → gridline defines that the style of the grid lines should be solid. <u>width: 0.25</u> → width defines that the width of the grid lines should be 0.25 points. <u>color: gray</u> → color defines that the colour of the grid lines should be gray. <u>unit: ---</u> → unit defines that the no unit name should be appended to the y-axis values. <u>Label: EWH [cm]</u> → label defines that the description of the y-axis should be “EWH [cm]”. <u>logarithmic: no</u> → logarithmic defines that no logarithmic scale should be used. <u>color: black</u> → color defines that the colour of the bars and labels of the y-axis should be black. <u>changeDirection: no</u>

→ changeDirection defines that the direction of the x-axis should not be changed from right / up to left / down.

axisY2: <none>
→ axisY2 defines that no second Y-axis should be plotted.

colorbar: <none>
→ colorbar defines that no colour bar should be plotted.

legend
legend: <enabled> → legend defines that a legend with descriptions should be plotted. width: 10 → width defines that length of the legend should be 10 cm. height: --- → height defines that the height of the plot given in centimetre should not be further specified. positionX: 1.05 → positionX defines that the x-position of the legend should be 1.05. positionY: 1.0 [= 1] → positionY defines that the y-position of the legend should be 1.0. anchorPoint: TL → anchorPoint defines that the anchor point should be located at the top left. Hence, the anchor point is the point where the related edges link to. columns: 1 → columns defines that the legend should consist of one column. textColor: <none> → textColor defines that there is no specified colour of the text of the legend. fillColor: <none> → fillColor defines that there is no specified colour with which the box of the legend should be filled. edgeLine: <none>

→ edgeLine defines that there is no specified style of the edge of the box of the legend.

options
width: 12 → width defines that the width of the plot should be 12 cm. height: 7 → height defines that height of the plot should be 7 cm. titleFontSize: 12 → titleFontSize defines that the fontsize of the title should be 12 points. marginTitle: 0.4 → marginTitle defines that the space between the figure title should be 0.4 cm. drawGridOnTop: no → drawGridOnTop defines that no grid lines should be drawn above all other lines and points. options: FONT_ANNOT_PRIMARY=10p → options defines that the font which is used for primary annotations should be 10 pixels. options: MAP_ANNOT_OFFSET_PRIMARY=0.1c → options defines that the distance from the end of the tick-mark to the start of the annotation should be 0.1 cm. options: FONT_LABEL=10p → options defines that the font, which is used to plot the labels below the annotation, should be 10 points. options: MAP_LABEL_OFFSET=0.1c → options defines that the distance between the base of the axis annotations and the top of the axis label should be 0.1 cm. options: FONT_ANNOT_SECONDARY=10p → options defines that the font for a secondary time axis should be 10 points. options: TIME_SYSTEM=MJD → options defines that the relative time should refer to the modified julian date. transparent: no → transparent defines that the background of the plot should not be transparent. dpi = 300 → dpi defines that resolution when rasterizing the postscript file should be 300 dots per inch.

<u>removeFiles: yes</u>
→ removeFiles defines that the .gmt and script files should be removed after the computation.
<u>viewPlot: yes</u>
→ viewPlot defines that the plot should be automatically shown after the computation.

Result:

The function PlotGraph generates one graph which illustrates the temporal variation of the equivalent water height values of an area which is located close to the Caspian Sea. The x-axis indicates the year and reaches from 01/2003 to 12/2016. Meanwhile, the y-axis indicates the equivalent water height values in the unit of centimetre. The curve represents the forward modelled equivalent water height values for an area which is located close to the Caspian Sea. These forward modelled equivalent water height values express the gravity field and function as removal correction. Since the selected area is located close to the respective water body, it is situated on the landside and hence, it is also effected by the Leakage effect. The Leakage effect occurs whenever the signal is filtered. By means of that, filtering always implies a spatial averaging of the signal which then leads to a smearing effect and thus also to a loss of signal information. Consequently, the spatial resolution decreases (Tripathi et al., 2022). Thus, the signal from the Caspian Sea is also smeared out and hence, it also effects the neighbouring grid cells on the landside. Consequently, the equivalent water height values within those neighbouring grid cells and thus also the estimated mass change, are falsified. Since the graph refers to the forward modelled equivalent water height values, which were only computed for the prevailing water bodies, an area outside a water body, should technique indicate equivalent water height values of zero. However, due to the Leakage effect, the equivalent water height values are not zero for an area close to a water body. How strong the influence of the Leakage effect is close to the Caspian Sea and with what magnitude this effect is associated, is represented by the curve which is illustrated in this graph.

25 Bibliography for the reference manual

Dawber, J., Salvati, N., Schmid, T., & Tzavidis, N. (2011). Scale estimation and data-driven tuning constant selection for M-quantile regression. Retrieved from https://doi.org/10.1111/insr.12267, last accssed on 04.08.2023.

House, D. (2014). Chapter 14 Spline Curves. 3D computer Graphics: Course Notes, p. 88. Retrieved.from.https://people.computing.clemson.edu/~dhouse/courses/405/notes/splines.pdf, last accessed on 04.08.2023.

Kusche, J., Schmidt, R., Petrovic, S., Rietbroek, R. (2009). Decorrelated GRACE time-variable gravity solutions by GFZ, and their validation using a hydrological model. Journal of Geodesy, pp. 903-913. Retrieved from https://link.springer.com/article/10.1007/s00190-009-0308-3, last accessed on 04.08.2023.

Mayer-Gürr, T., Behzadpour, S., Eicker, A., Ellmer, M., Koch, B., Krauss, S., Pock, C., Rieser, D., Strasser, S., Süsser-Rechberger, B., Zehentner, N., Kvas, A. (n.d.). GROOPS Documentation and Cookbook.

Rexer, M. (2012). Time-Variable Gravity Field: Contributions of GOCE Gradiometer Data to Monthly and Bi-Monthly GRACE Gravity Field Estimates. Technische Universität München: Master Thesis, p. 24. Retrieved from https://mediatum.ub.tum.de/doc/1369027/622207.pdf, last accsessed on 04.08.2023.

Tripathi, V., Groh, A., Horwath, M., Ramsankaran, R. (2022). Scaling methods of leakage correction in GRACE mass change estimates revisited for the complex hydro-climatic setting of the Indus Basin. Hydrology and Earth System Sciences: Volume 26, Issue 17, pp. 4515-4535. Retrieved from https://doi.org/10.5194/hess-26-4515-2022, last accessed on 04.08.2023.

Annika L. Walter wurde für ihre Masterarbeit, die sie an der HafenCity Universität Hamburg verfasst hat, mit dem DHyG Student Excellence Award 2024 ausgezeichnet.

Die Arbeit beschäftigt sich mit der Ableitung von Wasservolumen in global verteilten Binnengewässern. In diesem Zusammenhang wurden Satellitenaltimetriedaten zur Messung der Wasserhöhenänderungen und Verfahren der Fernerkundung zur Bestimmung der Oberflächenausdehnung miteinander kombiniert. Infolgedessen wurde untersucht, ob bei der Berechnung der Volumina die Nutzung einer realistischen zeitvariablen Oberflächenausdehnung bei sich änderndem Wasserstand, gegeben durch die Bathymetrie der Gewässer, im Gegensatz zu der vereinfachten Annahme einer statischen Wasserfläche, eine signifikante Rolle spielt. Aus hydrographischer Sicht besteht die Relevanz des Themas in der quantitativen Bestimmung globaler Süßwasservariationen aus Satellitendaten, welche in Zeiten knapper werdender Wasserressourcen auch eine hohe gesellschaftliche Bedeutung hat.