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Gravity variations determined from GRACE and GRACE-FO monthly solutions for analyzing water mass changes in the Aral Sea

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Abstract. The GRACE large-scale sequent GRACE-FO gravity satellite mission is providing monthly gravity field solutions for almost 20 years enabling a unique opportunity to monitor large-scale mass variation processes. The gravity anomaly time series for the Aral Sea region has been derived for the period of April 2002 to January 2022. The method of determining gravity anomaly time series from GRACE and GRACE-FO monthly solutions has been improved by taking into account the mass variations of the Caspian Sea. The gravity anomaly time series then has been compared to mass anomaly estimates. For deriving mass anomaly, beyond the available water volume data, density variations were determined by taking into account salinity and temperature changes. Unfortunately, no reliable information either on the salinity or on water temperature changes is available or accessible. Furthermore, not only the data but also the methodology of determining the density is not reliable. Still, the tests suggest that slight improvement in correlation due to the involvement of salinity information occurs.

Keywords: Aral Sea, temporal variations, gravity anomaly, salinity, mass anomaly

1 Introduction

The recession of the Aral Sea began in the 1960s. During the last years of the Soviet Union, it has subsequently led to a desiccation process carried on by the successor states around the Aral Sea [1]. The problems are generating severe environmental, economic, and human catastrophes, and at the present time no solution is outlined by a feasible action plan, monitoring of the process, and forecasting the foreseeable future scenarios with the use of the tools of geosciences and geoinformatics are essential contributions.

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The Gravity Recovery and Climate Experiment (abbr. GRACE) has provided gravity field models with a monthly resolution for the period of 2002 to 2017 [2], which is continued by the GRACE Follow-On (GRACE-FO) mission from 2018. The GRACE-FO is basically identical to the GRACE in its orbital configuration and technical design, apart from the inter-satellite range rate measurements, which are performed with lasers in addition to microwaves, to achieve more precise results [3]. These two missions provide a unique tool for determining temporal variations of gravity, consequently, mass redistribution processes generate the gravity change [4]. In the present study, GRACE and GRACE-FO-based gravity anomaly time series are determined and applied for analyzing the desiccation process of the Aral Sea.

This study is a continuation and a refinement of the work of Földváry et al. [5]. According to Figure 6 of Földváry et al. [5] in the reservoir of the Aral Sea, the correlation between water volume change and gravity anomaly was found to be 0.8636, which is a quite convincing relationship. However, from 2002 to about mid-2005, an increase in gravity anomaly was determined, which is opposite to the water volume change tendencies. In the present study, this unclear feature is expected to be analyzed with a more sophisticated method. The refined method is taking into account the effect of the water mass variations of the Caspian Sea at the Aral Sea region, furthermore, density variations of the water of the Aral Sea are also considered.

2 Materials and methods

Generally, gravity anomaly time series have been determined by using the classical spherical harmonic synthesis formulation, with some well-known tricks applied. Using GRACE and GRACE-FO monthly solutions, the spherical harmonic coefficients have been smoothed with a Gaussian filter of 300 km, additionally, the de-striping filter of Swenson and Wahr [6] was applied to them. This way gravity anomaly over a wide region of the Aral Sea has been determined in a 0.1-degree raster.

Subsequently, a linear trend on the resulting time series has been fitted to capture long-term mass variations. The resulting trends are visualized in Figure 1 [5]. Clearly, mass variations of the Caspian Sea have an impact on the gravity anomaly variations of the Aral Sea. Therefore, in the present study, gravity anomaly time series over the Aral basin have been corrected for the mass variations of the Caspian Sea. For this purpose, the prism modeling of [7] has been used. Since the effect of the Caspian Sea is essentially orders of magnitude smaller than that of the Aral Sea (when the location of the calculation is the center of the Aral Sea), approximate modeling of the Caspian Sea mass variations was found to be sufficient. Accordingly, the shape of the Caspian Sea has been replaced with a rectangle with the same area (400 km wide and 927.5 km long, equivalent to the 371.000 km2 area of the Caspian Sea), and located to the geometrical center of the Caspian Sea (Figure 2). This way, by multiplying the area of the rectangle with the height variations of the water level, the Caspian Sea is simplified to a single prism. Figure 3 shows the time series of the gravity anomaly at the center point of the Aral Sea (60.4°E, 44.9°N), along with the impact of the Caspian Sea at this point. Clearly, the impact of the Caspian Sea is negligible, however, it may impact comparison with certain properties of the water bodies.

The gravity anomaly time series has been compared to water volume variations of the Aral Sea. Water volume change was modeled by taking into account all the sub-basins of the Aral Sea. Furthermore, an attempt to determine mass variations by involving salinity and temperature to estimate water density has also been carried out. The concept simply assumes that water mass changes directly generate gravity anomaly change. The water mass change was determined as

$$\Delta m(t) = \rho(t)\Delta V(t) \qquad (1),$$

where Δm is the mass change, ρ is the density and ΔV is the volume change, and each variable is varying by time, t. Note that this equation implicitly assumes that the density changes concentrate only on the surface layers, and not affecting the whole water body. This is supported by the fact that as the desiccation of the Aral Sea began, a quite stable and strong vertical stratification of main water properties (density, temperature) was observed [8,9] (see also the discussion in the last paragraph of the Results chapter of these studies). This implicitly assumes that salinity observation may refer only to the layer of observation, which is in most cases practiced in the top layer. Accordingly, in this study, it is assumed that the salinity change refers to the top layers of the Aral Sea.

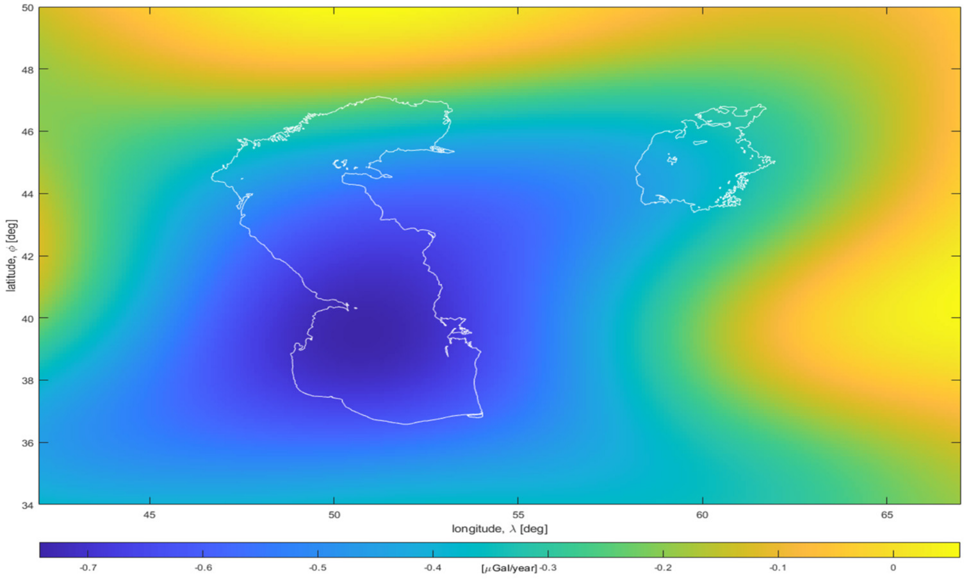

Fig. 1. The linear trend of gravity anomaly in the region of the Aral Sea and the Caspian Sea.

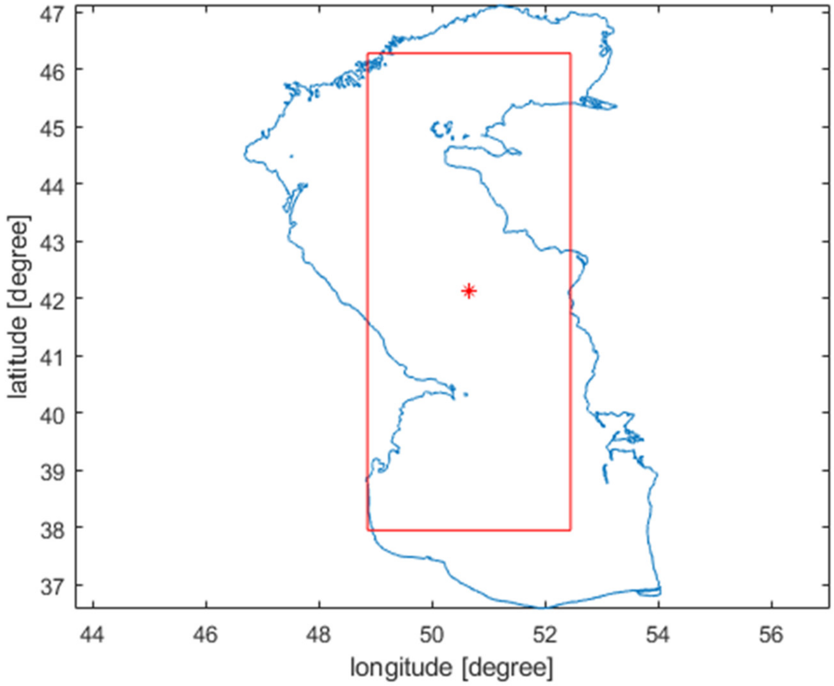

Fig. 2. Simplified model of the Caspian Sea to estimate its remote gravitational effect at the Aral Sea region.

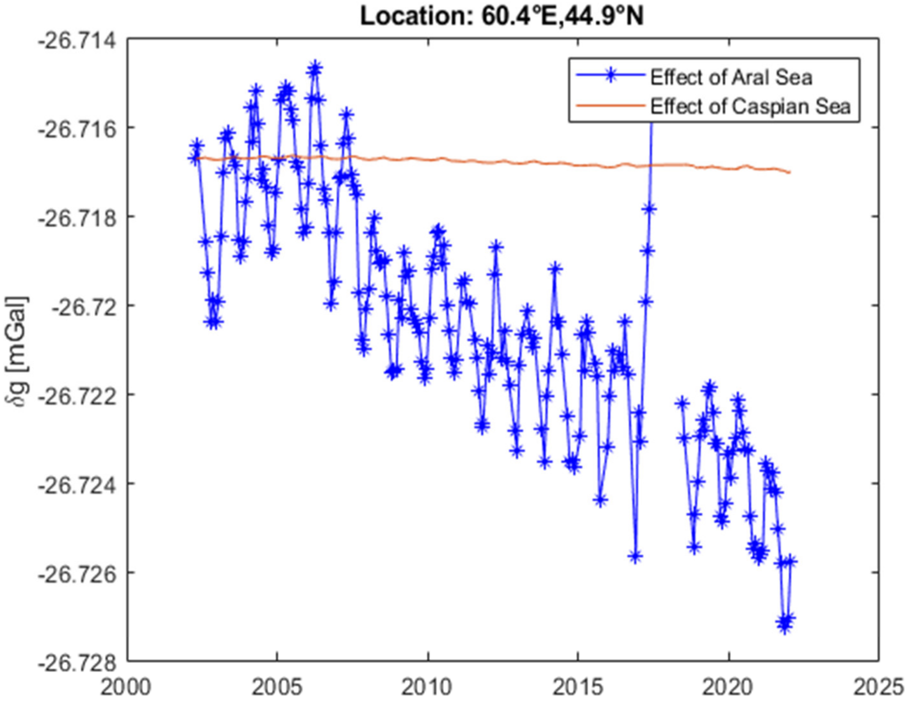

Fig. 3. Gravity anomaly time series at a central point (60.4°N, 44.9°E) of the Aral Sea with the gravitational effect of the Caspian Sea at the same location.

In order to determine the density, ρ, the method of Millero and Poisson [10] has been used. According to this method, the density of the water is determined as the function of the salinity and temperature of the water. Note that the formulation of Millero and Poisson [10] is validated for the salinity interval of 0.5 to 43 kg/m^3, and 0 to 40 ˚C of temperature, and certain values of salinity of the Aral Sea exceed this upper limit.

2.1 Used data

For the gravity anomaly time series calculations, GRACE and GRACE-FO monthly solutions released by UTC CSR have been used [2]. The version of the model was the RL06, with coefficients up to degree and order 60. The gravity anomaly time series has been determined for the period of April 2002 to January 2022.

Modeling of the water volume has been done by using the Hydroweb data [11]. The data consists of water level, area, and volume information as well from 1992 to the present day with a nominal temporal resolution of 10 days. In order to eliminate seasonal variations, annual averages are determined. In Figure 4, water volume data for the Aral Sea is displayed separately for the northern (Small Aral Sea) and the southern reservoirs (Large Aral Sea), where the latter has divided into eastern and western lakes around 2010 and is displayed separately from then on. Water volume is considered to be a relative change with respect to the first epoch. The total water volume variations are determined by a combination of the separated basins' volumes.

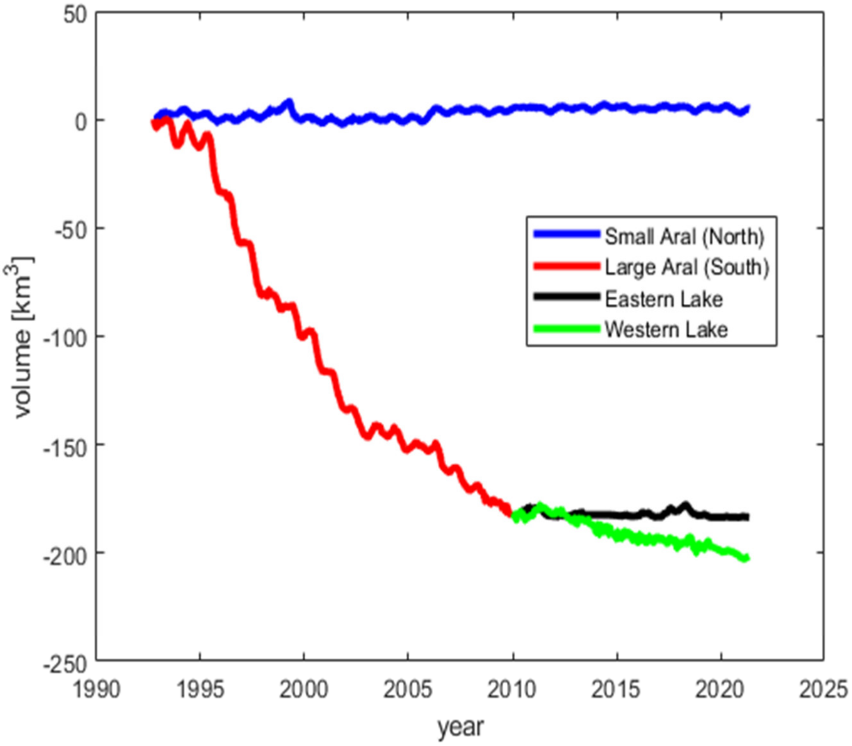

Fig. 4. Water volume changes in the Aral Sea. Each value is considered to be a relative change with respect to the first epoch.

Salinity is attempted to be modeled based on available information. Note that salinity is not observed and published regularly, therefore only inconsistent data is available with relevant gaps between epochs. Two different time series of salinity observations presented by Plotnikov [12] and Gaybullaev et al. [13] have been employed for the present study.

The source of the salinity values of Plotnikov [12] in Figure 2 is unclear, although it provides estimates for the interval of 1960 and 2007, after its disintegration, separately for the different basins of the Aral Sea. The water volume of the separated basins has been added up to represent the Aral Sea as a single water body.

For the period of 1957 to 2012, Gaybullaev et al. [13] made use of hydrological data of different kinds (runoff, evaporation, water volume, precipitation, and salinity) based on a vast number of sources, summarized in table 1. As for the source of the salinity data, information on the actual source could have not been traced.

The two models are shown in Figure 5, neglecting the historical data up to 1990. From 1990 to 1996, there is a relevant difference between the two salinity time series, both of them show a gradual increase from 1996 to 2005, however, there is a bias of approximately 30-40 kg/m3 between them, indicating that salinity data cannot be considered to be reliable.

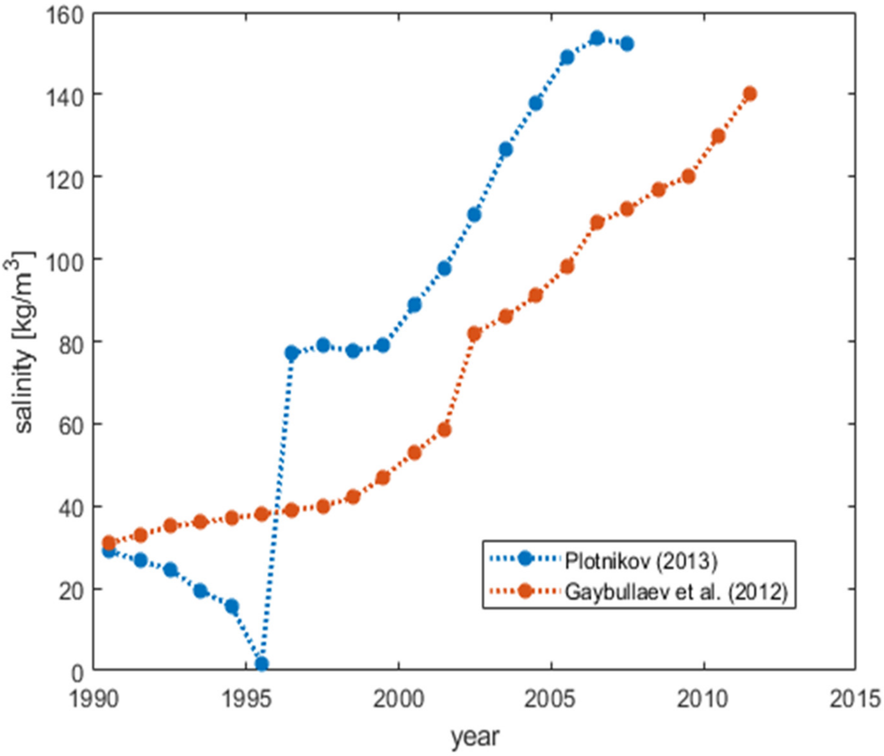

Fig. 5. Salinity models of the Aral Sea.

The average water temperature in the Aral Sea varies approximately between 4°C and 26°C, although locally relevant differences can be observed, it can exceed even 45°C [1].

Before the desiccation process of the Aral Sea took place, its water was quite homogeneous [14], except near the estuaries of the Amu-Darya and Syr-Darya rivers. Nowadays, the relevant differences in density and salinity in the different basins of the Aral Sea, and the stratification of different density layers within the basins can be observed [9].

The strong stratification of salinity impedes the mixing of different layers, as a consequence, exchange processes with the atmosphere and surface forcing affect only the surface layer of the water. Accordingly, due to the summer excess of solar heat, only the surface layer warms up and does not penetrate deeper waters, resulting in a very variable temperature distribution as well [9]. As a result, the temperature of the Aral Sea has not been attempted to be modeled. Instead, three scenarios were run, modeling the average temperatures known to be felt into the 4°C and 26°C intervals: temperature of 10°C, 20°C and 30°C with homogeneous distribution was considered.

3 Results

In Földváry et al. [5] gravity anomaly time series have been determined for the period of April 2002 to November 2019. The present study has been extended until January 2022. The shorter period resulted in a correlation coefficient with the water volume variations of 0.8636, for the extended period it became 0.8988, so the impact of the longer time series is obvious.

Further development was the modeling of the impact of the mass variations of the Caspian Sea for the Aral Sea regions (c.f. Figure 3). By considering the Caspian Sea, the correlation has increased to a value of 0.9013.

Further comparison has been done between gravity anomaly and salinity/density/mass anomaly, respectively. The gravity anomaly time series spans from 2002 to 2022, and salinity data are available between 1960 and 2007 [12] and between 1957 and 2012 [13]. Clearly, the overlapping period covers only a few years. Figure 6 shows some parts of the mentioned data including the overlapping period as well. According to equation (1), the volume change is inversely proportional to density, so an increase in density may increase the relevance of a smaller change in water volume. It can be seen in Figure 6 that the salinity is increasing between 2002 and 2005 in both models, which suggests an increasing density and consequently an increase in mass anomaly, which may account for some parts of the GRACE-observed increase in gravity anomaly.

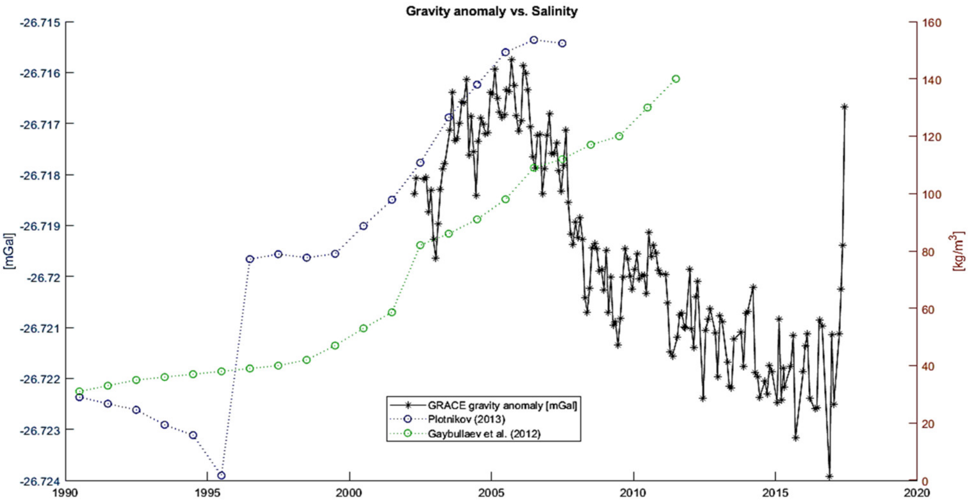

Fig. 6. Salinity vs. gravity anomaly time series.

By making use of the formulation of Millero and Poisson [10], density has been estimated for both salinity models, considering temperature values of 10°C, 20°C, and 30°C, as no reliable information on water temperature and distribution is available. Although the method of Millero and Poisson [10] is highly recognized, as it is validated for salinity values of 0.5 to 43 kg/m^3, for the case of the 2002-2005 period, when salinity varies between approximately 80 to 150 kg/m^3, it might result in incorrect estimates. According to Figure 7, the characteristics of the density variations follow the salinity variations, when the temperature (in the lack of information) was considered to be constant in time. Different constant values for the temperature results in a bias of the density curve inversely, so a higher temperature provides a lower density estimate. As a conclusion, as long as no reliable information on the temporal variations of the water temperature is available, variations of the density are linearly proportional to that of the salinity [15-16].

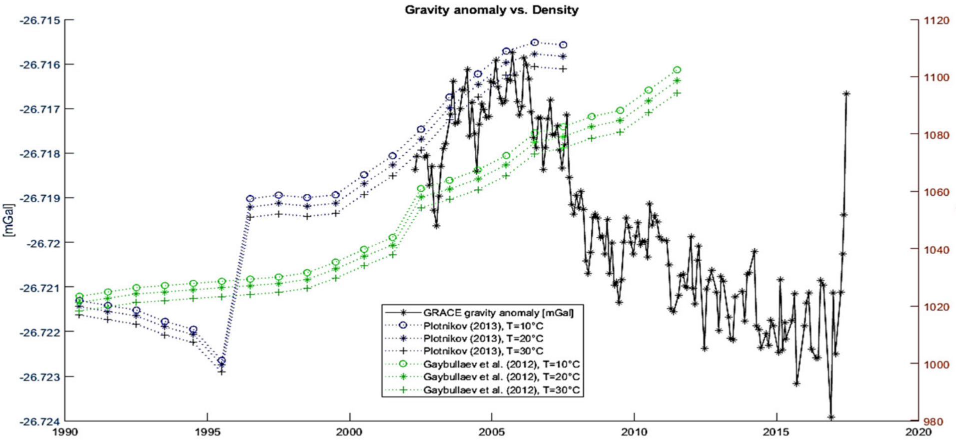

Fig. 7. Density vs. gravity anomaly time series.

Subsequently, the mass anomaly was determined using equation (1), displayed in Figure 8. No relevant difference in the different constant temperatures was observed. However, due to the change in the density, a change in the steepness of the mass anomaly curves can be detected. As a reference, the mass anomaly curve with a constant density (1000 kg/m^3) is included in Figure 8, which is equivalent to the water volume change (rescaled by a constant density).

The correlation between water volume change and gravity anomaly was found to be high in [5], yielding a correlation coefficient of 0.8636 for the whole period of GRACE and GRACE-FO time series. This has been improved by the extension of the GRACE-FO and of the water volume time series up to January 2022 to 0.9013. However, the comparison between mass anomaly and gravity anomaly can rely on a much shorter period with a rather sparse (annual) sampling, resulting in only 6 data pairs in the case of Plotnikov [12] and 10 data pairs in the case of [13] to be involved in the comparison. In the case of Plotnikov [12], no meaningful correlation values could be achieved, however for the model of Gaybullaev et al. [13], for the 10 data pairs the correlation coefficients could have been derived, c.f. Table 1.

The correlation coefficients in table 1 have no absolute meaning. The similarity of the gravity anomaly and water volume time series was achieved by taking into account the whole time series and resulted in a correlation of 0.9013. However, the same comparison considering only those 10 data pairs, where density could have been determined was reduced to 0.8000. Relatively to this value, a slight improvement in the correlation was achieved by considering salinity changes in the Aral basin, although none of the improvements are essential.

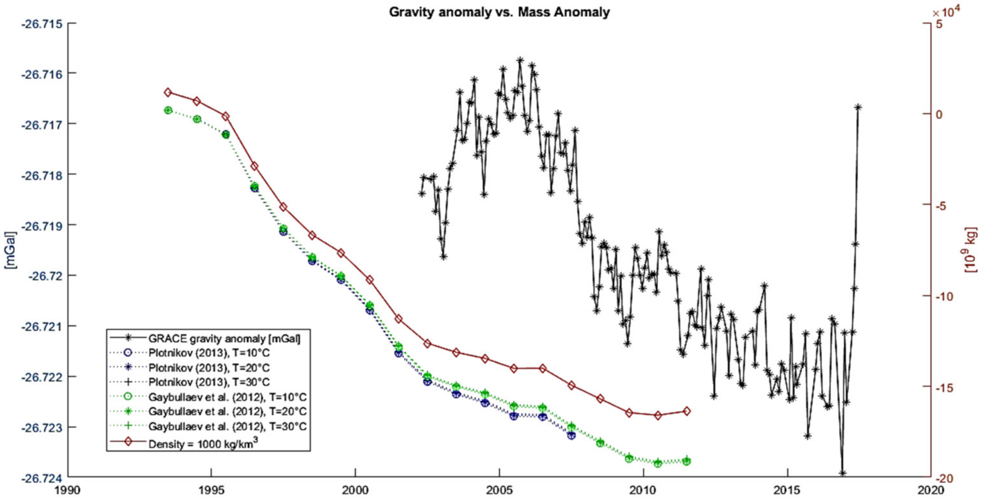

Fig. 8. Mass anomaly vs. gravity anomaly time series.

Table 1. Correlation between mass anomaly and gravity anomaly. Density is determined by using the salinity model of Gaybullaev et al. [13] with three different constant values for the temperature.

Model specification	2002-2005 (10 data pairs)	2002-2022 (197 data pairs)
Density: 1000 kg/m3	0.80001	0.90127
T=10°C	0.80041	
T=20°C	0.80039	
T=30°C	0.80037	

4 Conclusions

In the present study, the method of determining gravity anomaly time series from GRACE and GRACE-FO monthly solutions has been improved by taking into account the mass variations of the Caspian Sea.

Beyond methodological improvement, the basis of the comparison has been changed from water volume change to mass anomaly. This was achieved by determining density variations due to salinity and temperature changes that could be involved in the analysis. Unfortunately, no reliable information either on the salinity or on water temperature changes is available or accessible. Still, the tests suggest that slight improvement in correlation due to such information might occur, note, however, not only the data but also the methodology of determining the density is not reliable. As a consequence, the relevance of the slight improvement in correlation should not be overestimated. Obviously, it cannot account for the increasing gravity anomaly variation between 2002 and 2005 observed by the GRACE satellites.

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