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APPLICABILITY OF GRACE AND GRACE-FO FOR MONITORING WATER MASS CHANGES OF THE ARAL SEA AND THE CASPIAN SEA

ABSTRACT

The GRACE gravity satellite mission has provided monthly gravity field solutions for about 15 years enabling a unique opportunity to monitor large scale mass variation processes. By the end of the GRACE, the GRACE-FO mission was launched in order to continue the time series of monthly gravity fields. The two missions are similar in most aspects apart from the improved intersatellite range rate measurements, which is performed with lasers in addition to microwaves. An obvious demand for the geoscientific applications of the monthly gravity field models is to understand the consistency of the models provided by the two missions.

This study provides a case-study related consistency investigation of GRACE and GRACE-FO monthly solutions for the Aral Sea region. As the closeness of the Caspian Sea may influence the monthly mass variations of the Aral Sea, it has also been involved in the investigations. According to the results, GRACE-FO models seem to continue the mass variations of the GRACE period properly, therefore their use jointly with GRACE is suggested.

Based on the justified characteristics of the gravity anomaly by water volume variations in the case of the Aral Sea, GRACE models for the period March−June 2017 are suggested to be neglected. Though the correlation between water volume and monthly gravity field variations is convincing in the case of the Aral Sea, no such a correlation for the Caspian Sea could have been detected, which suggests to be the consequence of other mass varying processes, may be related to the seismicity of the Caspian Sea area.

KEYWORDS: data acquisition, gravity field, gravimetry, temporal variation

INTRODUCTION

Geoinformatics, basically, a tool for handling geographic information (or shortly geoinformation), that is data and information having an implicit or explicit association with a location relative to the Earth[4]. The data or information can be any kind, but it always relies (directly or indirectly) on observations, i.e. outcome of data acquisition.

In practice, the strength of Geographic information systems (GIS) with respect to classical map-based representation of location-based quantities is that they are supported by interactive tools, i.e. queries can be defined by the users, and different spatial data analyses can be implemented, and the map content according to the result of the analyses can be edited. All in all, GIS provides a much more flexible platform than electronic maps, therefore they became popular for numerous applications ranging from the simplest visual data screening through location intelligence studies to severe, elaborated geoscientific research.

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[4] ISO/TC 211. Multi-lingual glossary of terms. 2016. Web resource: http://www.isotc211.org/Terminology.htm (accessed 24.04.2020).

Among the quasi-infinite range of GIS applications, gravity field of the Earth can also make benefit of Geoinformation Science (GISc). Even though, the GIS era has been started in the late 1970^s or 1980^s, its potential has not become clear for the gravimetry community even until the 1990^s. Among the first papers on use of GIS for the gravity field, some has been inappropriately addressed, e.g. Maslov [1996] has labeled an analysis on the role of the marine gravity in measuring the sea surface topography as "GIS data sets optimization". An expedient attempt to test the applicability of GIS for geodesy has been delivered by Crippa, Sanso [1996]. This study has used the GRASS GIS for integrating and processing a geoid model and satellite altimetry data. Basically, the GIS tools, which were actually applied in that study were:

1) representation of the data sets (both gridded and sparse data);
2) interpolation of one data to the points of the other;
3) outlier detection by comparison the interpolated data with the other;
4) smoothing of the outlier-eliminated data and interpolation back to the original points.

Even though they have concluded that GIS was fast and reliable, they have also found that it may have a little, but meaningful impact on geodesy. By the time, both GIS tools and geodetic observation techniques improved a lot, as so, it makes sense to revisit this conclusion.

There are very few published attempts for applying GIS software for gravity field variables are known so far. An online GIS service, the Gravity Information System (SIS) has been developed at the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany[1]. This system is presented on a Java platform, which enables query of gravity information (the gravity value, or free-air or Bouguer anomaly, also contour lines of gravity referred to as "gravity zones") by coordinates (or by clicking on the base map) at the physical surface (approximated by the SRTM DEM model) or at any arbitrarily defined altitude above it. The background of the workspace can either be topographic or gravity anomaly map. This system makes only partially use of the benefits of the GIS in both on data query and on data representation.

The China Regional Gravity Information System (RGIS) has been developed by the China Geological Survey [*Zhang et al.*, 2011]. This system is based on the MapInfo platform with OLE technology. As it is stated in Zhang et al. [2011], the system can visually interpret data of spatial geography, geology and gravity for China. It furthermore enables graphical data editing and data table operations, and what is really specific is that there are classical gravimetric tools are defined, such as gravity reduction, gravity (and magnetic) field transformation, and gravity anomaly inversion. The system has been developed for regional use. The system is developed for terrestrial gravimetric data. Unfortunately, the system cannot be tested, as no internet availability could be found.

Further attempts for gravity field GIS are provided by Hobbs et al. [2000], Hinze et al. [2005], Wang, Zhang [2008], Tracey, Nakamura [2010] and Földváry et al. [2015]. The latter has developed a GIS package termed Gravity_RS_GIS, which has used as input data for temporal gravity variation GRACE monthly solutions for the period of April 2002 to April 2015 [*Földváry et al.*, 2015]. As time is passing by, update of the input data is essential, which is in the focus of this study. Meanwhile the GRACE mission has been ended, and for its replacement the GARCE-FO has been launched. It is essential to check the consistency of the earlier of the new monthly solutions, how smooth the continuation of the time series has been achieved, in order to derive proper queries and geostatistics. The investigations were performed with the Gravity_RS_GIS package [*Földváry et al.*, 2015] and with MATLAB ver. R2018b.

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[1] Schwere-Informationssystem. Online GIS service. Web resource: https://www.ptb.de/cms/ptb/fachabteilungen/abt1/fb-11/fb-11-sis.html (accessed 24.04.2020)

MATERIALS AND METHODS OF RESEARCHES

The Gravity Recovery and Climate Experiment (abbr. GRACE) has provided gravity field models with monthly resolution for the period of 2002 to 2017 [*Bettadpur*, 2018]. This is a unique option for determining temporal variations of the gravity, consequently, mass redistribution processes generating the gravity change [*Wahr*, *Schubert*, 2007]. Seasonal mass variations (annual and semi-annual) of the Earth, which are capable by the GRACE monthly solutions are contributed by atmospheric, hydrologic, cryospheric and oceanographic masses [*Ilk et al.*, 2005]. Accordingly, the GRACE monthly models can efficiently be applied for investigation of seasonal periodical processes over large areas, such as oceanic transport process [*Chambers et al.*, 2004; *Chen et al.*, 2019] or hydrological processes [*Andersen et al.*, 2008; *Kiss, Földváry*, 2017a], and also for long periodic or secular mass variation, such as crustal motions [*Wang et al.*, 2019] or ice mass balance variations [*Shum et al.*, 2008; *Földváry*, 2012; *Kiss, Földváry, 2017b].*

Due to its success and notable contribution to Earth sciences and climate change related monitoring, by the end of the GRACE, the need for its continuation was obvious. The GRACE Follow-On (GRACE-FO) has been launched in 2017, providing further monthly solutions with a notable gap in the time series. The GRACE-FO is basically identical to the GRACE in its orbital configuration and technical design, apart from the intersatellite range rate measurements, which is performed with lasers in addition to microwaves, to achieve more precise results [*Yu*an, 2019].

As for the derived monthly gravity solutions, there are inconsistencies during the GRACE lifetime, also there is a gap between the GRACE and GRACE-FO. Table 1 summarize the available monthly solutions derived using GRACE (until 2017) and GRACE-FO (from 2018) observations. Comments to the notations in the table: X — a regular monthly solution, s — model for a notably shorter period, d — the actual period is notably delayed with respect to the nominal period, a — the actual period is notably advanced with respect to the nominal period.

Table 1. GRACE and GRACE-FO monthly solutions

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2002				X	s			X	X	X	X	X
2003	X	X	X	X	s		X	X	X	X	X	X
2004	s	X	X	X	X	X	X	X	X	X	X	X
2005	X	X	X	X	X	X	X	X	X	X	X	X
2006	X	X	X	X	X	X	X	X	X	X	X	X
2007	X	X	X	X	X	X	X	X	X	X	X	X
2008	X	X	X	X	X	X	X	X	X	X	X	X
2009	X	X	X	X	X	X	X	X	X	X	X	X
2010	X	X	X	X	X	X	X	X	X	X	X	X
2011		s	X	X		X	X	X	X	X	a	d
2012	X	X	X	a		X	X	X	X		X	X
2013	X	X		s	X	X	X			X	X	X
2014	s		X	X	X	s		X	X	X	X	
2015	s	X	X	X	a		X	X	X			d
2016	X	X	X		X	X	X	d			d	d
2017	d		d	d	s	a						
2018						X	s			d	X	X
2019	X	X	X	X	X	X	X	X	X	X		

For the period of April 2002 to November 2019, monthly solutions could have been derived for 178 cases, which is 84.4 % of the potentially desired 211 models. Beyond the missing 33 months, only the 87.1 % of the available monthly solutions (i.e. 155 months) fulfill its requirements, the remaining models are partially successful attempts to derive some solution by the available data: for 10 months (5.6 %) models could derived using shorter time span (data length ranges from 14 to 20 days), and for further 13 models (7.3 %) it could be derived by shifting relevantly (i.e. even with 2 weeks) the its period. It obviously shows that the different monthly solutions are not consistent in accuracy, also the timing of the models cannot considered be as regular. For each monthly solution, a posteriori covariance information is provided, which can be applied for weighting the different monthly solutions. As for the irregular timing, a more reliable reference day can be defined by considering the days of actual observations for each model. This way, however, the data is not consistent and not regularly sampled anymore.

The inconsistency of the GRACE monthly solutions is particularly important for two periods: basically, models in 2002 and models from August 2016 until the end of mission are less accurate. The latter case is a consequence of the malfunction (and then the subsequent turn-off) of the accelerometer of GRACE B satellite. It is important therefore to understand that the nominal gap of 11 months between GRACE and GRACE-FO is rather longer as the later models of GRACE are less accurate, particularly the last 3 epochs show anomalous behavior. In the following section, i.e. the cases studies, the less accurate periods of GRACE are indicated.

RESULTS OF RESEARCH AND THEIR DISCUSSION

As the shrinking of the Aral Sea yields notable mass loss over large area [*Gaybullaev et al.*, 2012], it should be detected by GRACE and GRACE-FO as well. In order to analyze it, CSR RL06 monthly solutions have been used up to degree and order 60 to determine time series of gravity anomaly for the Aral Sea region. The models have been smoothed with a Gaussian filter of 300 km, and the de-striping filter of Swenson, Wahr [2006] was applied. Then a linear trend on the resulted time series of gravity anomaly has been fit to capture long-term mass variations.

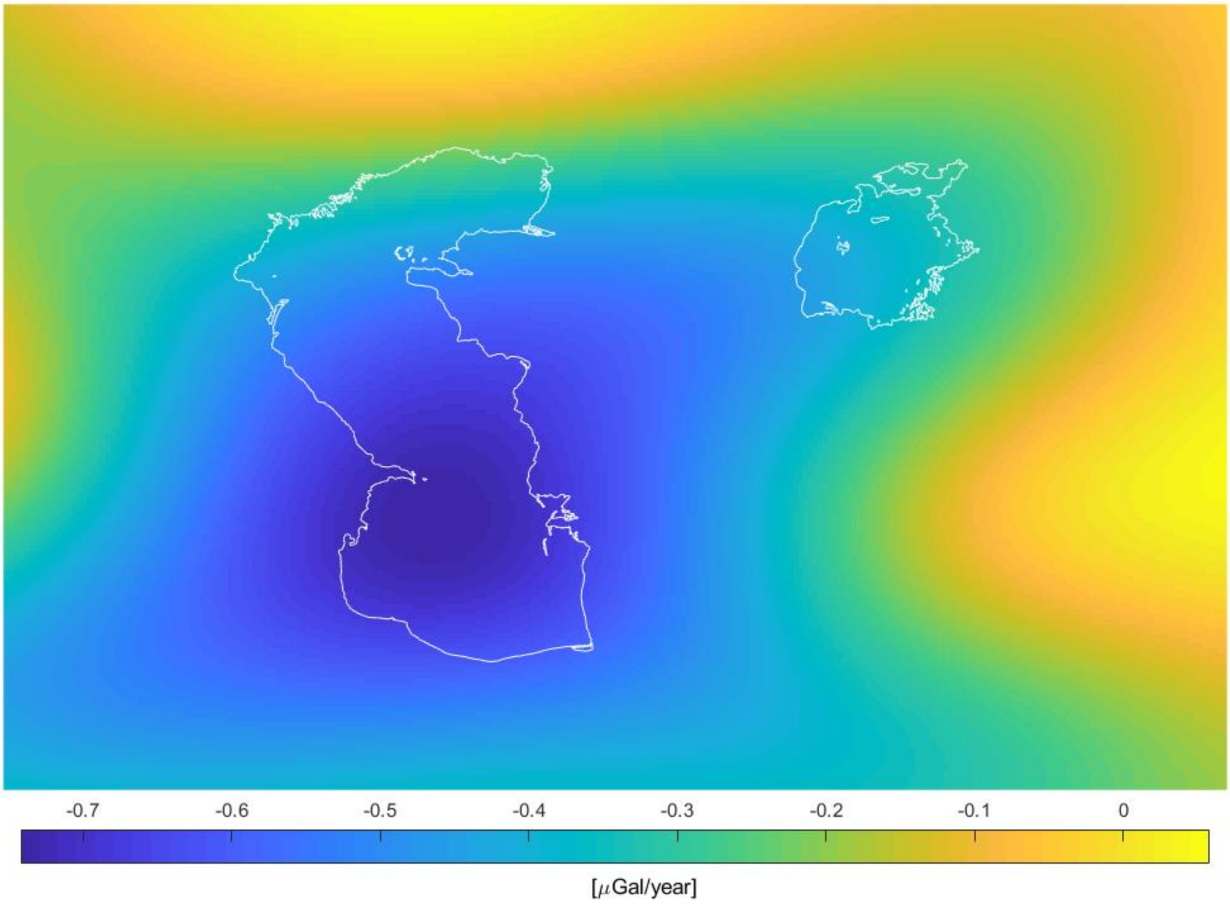

Fig. 1. Linear trend of gravity anomaly in the region of the Aral Sea and the Caspian Sea

Fig. 1 shows the resulted linear trends of gravity anomaly in μGal/year unit for the region covered by meridians of 42 °E and 67 °E longitude, and by parallels of 34 °N and 50 °N latitudes. It is obvious from fig. 1 that analysis of the Aral Sea cannot be done without considering the effect of the nearby Caspian Sea.

The notably larger mass variation of the Caspian Sea is a consequence of its notably larger area: the Caspian Sea has constantly an approximate area of ~371,000 km^2 (without the Kara-Bogaz-Gol Bay) [*Chen et al.*, 2017], while the Aral has been shrunk to an area of ~7,000 km^2 (in 2014) [*Sun*, *Ma*, 2019] from its original area of ~68,900 km^2. Note that due to the characteristics and the altitude of the GRACE orbit, furthermore due to the unavoidable use of smoothing and de-striping filters, reasonable results can be expected for test area of at least 200.000 km^2 [*Swenson*, *Wahr*, 2007], thus the area affected by the Aral Sea surface and subsurface water mass variations is just at the edge of the suitable resolution.

In fig. 2 and fig. 3 the annual change of water level and volume is shown based on Hydroweb data [*Cretaux et al.*, 2011]. Note that the used water level and volume variations data are of monthly resolution, annual averages in fig. 2 and fig. 3 are only used for display in order to eliminate seasonal variations to get a clear picture on the tendencies of variations. In fig. 2, the water level 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 parts around 2010 and is displayed separately from then on. As for the water volume in fig. 3, the water volume of the separated reservoirs of the Aral Sea is added. As for the Caspian Sea, only water level data is available, which has been converted to volume change for fig. 3 by multiplication with the inundation area.

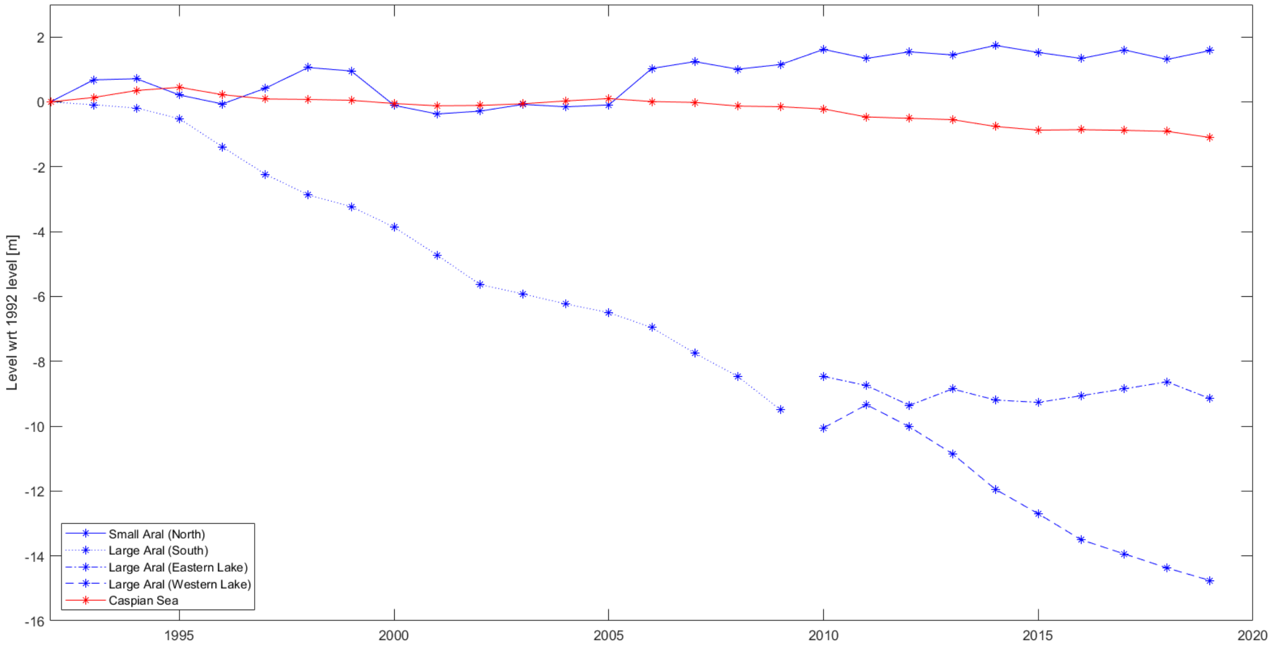

Fig. 2. Annual water level change of the Aral Sea and the Caspian Sea

Even though in the case of the Aral Sea, water level variations occur in the range of 10 cm/year, and that of the Caspian Sea is only in the range of cm/year (fig. 2), the larger area result in larger changes in volume of water (fig. 3). The average sea level change of the Caspian Sea for the 1996–2010 period were estimated by Chen et al. [2017] to be -6.72 cm/year, which is equivalent to volume change of -24.93 km^3/year. It is similar to our estimation, when linear trend of volume change is determined concentrating only on the GRACE era, i.e. 2002–2017. It has resulted in -25.62 km^3/year and -3.40 km^3/year, respectively for the Caspian Sea and for the Aral Sea (the estimated averages are shown on the figure with dashed lines). According to this estimate, roughly 7.5 times more mass loss is expected in the Caspian Sea, though notable differences may be observed due to salinity and temperature differences of the water bodies.

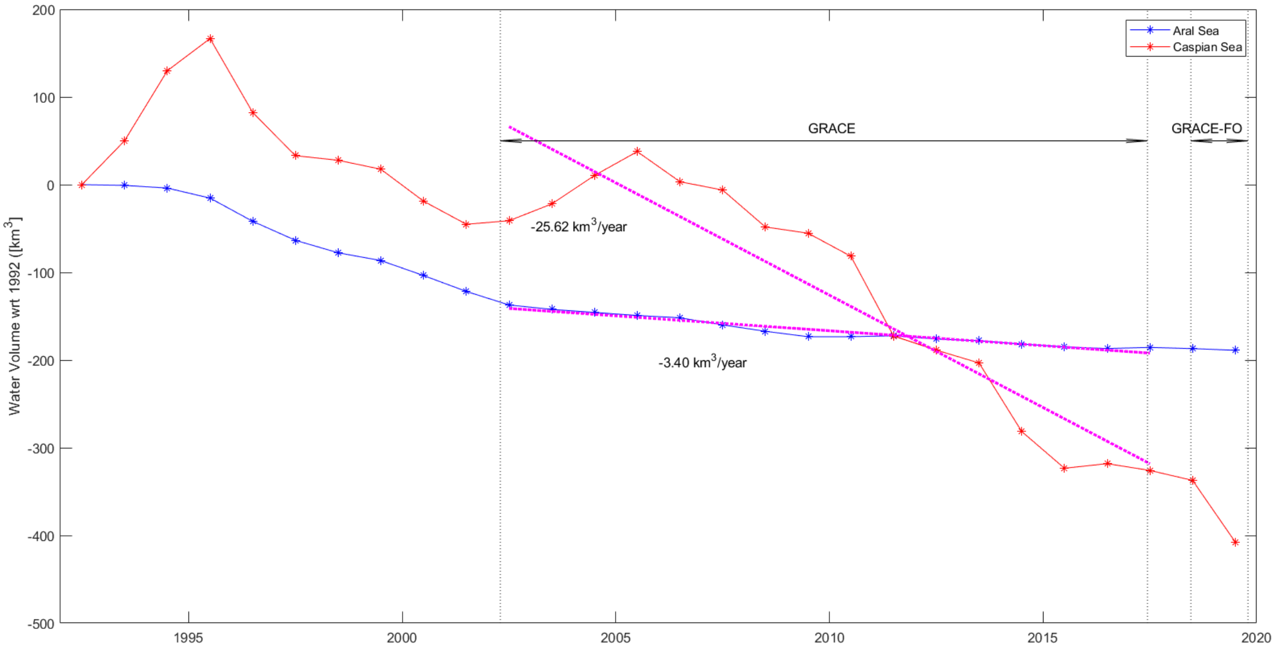

Fig. 3. Annual water volume change of the Aral Sea and the Caspian Sea

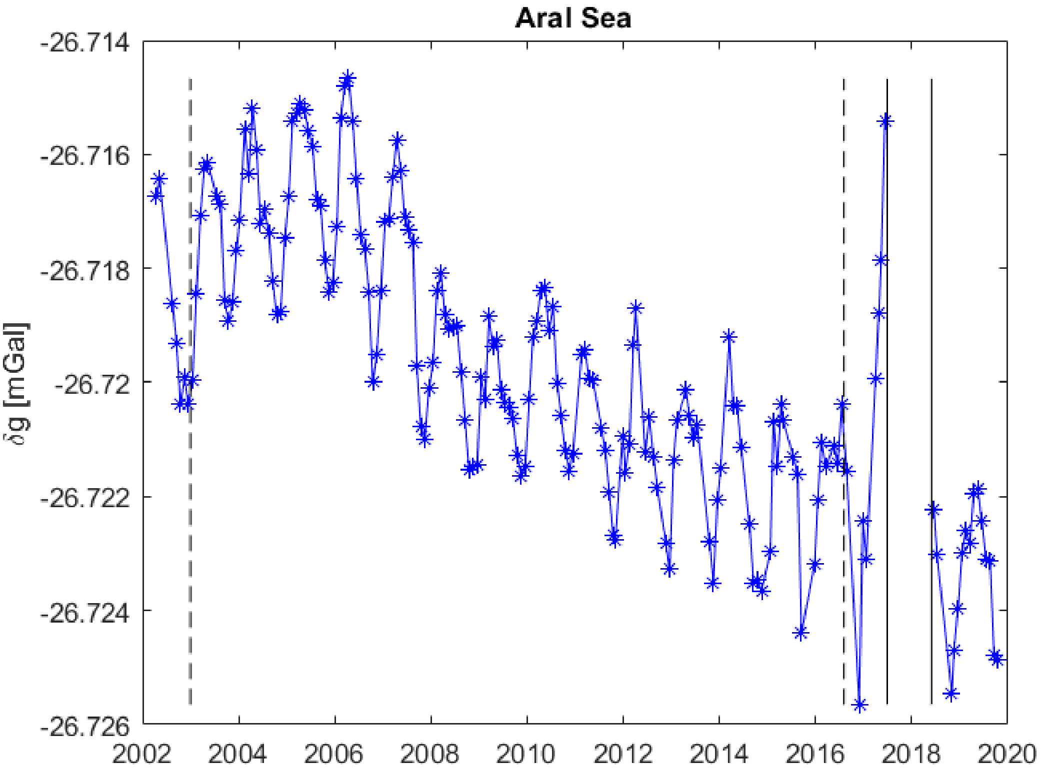

Fig. 4. Time series of gravity anomaly at (60.43 °E, 44.93 °N)

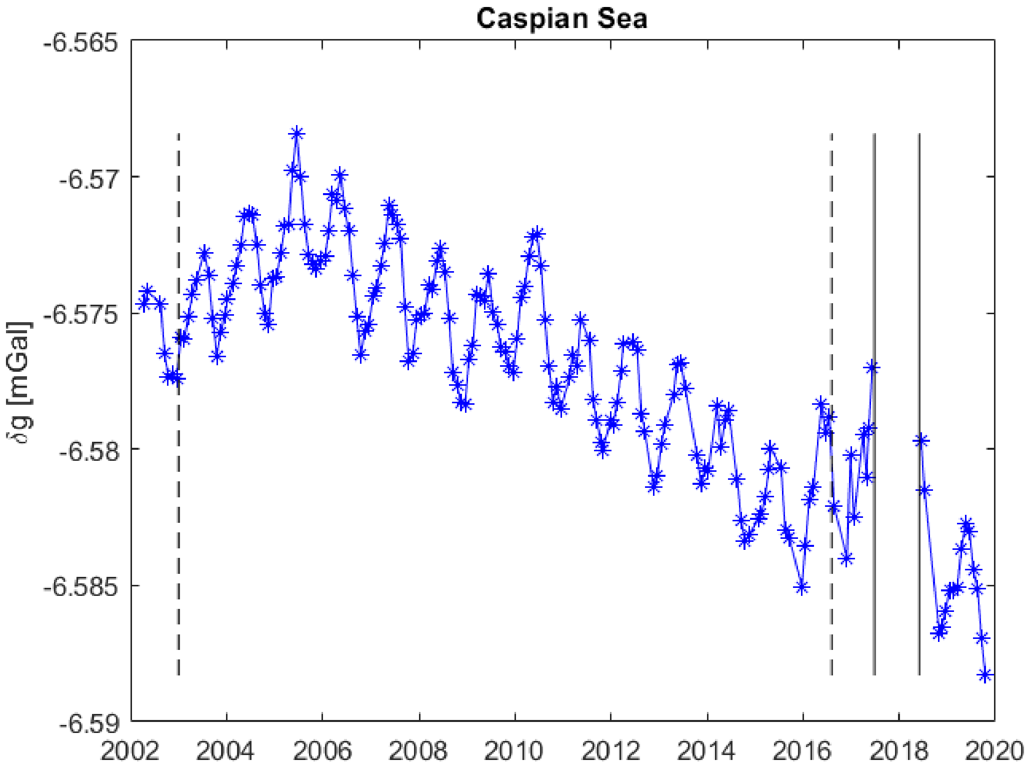

Fig. 5. Time series of gravity anomaly at (50.65 °E, 43.11 °N)

Time series of gravity anomaly at the geometrical centre point of the Aral Sea (at 60.43 °E and 44.93 °N according to the original coastlines [*Lehner*, *Döll*, 2004]) is shown in fig. 4. Similarly, time series of the gravity anomaly is determined for the Caspian Sea (at 50.65 °E and 43.11 °N) is shown on fig. 5. In both figures the periods of less-reliable GRACE monthly solutions, i.e. in 2002 and from August 2016 until June 2017 (c.f. table 1) is displayed by vertical black dashed lines, while the gap between GRACE and GRACE-FO, i.e. from August 2017 to May 2018 is displayed with vertical black solid lines. Visually it seems that GRACE models for the August 2016 to June 2017 period does not follow the tendencies before, therefore their use is not recommended.

Both fig. 4 and fig. 5 indicate a strong seasonal behavior. In order to see behind the seasonality, an annual signal has been fit and removed, c.f. fig. 6 and fig. 7. These figures should indicate tendencies in the mass variations. In this region relevant mass variations are known to be related to water bodies therefore water volume variations are also visualized (see its y-axis on the right side). Seasonal component of water volume changes has also been removed.

According to fig. 6, in the reservoir of the Aral Sea the correlation between water volume and gravity anomaly was found to be 0.8636, which is particularly strong from 2006. Also is it clear, that water mass variations do not justify the utility of the latest GRACE models (from August 2016 till the end of mission). The correlation with the (radar satellite altimetry derived) water volume change is more convincing than in earlier investigations [*Singh*, *Seitz*, 2012; *Singh et al.*, 2012], though those studies has been performed for a shorter time span but with a very similar processing method. Note however, that those studies have not observe the differences in the first period of the time series, i.e. until and of 2015. A major difference with these studies is, however, that fig. 7 has been determined point-wisely to the centre of the Aral region, while Singh, Seitz [2012] and Singh et al. [2012] has determined an average areal value for the region bounded by latitudes of 43.5 °N and 47.5 °N and longitudes of 58 °E and 62 °E, thus, such a local deviation may indicate a local phenomenon.

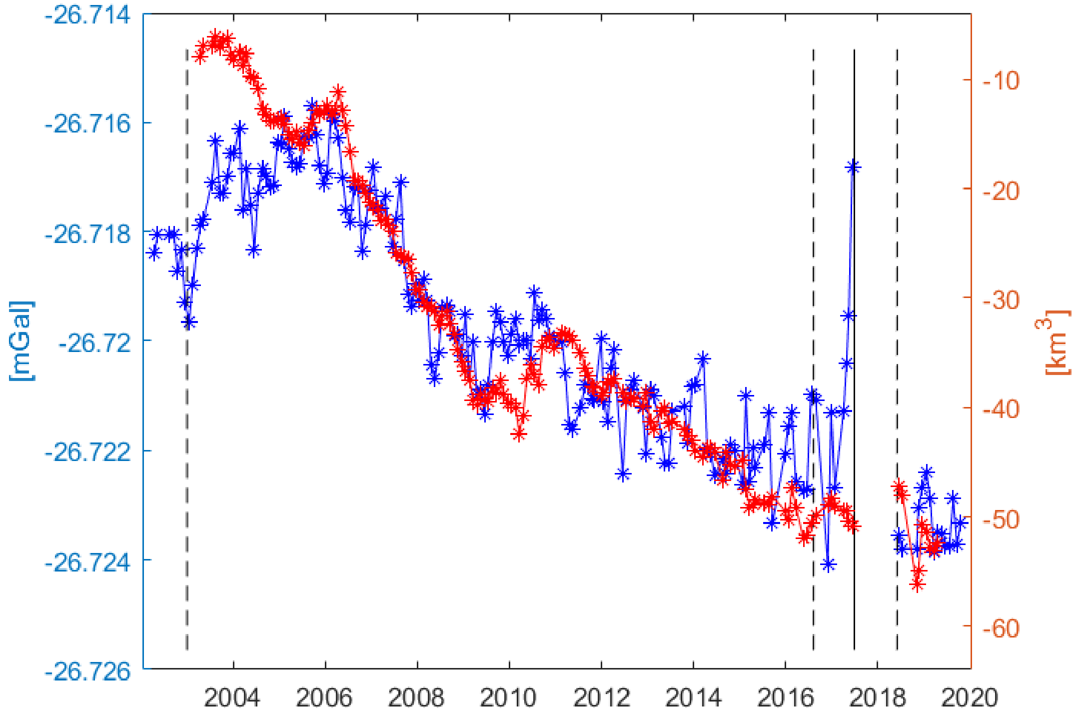

Fig. 6. Time series of gravity anomaly at (60.43 °E, 44.93 °N) vs. water volume change

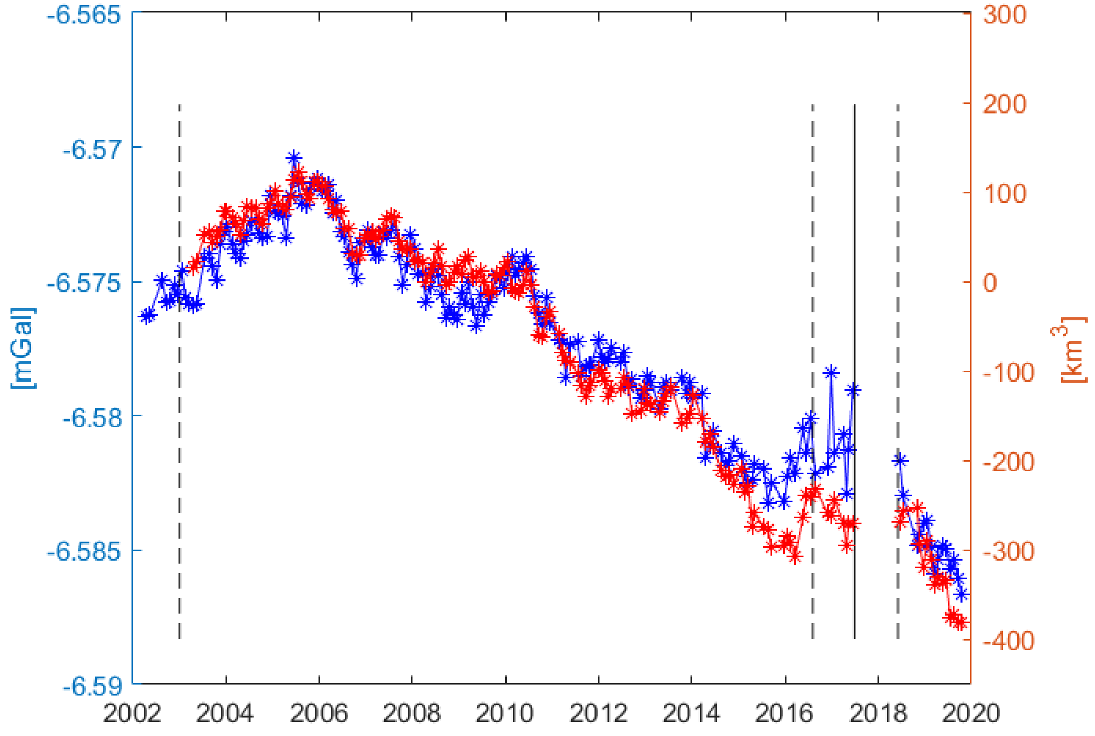

Fig. 7. Time series of gravity anomaly at (50.65 °E, 43.11 °N) vs. water volume change

In case of the Caspian Sea, the tendencies of the water mass variations also properly explain the mass variations (c.f. fig. 7). The correlation for the Caspian Sea is even more convincing: the correlation coefficient was found to be 0.9748.

For both figures, a linear trend has been fit. It is -0.67 μGal/year and -1.15 μGal/year for the Aral Sea and for the Caspian Sea, respectively. So, even though the volume of the water is 7.5 times more in the case of the Caspian Sea, it affects gravity changes only approximately 2 times more for the Caspian Sea than for the Aral Sea.

CONCLUSIONS

This study provides a case-study related consistency investigation of GRACE and GRACE-FO monthly solutions. Indeed, there are obvious inconsistencies of GRACE data, meanwhile the continuation with GRACE-FO should also be smooth, therefore different case studies can contribute on deciding on the joint applicability of the “new” GRACE-FO and the “old” GRACE data. Basically, based on the justified characteristics of the gravity anomaly and of the water volume variations in the case of the Aral Sea, GRACE models for the period March−June 2017 are suggested to be neglected. Also, GRACE-FO models seem to continue the mass variations of the GRACE period properly, therefore their use jointly with GRACE is suggested.

From geophysical aspect, it can be concluded that the main source of mass variation in the Caspian Sea and Aral Sea region is generated by the water mass variations. Also, it became obvious that the mass variations of the Aral Sea cannot be investigated without considering the Caspian Sea as well, since mass variations of the two reservoirs are overlapping.

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REFERENCES

1. *Andersen O., Berry P., Freeman J., Lemoine F.G., Luthcke S., Jakobsen K., Butts M.* Satellite altimetry and GRACE gravimetry for studies of annual water storage variations in Bangladesh. Terrestrial, Atmospheric and Oceanic Sciences, 2008. V. 19. P. 47–52. DOI:10.3319/TAO.2008.19.1-2.47(SA).

2. *Bettadpur S.* Gravity recovery and climate experiment level-2 gravity field product user handbook. Center for Space Research at The University of Texas at Austin, 2018. Web resource: https://podaac-tools.jpl.nasa.gov/drive/files/allData/grace/docs/L2-UserHandbook_v4.0.pdf (accessed 24.04.2020).

3. *Chambers D.P., Wahr J., Nerem R.S.* Preliminary observations of global ocean mass variations with GRACE. Geophysical Research Letters, 2004. V. 31. L13310. 4 p. DOI:10.1029/2004GL020461.

4. *Chen J.L., Pekker T., Wilson C.R., Tapley B.D., Kostianoy A.G., Cretaux J.-F., Safarov E.S.* Long-term Caspian Sea level change. Geophysical Research Letters, 2017. V. 44. P. 6993–7001. DOI:10.1002/2017GL073958.

5. *Chen J., Tapley B., Seo K.-W., Wilson C., Ries J.* Improved quantification of global mean ocean mass change using GRACE satellite gravimetry measurements. Geophysical Research Letters, 2019. V. 46. P. 13984–13991. DOI: https://doi.org/10.1029/2019GL085519.

6. *Cretaux J-F., Jelinski W., Calmant S., Kouraev A., Vuglinski V., Bergé-Nguyen M., Gennero M.C., Nino F., Abarca Del Rio R., Cazenave A., Maisongrande P.* SOLS: a lake database to monitor in the near real time water level and storage variations from remote sensing data. Advances in Space Research, 2011. V. 47. P. 1497–1507.

7. *Crippa B., Sanso F.* A quick look on the sea surface topography of the Mediterranean from the Geomed geoid and the ERS 1 geodetic mission. Proceedings of the International Centre for

Mechanical Sciences Workshop on Data Acquisition and Analysis for Multimedia GIS. New York: Springer-Verlag, 1996. P. 237–247.

8. *Földváry L.* Mass change acceleration in Antarctica from GRACE monthly gravity field solutions. Geodesy for Planet Earth, Proceedings of IAG Symposium in Buenos Aires. IAG Symposia Series. Berlin, Heidelberg: Springer-Verlag, 2012. V. 131. P. 591–597.

9. *Földváry L., Kemény M., Huang X.Z.* First results of implementing satellite-borne gravity data to GIS and future perspectives. 10th International Symposium on Applied Informatics and Related Areas – AIS2015. Székesfehérvár, 2015. Paper P03.

10. *Gaybullaev B., Chen S.C., Gaybullaev D.* Changes in water volume of the Aral Sea after 1960. Applied Water Science, 2012. V. 2. P. 285−291. DOI: https://doi.org/10.1007/s13201-012-0048-z.

11. *Hinze W.J., Aiken C., Brozena J., Coakley B., Dater D., Guy Flanagan G., Forsberg R., Hildenbrand T., Keller R.G., Kellogg J., Kucks R., Lee X., Mainville A., Morin R., Pilkington M., Plouff D., Ravat D., Roman D., Urrutia-Fucugauchi J., Véronneau M., Webring M., Winester D.* New standards for reducing gravity data: the North American gravity database. Geophysics, 2005. V. 70. P. J25 – J32.

12. *Hobbs S.F., Kimbell S.F., Coats J.S., Fortey N.J.* BGS databases for mineral exploration: status in 2000. BGS Research Report RR/00/11. DTI Minerals Programme Publication No 6. Keyworth, Nottingham: British Geological Survey, 2000. 37 p.

13. *Ilk K.H., Flury J., Rummel R., Schwintzer P., Bosch W., Haas C., Schröter J., Stammer D., Zahel W., Miller H., Dietrich R., Huybrechts P., Schmeling H., Wolf D., Götze H.J., Riegger J., Bardossy A., Günter A., Gruber Th.* Mass transport and mass distribution in the Earth system. Contributions of the new generation of satellite gravity and altimetry missions to the Geosciences. Proposal for a German priority research program, 2nd edition. München, Potsdam: GOCE-Projektbüro Deutschland, Techn. Univ. München, GeoForschungsZentrum Potsdam, München, Potsdam, 2005. 136 p.

14. *Kiss A., Földváry L.* Seasonal hydrologic variations in the La Plata basin from GRACE gravity field models. Acta Geodynamica et Geomaterialia, 2017 (a). V. 14. No 2. P. 145–152.

15. *Kiss A., Földváry L.* Uncertainty of GRACE-borne long periodic and secular ice mass variations in Antarctica. Acta Geodaetica et Geophysica, 2017 (b). V. 52. No 4. P. 497–510.

16. *Lehner B., Döll P.* Development and validation of a global database of lakes, reservoirs and wetlands. Journal of Hydrology, 2004. V. 296. No 1–4. P. 1–22.

17. *Maslov I.A.* The use of gravity for GIS data sets optimization. ISPRS Archives, 1996. V. XXXI. Part B3. P. 511–516.

18. *Shum C.K., Kuo C., Guo J.* Role of Antarctic ice mass balances in present-day sea level change. Polar Science, 2008. No 2. P. 149–161. DOI: 10.1016/j.polar.2008.05.004.

19. *Singh A., Seitz F.* Water storage variations in the Aral Sea from multi-sensor satellite data in comparison with results from GRACE gravimetry. 2012 IEEE International Geoscience and Remote Sensing Symposium. Munich: IEEE, 2012. P. 3042–3045. DOI: 10.1109/IGARSS.2012.6350784.

20. *Singh A., Seitz F., Schwatke C.* Inter-annual water storage changes in the Aral Sea from multimission satellite altimetry, optical remote sensing, and GRACE satellite gravimetry. Remote Sensing of Environment, 2012. V. 123. P. 187−195.

21. *Sun F., Ma R.* Hydrologic changes of Aral Sea: a reveal by the combination of radar altimeter data and optical images. Annals of GIS, 2019. V. 25. No 3. P. 247–261. DOI: 10.1080/19475683.2019.1626909.

22. *Swenson S., Wahr J.* Post-processing removal of correlated errors in GRACE data. Geophysical Research Letters, 2006. V. 33. Iss. 8. L08402. 4 p. DOI: https://doi.org/10.1029/2005GL025285.

23. *Swenson S., Wahr J.* Multi-sensor analysis of water storage variations of the Caspian Sea. Geophysical Research Letters, 2007. V. 34. Iss. 16. 5 p. L16401. DOI:10.1029/2007GL030733.
24. *Tracey R., Nakamura A.* Complete Bouguer anomalies for the Australian National Gravity Database. ASEG Extended Abstracts, 2010. V. 1. P. 1–3.
25. *Wahr J., Schubert G.* Treatise on Geophysics. Time-Variable Gravity from Satellites. 1st edition. Oxford, Elsevier Ltd., 2007. P. 213–218.
26. *Wang C.X., Zhang M.H.* Co-development of MapInfo and Surfer in regional gravity information system. Geophysical and Geochemical Exploration, 2008. V. 32. No 4. P. 445–447.
27. *Wang L., Khan S.A., Bevis M., van den Broeke M.R., Kaban M.K., Thomas M., Chen C.* Downscaling GRACE predictions of the crustal response to the present-day mass changes in Greenland. Journal of Geophysical Research: Solid Earth, 2019. V. 124. P. 5134–5152. DOI: https://doi.org/10.1029/2018JB016883.
28. *Yuan D.N.* GRACE Follow-On level-2 gravity field product user handbook. Jet Propulsion Laboratory. JPL D–103922, 2019. Web resource: https://podaac-tools.jpl.nasa.gov/drive/files/allData/gracefo/docs/GRACE-FO_L2-UserHandbook_v1.0.pdf (accessed 24.04.2020).
29. *Zhang M.H., He H., Wang C.X.* The launch of a large regional gravity information system in China. Applied Geophysics, 2011. V. 8. No 2. P. 170–175.