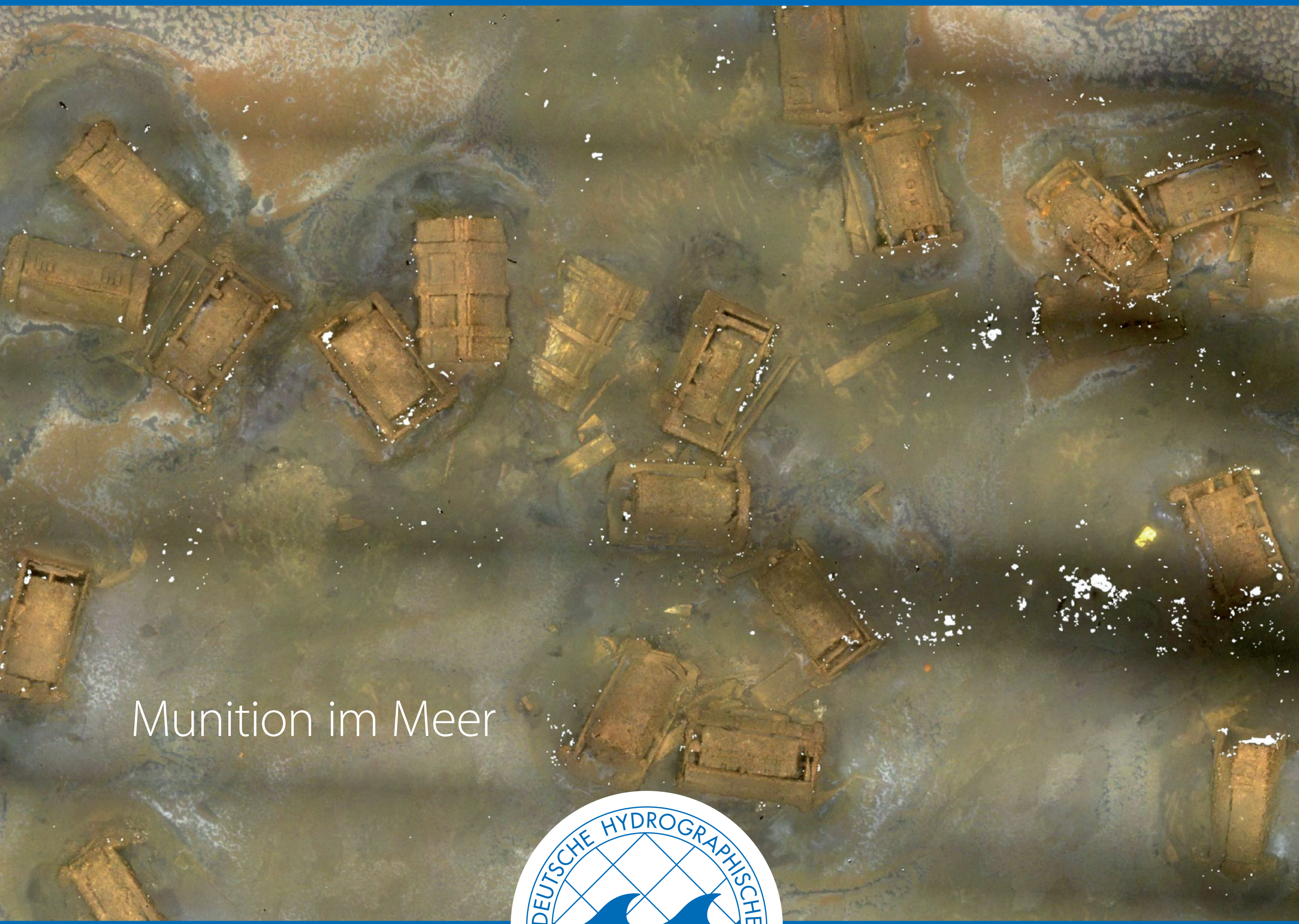
HYDROGRAPHISCHE NACHRICHTEN

Journal of Applied Hydrography 06/2024 HN 128



DOI: 10.23784/HN128-01

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

An article by ANNIKA L. WALTER

The satellite mission Gravity Recovery and Climate Experiment (GRACE) measures gravity field variations caused by mass redistributions across the atmosphere, the continents and the oceans. Since the redistributions over the continents are linked to changes in the total water storage (TWS), expressed as equivalent water heights (EWH), the observations can be used to quantitatively assess global freshwater variations, which is of great social importance in times of increasingly scarce water resources. If the focus of interest refers to groundwater related variations explicitly, all other storage compartments (here: surface waters) have to be reduced from the GRACE observations. Therefore, the retrieved signal has to be decomposed into its individual components. To achieve this, the water volume can be estimated by forward modelling satellite altimetry and remote sensing data, considering both static and dynamic surface expansions. It will be discussed, that using a dynamic instead of a static surface area extent (1) will change the equivalent water height values in a magnitude between 0.006 cm and 0.243 cm, (2) causes the largest deviation for the Lake Mead 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.

surface water bodies | GRACE | dynamic surface area extent | forward modelling | freshwater resources
Oberflächengewässer | GRACE | dynamische Oberflächenausdehnung | Vorwärtsmodellierung | Süßwasserressourcen

Die Satellitenmission Gravity Recovery and Climate Experiment (GRACE) misst Schwerefeldschwankungen, die durch Massenumverteilungen in der Atmosphäre, auf den Kontinenten und in den Ozeanen entstehen. Da die Umverteilung auf den Kontinenten auf Änderungen des Gesamtwasserspeichers (TWS), ausgedrückt als äquivalente Wasserhöhen (EWH), zurückzuführen sind, können die Beobachtungen für die quantitative Bestimmung globaler Süßwasservariationen, welche in Zeiten von knapper werdenden Wasserressourcen eine hohe gesellschaftliche Bedeutung hat, verwendet werden. Liegt der Fokus explizit auf grundwasserbezogenen Veränderungen, dann müssen alle anderen Speicherkomponenten (hier: Oberflächengewässer) aus den GRACE Beobachtungen herausgerechnet werden. Hierfür muss das empfangene Signal in seine einzelnen Komponenten zerlegt werden. Um dies zu erreichen, kann unter Berücksichtigung von sowohl statischen als auch dynamischen Oberflächenausdehnungen eine Schätzung des Wasservolumens durch die Vorwärtsmodellierung von Satellitenaltimetrie- und Fernerkundungsdaten vorgenommen werden. Es wird diskutiert, dass die Verwendung einer dynamischen anstelle von einer statischen Oberflächenausdehnung (1) die äquivalenten Wasserhöhenwerte in einer Größenordnung zwischen 0,006 cm und 0,243 cm verändert, (2) die größte Abweichung für den See Mead verursacht und (3) die Frage, ob eine dynamische oder eine statische Oberflächenausdehnung in Betracht gezogen werden sollte, von der Interaktion verschiedener Parameter bestimmt wird.

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Motivation

In times of increasingly scarce water resources, a profound understanding of the global water cycle and its storage compartments, both key elements of hydrography, has become an essential aspect. To gather such an understanding on a global scale, observations from various satellite missions such as GRACE, which measures the total water storage, play a crucial role. Hence, the respective data can be used to assess mass variations and thus to proportionally track volume variations of different water storage compartments (Swenson, n. d.).

The main difficulty with using GRACE observations is, that GRACE delivers column-integrated total water storage changes. Hence, the hydrology related mass variations are composed by mass variations which are caused by for instance groundwater, soil moisture or surface water bodies such as lakes and reservoirs (Deggim et al. 2021). If the focus of interest refers to ground water related mass variations only, the other impacts have to be removed. This can be done by forward modelling the unwanted mass variations and subtracting them from the initial observations. In the scope of this study, this procedure was conducted for surface water bodies. Since previous studies (Deggim et al. 2021), 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. Therefore, a dynamic surface area extent was introduced.

Data basis

For this study, GRACE data in the form of monthly gravitational field potential coefficients, provided by the TU Graz, were utilised (Kvas et al. 2019). To derive volume variations of surface water bodies under the consideration of a static surface area extent, static polygons derived by remote sensing from the Global WaterPack project (Earth Observation Center, n. d.) and water level time series derived by satellite altimetry from the database for hydrological time series of inland waters (DAHITI) were used (German Geodetic Research Institute, n. d.). By multiplying the area extent derived from the polygon by the mean water level, a volume variation based on a static water body shape was retrieved. This volume variation was then compared to a volume variation time series, considering a time-variable surface water body shape, which was directly provided in DAHITI. Driven by the number of available data sets, finally 29 globally distributed surface water bodies, whose location is depicted in Fig. 1, were analysed in the scope of this study.

Methods

To combine the various input data products with the observations retrieved from GRACE, several steps had to be carried out.

Pre-processing

To match the temporal resolution of the monthly GRACE gravity field models, the water level and the volume variation time series were averaged to monthly mean values. Besides, 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 achieve a better comparability, the time series were reduced by their 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 equivalent water height values, which could then enter the forward modelling procedure.

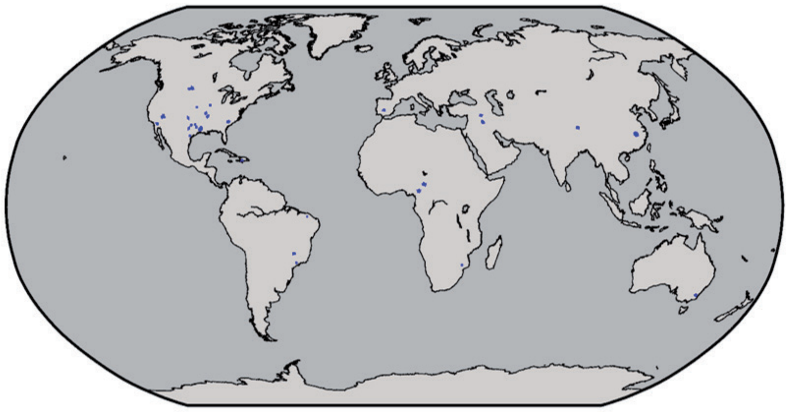

Fig. 1: Map of all 29 considered surface water bodies

Following, the Gravity Recovery Object Oriented Programming System (GROOPS) (Mayer-Gürr et al. 2021) was used to discretise the surface water body shapes on a fine-resolution grid with a cell size of 0.0025° × 0.0025°. As a result, also long and narrow water bodies, which are e.g. 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 derived from the volume variation time series were used. Subsequently, an estimation regarding the temporal variation of the water volume values within each grid cell could be retrieved. To reduce the computation time, the volume values were distributed over a lower resolution grid of 0.5° × 0.5°. As a result, an information about the water level anomaly of each grid cell could be derived. These global water height anomaly values then entered a forward modelling algorithm.

Forward modelling

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. To perform this forward modelling procedure, the gridded water level anomaly values were expanded into spherical harmonic coefficients.

Filtering

The forward modelled spherical harmonic potential coefficients were smoothed by applying the order-convolution DDK3 filter (Kusche et al. 2009).

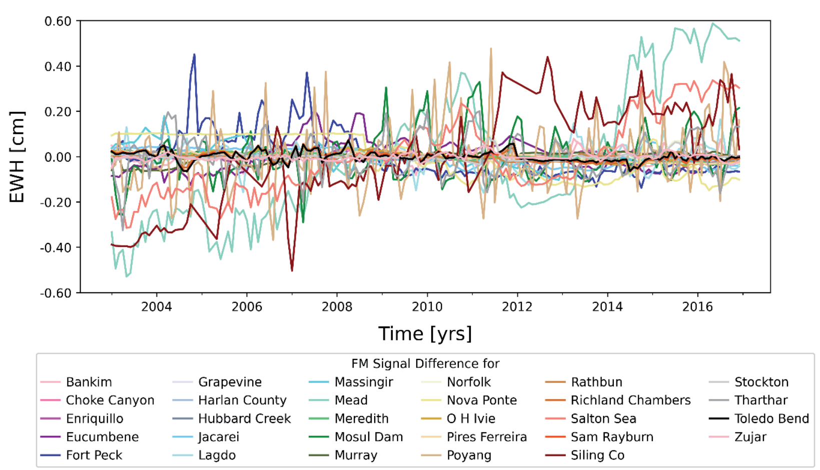

Fig. 2: FM difference EWH based on a dynamic and a static lake shape for all considered water bodies

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 water body. To obtain a grid-based solution, a re-computation had to be performed. As a result, the total water storage for every grid cell could be calculated.

Results

The retrieved results are summarised in Fig. 2, which illustrates the difference in the temporal variation of all forward modelled equivalent water height difference values when using dynamic instead of static water body shapes. Subsequently, it can be seen that all forward modelled equivalent water height difference values indicate a temporal variation between −0.529 cm and 0.588 cm. The largest variations are shown by the green coloured curve, which refers to the equivalent water height difference values which were computed for the Lake Mead.

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 was computed.

The result presented in Fig. 3 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.

Despite of that, Fig. 4 (top) shows the forward modelled signal, i.e. the water surface variations which appear when they are converted to the spatial resolution of GRACE. When assuming that GRACE has an accuracy of 1 cm to 2 cm equivalent water height, it can be seen that only 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, the difference between using a static and a dynamic surface area extent has a noticeable effect. The difference values of the remaining water bodies gather a higher visibility once the scale of the colour bar is adjusted. The result is depicted in Fig. 4 (bottom), which also emphasises that the Lake Mead and the Lake Siling Co experience severe negative differences. Thus, 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 visualised in this 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 blue-coloured positive removal correction. 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 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

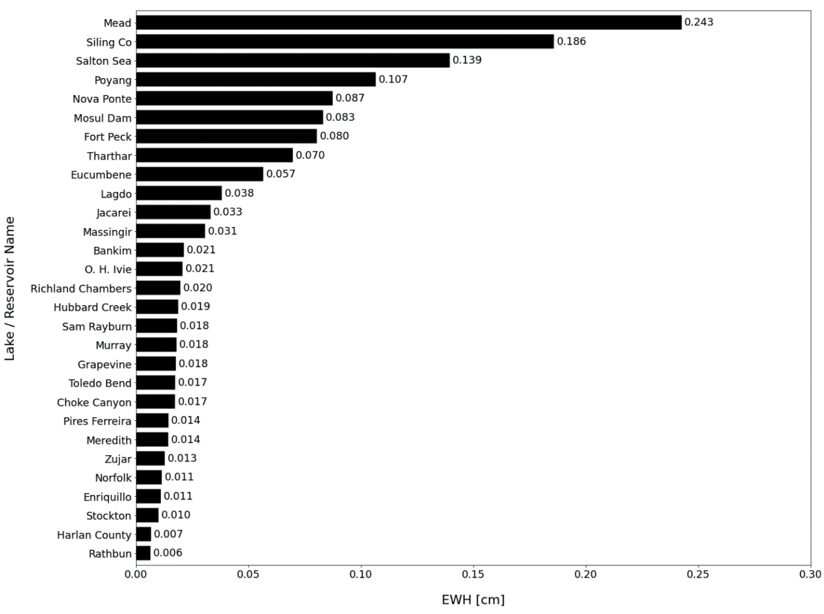

Fig. 3: FM mean EWH difference values for all considered water bodies

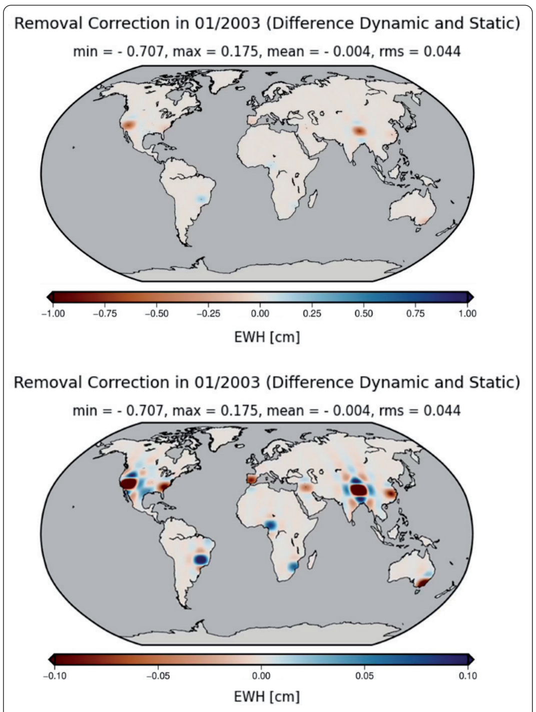

Fig. 4: Removal correction difference in 01/2003 for all considered water bodies [top] and with an adjusted scale of the colour bar [bottom]

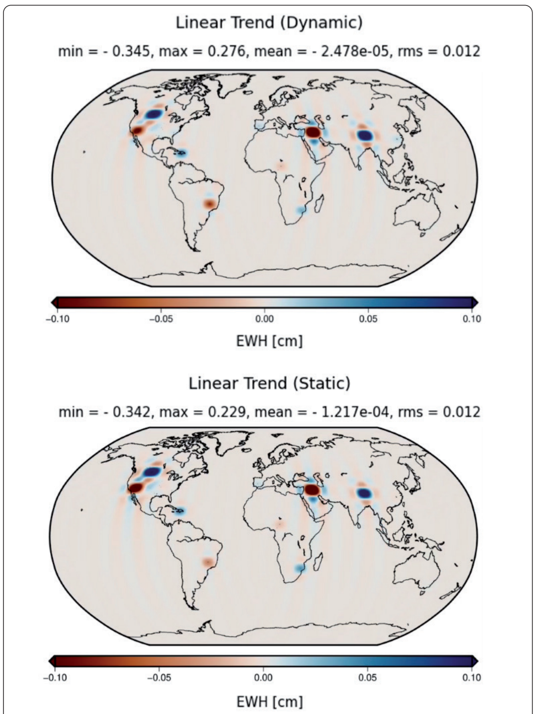

Fig. 5: Linear trend based on a dynamic [top] and a static [bottom] water body shape for all considered water bodies

of the two forward modelled equivalent water height signals were evaluated.

Subsequently, a long-term trend of the forward modelled equivalent water height values over a time frame from 01/2003 to 12/2016 was computed. The results are depicted in Fig. 5.

While the consideration of dynamic water body shapes causes a global trend, which fluctuates between −0.345 cm and 0.276 cm, the consideration of static water body shapes causes the global trend to reach from −0.342 cm to 0.229 cm. Hence, the computed mean value of the trend deviates by −9.692e-5 cm. Thus, the forward modelled equivalent water height values of for example the Lake Mead experience a decline, no matter whether a dynamic or a static water body shape is taken into consideration. Hence, the Lake Mead loses mass. When evaluating the mean values, which are both negative, it can further be said that the water storage decrease overweights the water storage increase. Hence, the majority of the considered water bodies experience a loss of mass within the evaluated time frame. Possible reasons for such a decline are usually attributed to climate change and the related rising temperatures.

The result for the amplitudes of both forward modelled equivalent water height signals is shown in Fig. 6.

Hence, Fig. 6 illustrates, 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

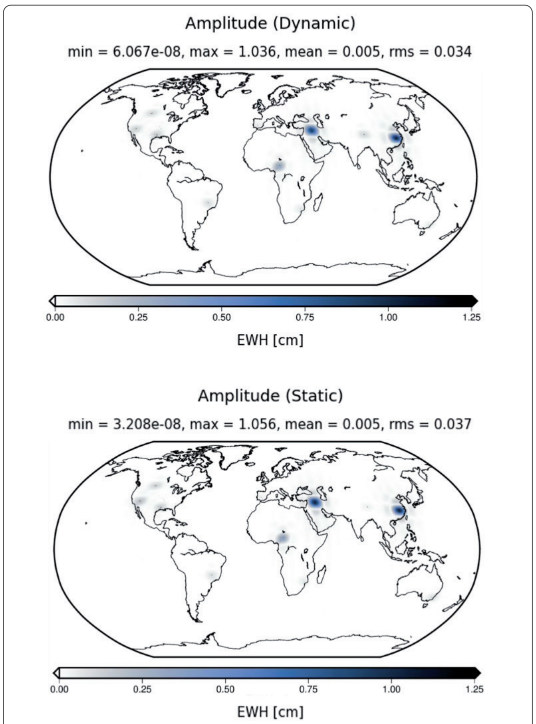

Fig. 6: Amplitude based on a dynamic [top] and a static [bottom] water body shape for all considered water bodies

static water body shapes. Considering the maximum amplitude values, which amount to 1.036 cm and 1.056 cm, it can be seen, that the mean values do not differ, at least for the first three digits, from each other. Hence, the most prominent features are the Lake Poyang in east China as well as the

Reservoir Mosul Dam and the Lake Tharthar, which are both located southwest 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.

Conclusion

The overall investigation of the 29 globally distributed water bodies 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. Consequently, neither the features of the investigated water body itself, including its size, its volume variation and its volume variation difference, nor potential differences regarding the input parameters, but rather an interplay of all of these parameters attributed to the final results. Therewith, the resulting differences are driven by reciprocally acting characteristics. Hence, the largest deviation could be attributed to the Lake Mead, for which the forward modelled equivalent water height values encountered a mean difference of 0.243 cm.

Ultimately, it can be said that the derived results have a consistently marginal and non-significant influence which cannot, except for the Lake Mead and the Lake Siling Co, be detected from GRACE when assuming an accuracy of 1 cm to 2 cm. 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 to examine variations in e.g. groundwater resources. Finally, the extent to which those differences can be allowed, primarily depends on the requirements of the end product and in the last instance from the client and the user.

Discussion and outlook

Although it was ensured that the used data is of sufficient quality, it has to be considered that the selection of the 29 water bodies was not driven by a thoughtful deliberation but by the availability of the required data. Against the background that GRACE has a spatial resolution of 300 km to 400 km (Swenson, n. d.) 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 resilience of the obtained results is limited and should therefore not be generalised. Hence, further studies and the inclusion of larger water bodies are essential to estimate the maximum difference that the consideration of dynamic instead of static water body shapes might cause. //

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