



Evaluation of annual and semiannual total mass variation over the Mediterranean Sea from satellite data

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Received: 1 December 2020 / Accepted: 27 April 2021 / Published online: 16 May 2021
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Abstract

Satellite gravity missions represent an important contemporary source of data for both hydrological and oceanic studies. The present study assesses the seasonal variability of Mediterranean Sea level using temporal observations from the Gravity Recovery and Climate Experiment (GRACE) mission. The GSM and GAD solutions from the German Research Centre for Geosciences (GFZ) were utilized together with equivalent water height of different basins to restore the signal over the eastern part of Mediterranean Sea and its surroundings. Twelve points were selected (i.e., 8 points on land and 4 points within the Mediterranean Sea) to extract time series of terrestrial water storage (TWS) over the Eastern Mediterranean. Significant regional TWS variability on land is correlated to continuous charging and discharging of water supply from river basins in the northern Mediterranean. On the other hand, less significant TWS variations were reported from the southern Mediterranean, where arid/hyper-arid desert conditions are prevailing. Findings obtained from points within the Mediterranean Sea indicated that the middle part of the Mediterranean Sea is affected by strong oceanic currents and the seawater mass variation has a larger annual and semiannual amplitude compared to that obtained over the coastal areas. These findings demonstrate that satellite gravity can be an essential tool for regional hydrological assessment under complex climatic settings.

Keywords Eastern Mediterranean Sea · Total water storage · Temporal gravity variation · Satellite altimetry

This article is part of the Topical Collection on *Advances of Geophysical and Geological Prospection for Natural Resources in Egypt and the Middle East*

Responsible Editor: Zakaria Hamimi

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Introduction

The Mediterranean Sea is regarded as one of the world's most valuable oceans. Historically, the Mediterranean region has seen a lot of human activity and the Mediterranean coasts have been the conveyor belt for trade and the sink for the region's accumulated impacts (Fusaro et al. 2010). It is essential to understand the natural characteristics of the Mediterranean Basin in order to analyze the various environmental problems and issues that affect the Mediterranean marine and coastal ecosystems.

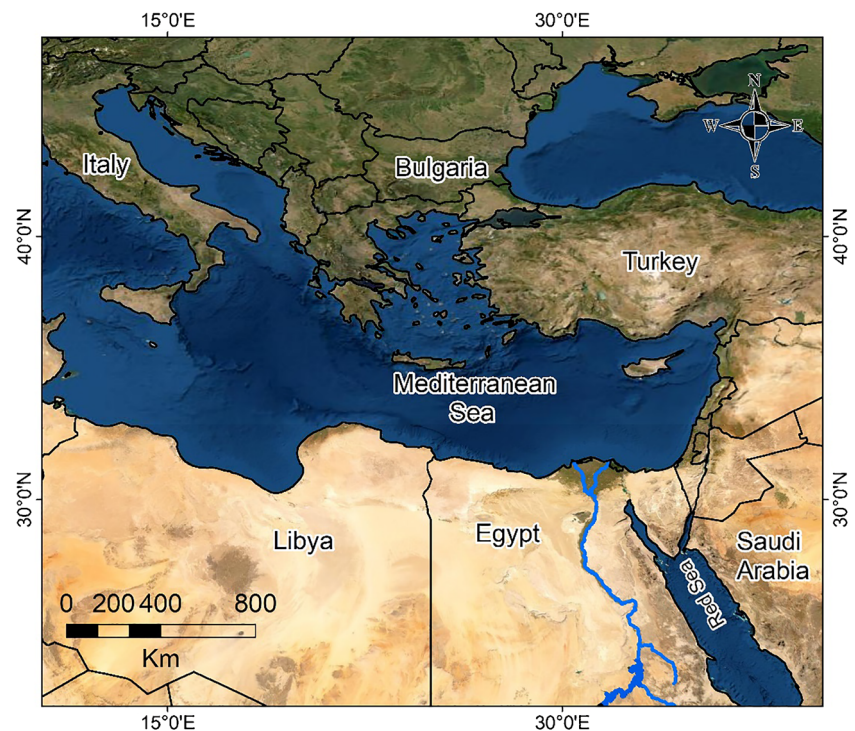
The Mediterranean is known for its heavy winter rainfall and long, dry summers. Despite the fact that the Mediterranean basins have a wide range of climate variability and diversity, many areas can be categorized as arid or semi-arid. The Mediterranean is a transition zone between temperate Europe, where water resources are plentiful, and the arid African and Arabian deserts, where water is scarce (Abotalib et al. 2016; Abotalib et al. 2019; Yousif et al. 2020). Due to a variety of factors ranging from climate change to anthropogenic pressures such as increased water demand for domestic

and industrial uses, expansion of irrigated areas, and tourism activities, the Mediterranean region is experiencing significant stress on its water supplies (Rateb and Abotalib 2020; Hegazy et al. 2020; Khalil et al. 2021). Water resources availability in the Mediterranean has already been affected by environmental changes, and is seriously threatened in future environmental, economic, and demographic scenarios (Garcia-Ruiz et al., 2011). The majority of global hydrological models are focused on predicted precipitation and temperature patterns. However, some studies have shown that land cover has an effect on river discharge and water resources (Khalil et al. 2021). Therefore, climate and land cover changes are likely to intensify water stress in the Mediterranean, owing to a combination of reduced water supply availability and increased water use demand due to economic growth and urban expansion.

The Mediterranean Sea can be considered as a lagoon-type basin (Fig. 1). The long-term hydrological components of the Mediterranean sea level are strongly affected by the North Atlantic Oscillation (NAO) (Woolf et al. 2003). Yet, the general pattern over the Mediterranean region shows anticorrelation between winter sea level and NAO. Additionally, the annual and semiannual components of the water cycle are not well understood (Fenoglio-Marc et al. 2012). Both complex hydrological and climatological settings of the Mediterranean Sea represent a big challenge to investigate the variations of seasonal components and the hydrological interaction between the Mediterranean Sea and the surrounding basins.

The Gravity Recovery and Climate Experiment satellite mission (GRACE) is a joint project between the Deutschen Zentrum für Luftund Raumfahrt (DLR) in Germany and the National Aeronautics and Space Administration (NASA) in the USA that was launched in 2002 to monitor the monthly temporal change in Earth's global gravity field and the Earth's mean gravity field (Tapley et al. 2004a, 2004b). The temporal variation in the gravity field solutions is largely contributed to the mass redistribution on the Earth's surface (Wahr et al. 2004). GRACE is measuring the variability in the terrestrial water storage (TWS); the term of the TWS refers to the total water column that includes the soil moisture, surface water, groundwater, and snow water equivalent. GRACE has been successfully used to track the global change in the TWS. GRACE solutions has been successfully used for monitoring the TWS variations over the Amazon basin (Crowley et al. 2008; Syed et al. 2005; B. D. Tapley et al. 2004; Xavier et al. 2010), Nile basin (Abdelmalik and Abdelmohsen 2019), Mississippi basin (Rodell et al. 2004; Syed et al. 2005), Oklahoma (Swenson et al. 2008), Volta (Ferreira et al. 2012), Arabian-Saharan desert belt (Abdelmohsen et al. 2019, 2020; Ahmed and Abdelmohsen 2018; Othman et al. 2018; Othman and Abotalib 2019; Sultan et al. 2019, 2013), Middle East (Voss et al. 2013), India (Rodell et al. 2009; Tiwari et al. 2009), China (Feng et al. 2013), Michigan (Sahour et al. 2020), California (Scanlon et al. 2012), Lake Victoria (Swenson and Wahr 2009), three Gorges (Wang et al. 2011), estimating flooding (Reager and Famiglietti 2009), drought (Li et al. 2019; Rodell et al. 2018), and to measure the TWS variations over large hydrologic systems (Ahmed

Fig. 1 The location map of the study area



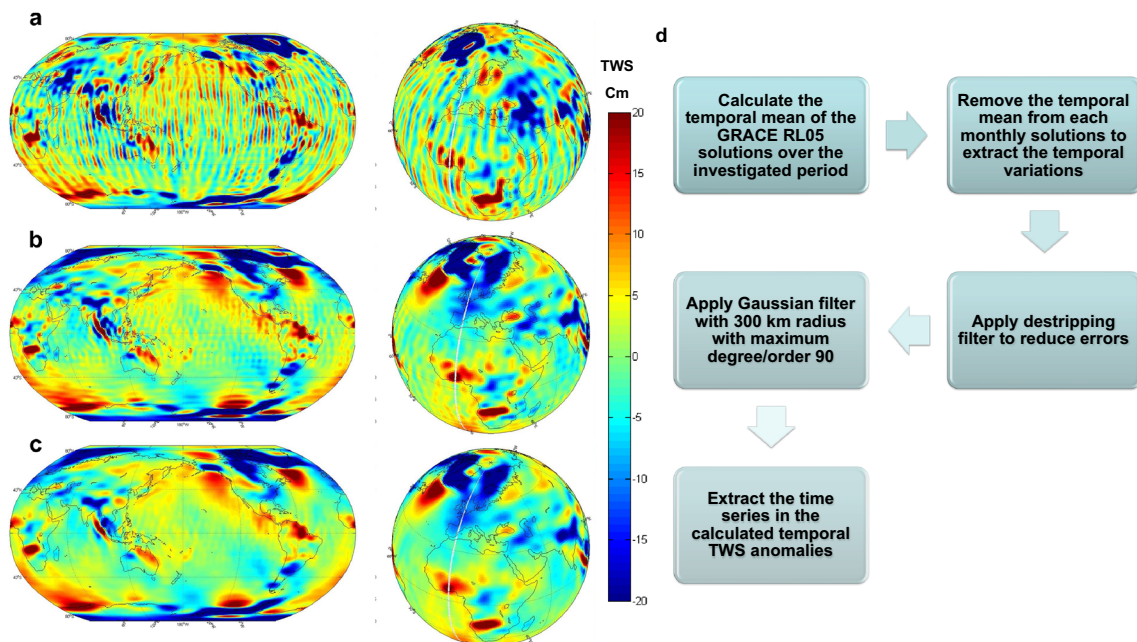


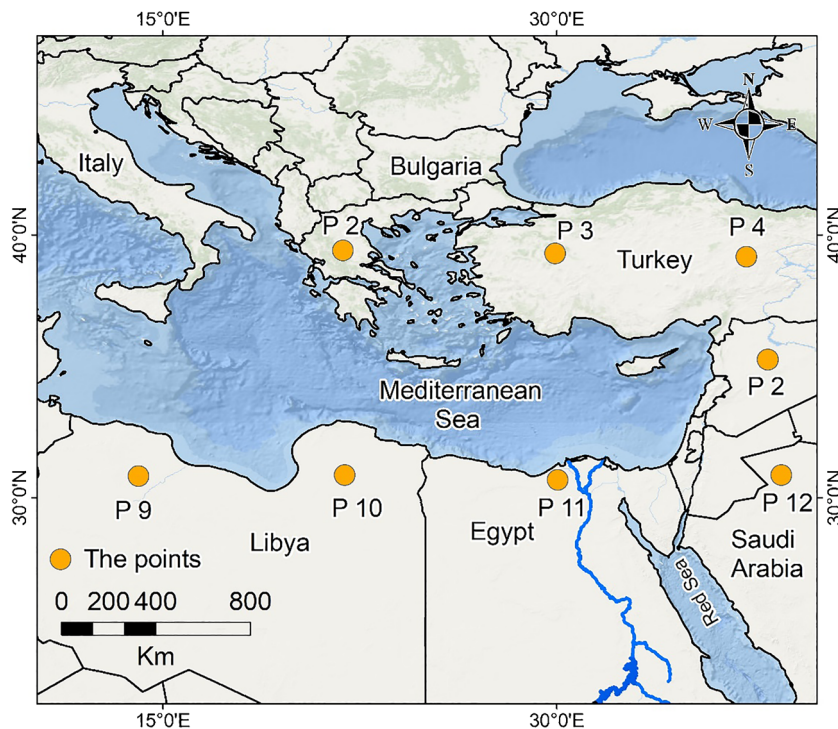
Fig. 2 (a) Un-despiked TWS trend with Gaussian filter 200 km, (b) despiked TWS trend with Gaussian filter 200 km, and (c) TWS trend with Gaussian filter 300 km

et al. 2016; Ahmed et al. 2014; Mohamed et al. 2016; Sultan et al. 2014; Sultan et al. 2013; Wouters et al. 2014).

The Mediterranean Sea is characterized by advanced hydrological system that requires a large-scale data for a better understanding of its situation. In this manuscript, GRACE temporal solutions were integrated with equivalent water

height of different basins and altimetry data to assess the TWS variability in the Eastern Mediterranean region (Fig. 1). The results demonstrate that throughout the investigated period (April 2002 to June 2014), the observed GRACE temporal variations are mainly controlled by the change in the basin equivalent water height and strong oceanic currents.

Fig. 3 Distribution of grid points on land part



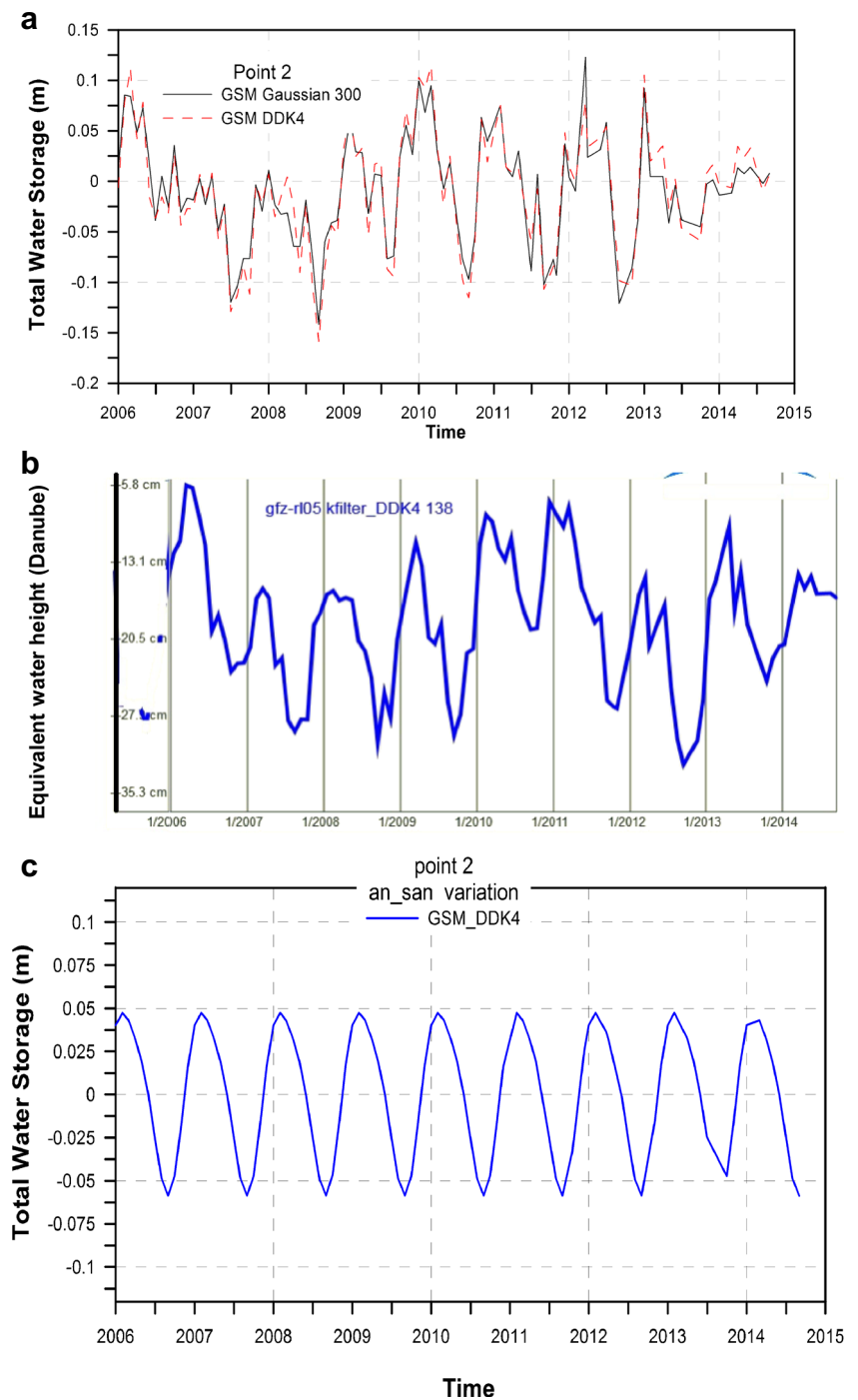
Material and methods

Data processing and analysis

We selected 12 points of 420 km spacing in north-south direction and 720 km in east-west direction over the Mediterranean region to generate the time series of the TWS. To compute the TWS over the non-marine areas, we used GRACE solutions (GSM) from the Geo Forschungs Zentrum Potsdam (GFZ)

Release 5a between January 2006 and July 2014. C20 values of the RL05a were replaced by values from GRACE Technical Note 07. The data were downloaded from the GRACE database provided by the International Data Center of Global Earth Modeling-Potsdam (ICGEM; <http://icgem.gfz-potsdam.de/home>). The GRACE data are represented in terms of fully normalized spherical harmonic up to degree (l) and order (m) of 60. The temporal mean of the gravity field was estimated by removing the long-term mean of the Stokes coefficients from the

Fig. 4 (a) The time series of the TWS in point 2, (b) plot shows the time series of equivalent water height over the Danube basin computed from ICGEM-Potsdam, and (c) annual and semiannual variation in the TWS of point 2

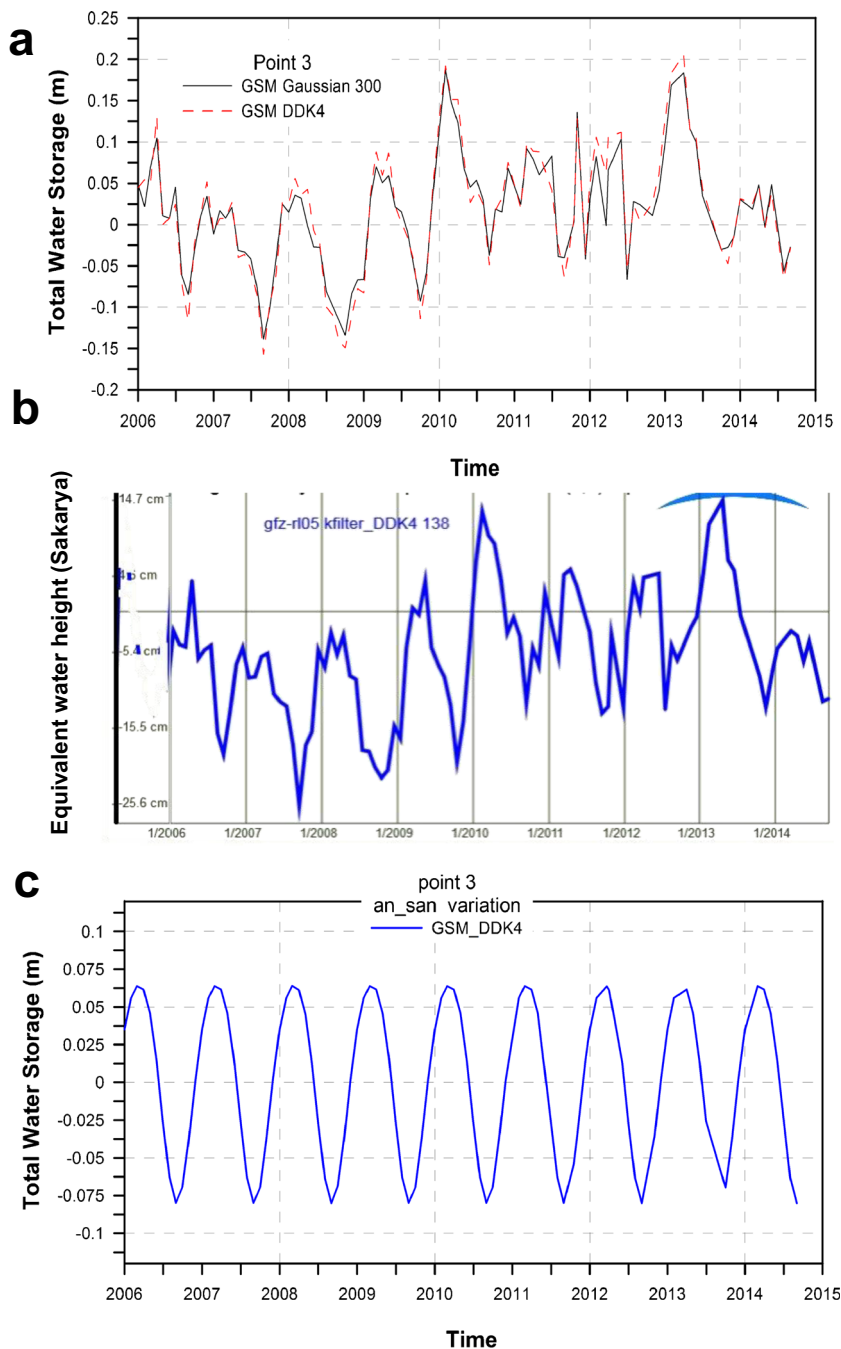


monthly values. Then the temporal variations in these coefficients have been extracted. The DDK destripping filter (Kusche et al. 2009) was applied to remove the correlated errors or stripes (i.e., long, linear, north-to-south-oriented features). A least-square technique was used to best fit to a fourth-order polynomial function for both odd and even degrees. Then the residuals were generated by subtracting those polynomials from the original coefficients. The residuals of monthly gravity anomaly have been used to estimate TWS anomalies over the fully normalized Associated Legendre Polynomials of degree l and order m . The Love numbers were estimated via a linear

interpolation of the calculated data by Han and Wahr (1995). To reduce the ratio of noise to signal of the gravity field solutions, Gaussian-smoothing radius of 300 km was applied.

The gravity field monthly (GSM) solutions which include both atmosphere and ocean corrections for the gravity field solutions are expressed in stocks coefficient to maximum degree 90 (Fenoglio-Marc et al. 2012). To compute the mass change, we reconstructed the signal over the ocean using the GAD GRACE product that contains monthly average values of the ocean model for circulation and tides (OMCT) and the atmospheric model of European Center for the Medium Range

Fig. 5 (a) The time series of the TWS in point 3, (b) the time series of equivalent water height over the Sakarya basin computed from ICGEM-Potsdam, and (c) annual and semiannual variation in the TWS of point 3



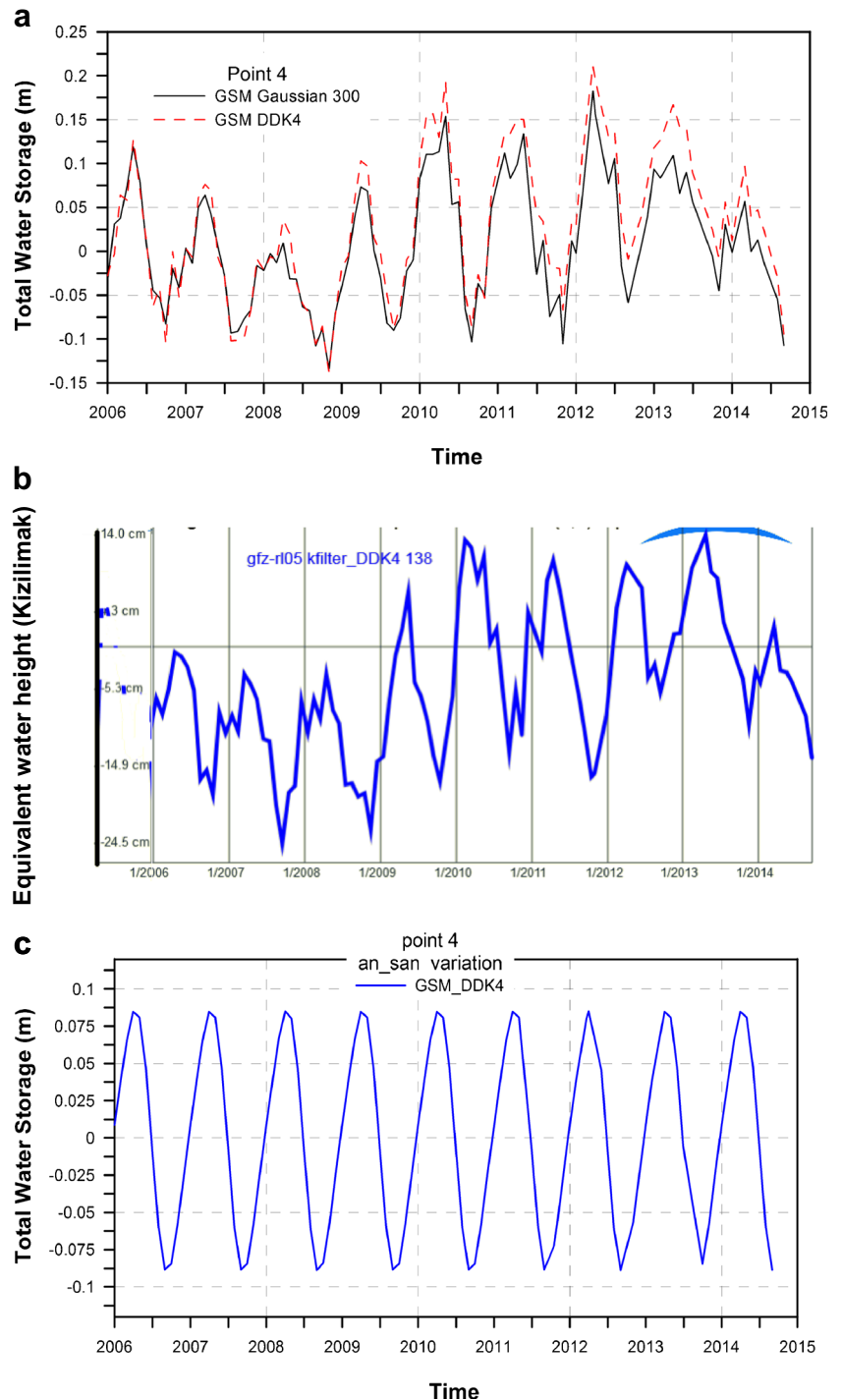
Weather Forecasts (ECMWF) (Flechtner, 2007). The computed the TWS change as a gridded data was defined by the vectors lambda and theta in spherical approximation as:

$$\Delta TWS(\lambda, \theta) = \frac{\rho_e R}{3} \sum_{n=0}^{\infty} \frac{2n+1}{1+k_n^l} \sum_{m=0}^n \bar{P}_{nm}(\cos\theta) (\Delta \bar{C}_{nm} \cos(m\lambda) + \Delta \bar{S}_{nm} \sin(m\lambda))$$

With the mean density of the Earth $\rho_e = 5540 \text{ kg/m}^3$.

1. For the grid points on land, GSM R05a unfiltered solutions applying Gaussian Filter 300 km and GSM with DDK4 filter were applied.
2. For the grid points on marine: GSM R05a unfiltered solutions with GAD R105a unfiltered applying Gaussian

Fig. 6 (a) The time series of the TWS in point 4, (b) the time series of equivalent water height over the Kizilirmak basin computed from ICGEM-Potsdam, and (c) annual and semiannual variation in the TWS of point 4



Filter 300 km used, because GAD filtered with DDK4 are not available.

Satellite altimetry data

The altimetry water levels data from the Lake Monitoring (GRLM) and Hydroweb and Global Reservoir databases were used in this study. These databases were selected because of the time-based resolution and availability for the study area. The Global Reservoir and Lake Monitor data (GRLM) are provided by the United States Department of Agriculture’s Foreign Agricultural Service (USDA-FAS) in collaboration with NASA. The Hydroweb is provided by LEGOS/GOHS (Laboratoire d’Études en Géophysique et Océanographie Spatiale/Equipe Geodesie, Oceanographie et Hydrologie Spatiale) in Toulouse, France, where the Topex/Poseidon, ERS-1 and 2, Envisat, Jason-1, and GFO satellites have used to derive the altimetry data. The data is monthly average water level and referenced to GRACE Gravity Model 02 (GGM02) geoid.

Stripes signal over the Eastern Mediterranean region

The North African regions reveals strong stripes signal oriented to the north-south direction. After applying Gaussian smoothing radius 200 km and removing GIA, the contribution of stripes still highly affecting the mass signal (Fig. 2a). Therefore, we further applied Gaussian smoothing radius 200 km, DDK filter, and removing GIA (Fig. 2b), which partially removed most of stripes that associated to the true signal but partial contribution of strip signals over chad and Libya can still be seen. As a final step to remove the noise and stripe contributions, we applied Gaussian smoothing radius 300 km, destriping filter, and removing GIA (Fig. 2c). The results were improving the coveted signal but with mass losing due to feebleness of signal of water mass over the desert area of North Africa.

Results and discussion

TWS in points on land

The distribution of grid points on the land part is shown in Fig. 3. In the northern part of the Mediterranean Sea, point 2 is located in Greece where points 3 and 4 are located in Turkey

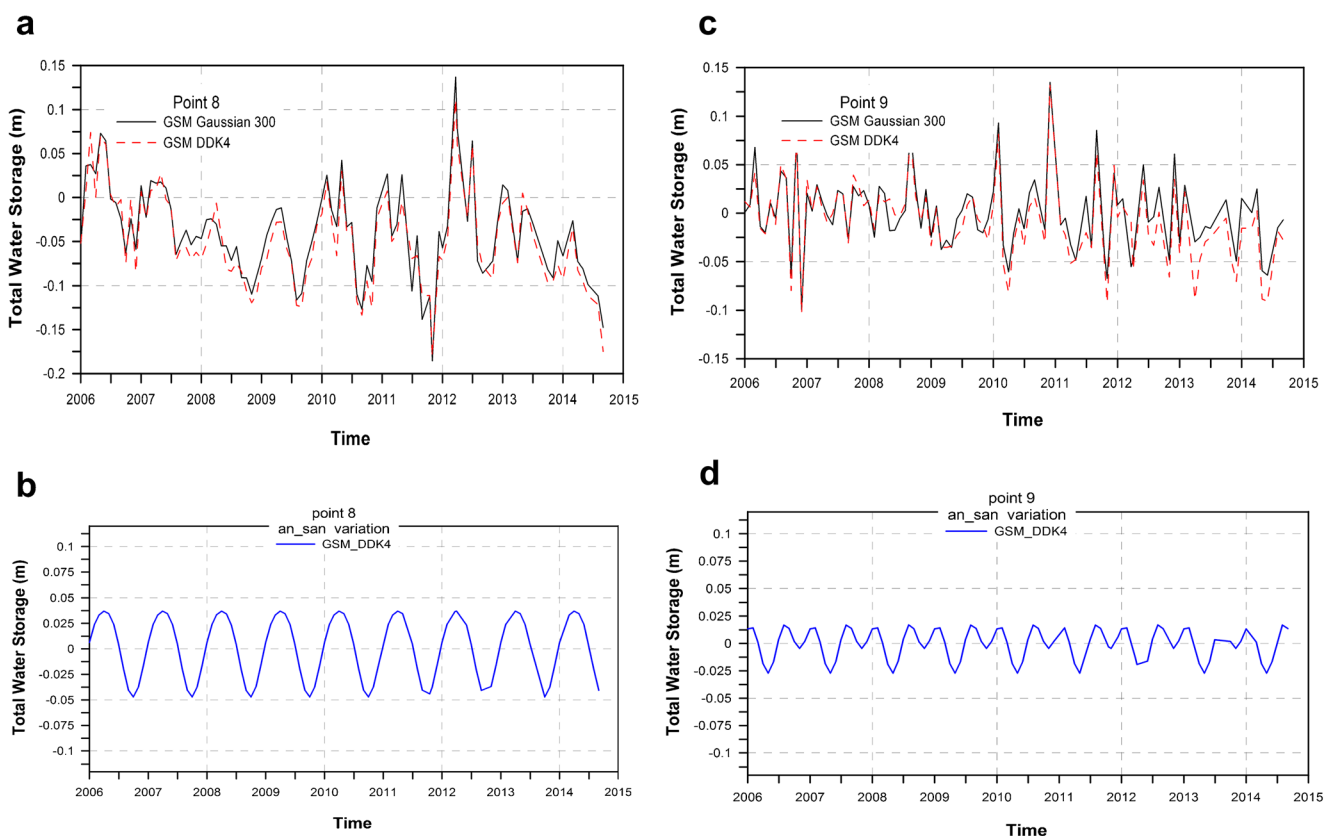


Fig. 7 (a) The time series of the TWS in point 8, (b) the time series of the TWS in point 9, (c) the annual and semiannual variation in the TWS in point 8, and (d) the annual and semiannual variation in the TWS in point 9

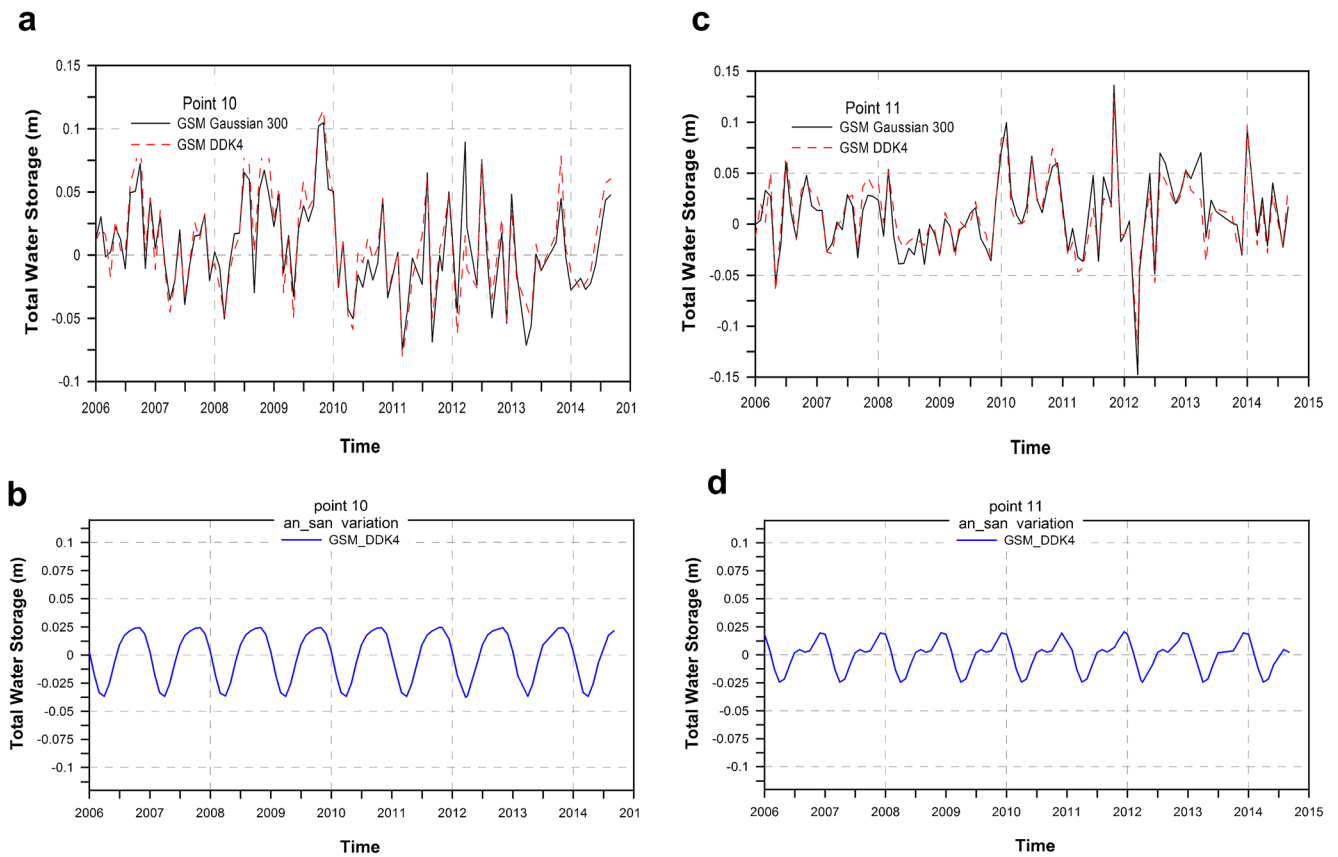


Fig. 8 (a) The time series of the TWS in point 10, (b) the time series of the TWS in point 11, (c) the annual and semiannual variation in the TWS in point 10, and (d) annual and semiannual variation in the TWS in point 11

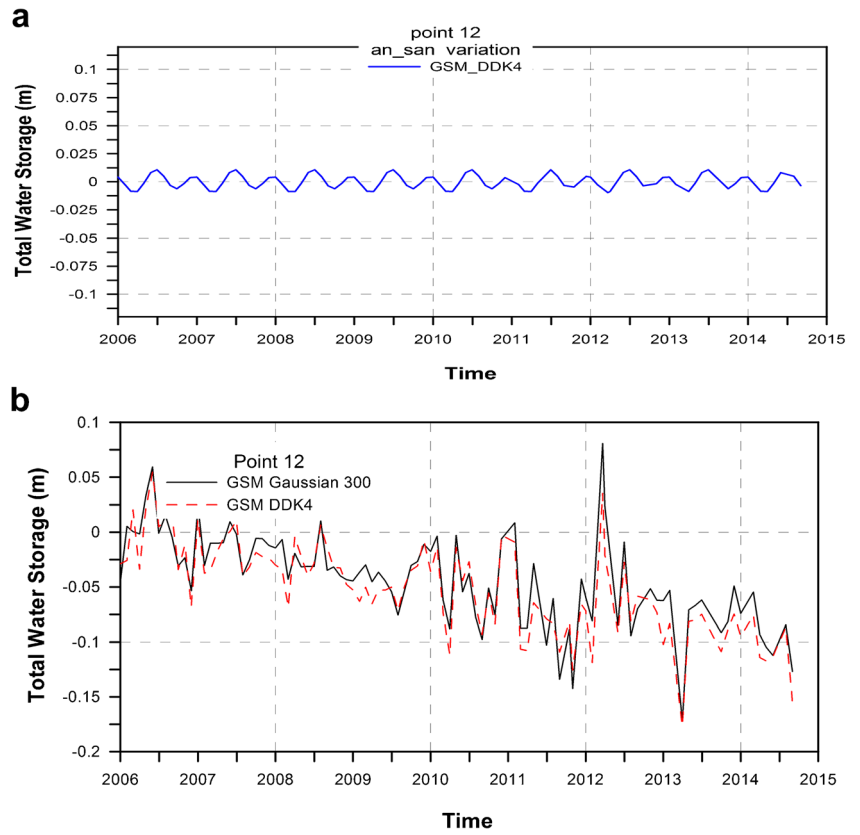
and east of Mediterranean Sea; point 8 is in Syria. In the southern part, point 9 is located on the coast of Libya while points 10 and 11 are located on the north coast of Egypt. The point 12 is located in Saudi Arabia. It is very important to see the TWS variation in every point and how likely it was influenced by the

Mediterranean Sea and the nearby basins. Generally the points of the coast area on the northern part of Mediterranean Sea (points 2, 3, and 4) revealed high annual and semiannual amplitude in the time series of the TWS which is larger than the other points of land parts. By comparing our results of point 2 to the

Table 1 Amplitude, phase, mean, and trend of the most dominant periodic features of the grid points on Mediterranean region

Point No.	Annual amplitude	Annual phase	Semiannual amplitude	Semiannual phase	Mean (m)	Trend (m)
Point 1	0.025	-0.0094	0.0047	0.061	0.0032	0.0034
Point 2	0.0513	0.1386	0.0088	-0.049	-0.0051	0.0072
Point 3	0.0722	0.1783	0.0079	-0.0853	-0.0069	0.0038
Point 4	0.085	0.2327	0.0127	-0.1284	-0.0127	-5.34×10^{-4}
Point 5	0.0251	-0.1271	0.012	0.0803	0.0102	0.0064
Point 6	0.029	-0.0628	0.0079	-0.0572	-0.0052	5.90×10^{-3}
Point 7	0.0314	0.0695	0.009	-0.0174	-0.002	0.0088
Point 8	0.042	0.2448	0.0051	-0.017	-0.0011	0.005
Point 9	0.0114	-0.1852	0.0158	0.0775	0.0131	0.0089
Point 10	0.0304	-0.2672	0.0073	-0.0422	-0.0037	0.0063
Point 11	0.0163	-0.167	0.0104	-0.0044	-5.82×10^{-4}	0.0104
Point 12	0.0035	-0.4455	0.0079	-0.0293	-0.0028	0.0074

Fig. 9 (a) The time series of the TWS in point 12, (b) the annual and semiannual variation in the TWS

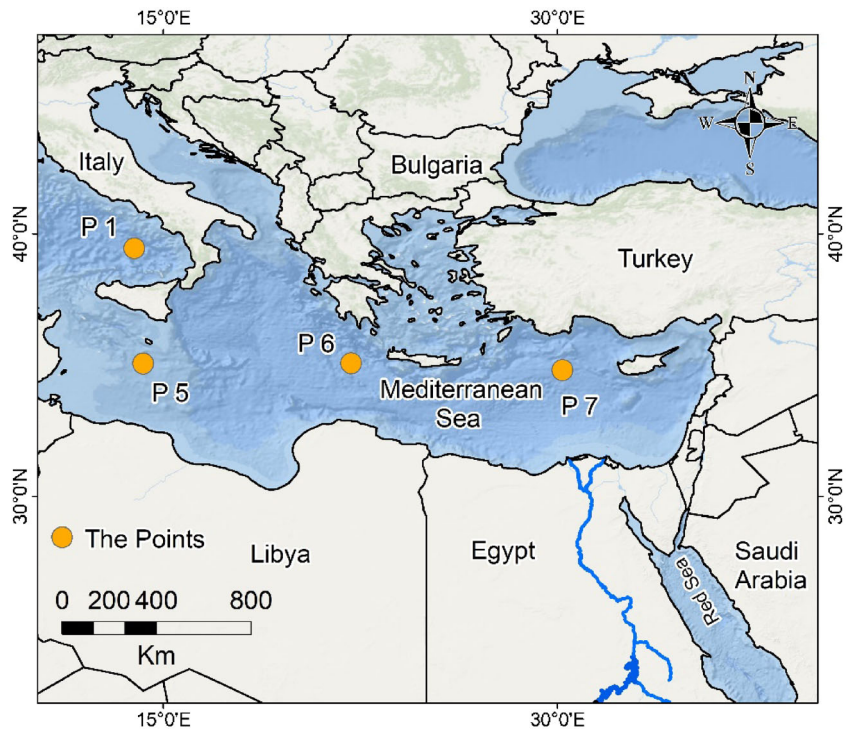


computed equivalent water height over the Danube basin based on ICGEM-Potsdam (Fig. 4), the results showed similar behavior as the Danube basin. Most of the maximum increasing periods were the same in the two time series such as January of

2006, May of 2010, and February of 2011. The estimated annual amplitude of the TWS (Fig. 4c) was about 5 cm.

Similarly, comparing the TWS computed of point 3 to the computed equivalent water height over the Sakarya basin in

Fig. 10 The distribution of points over the Mediterranean Sea



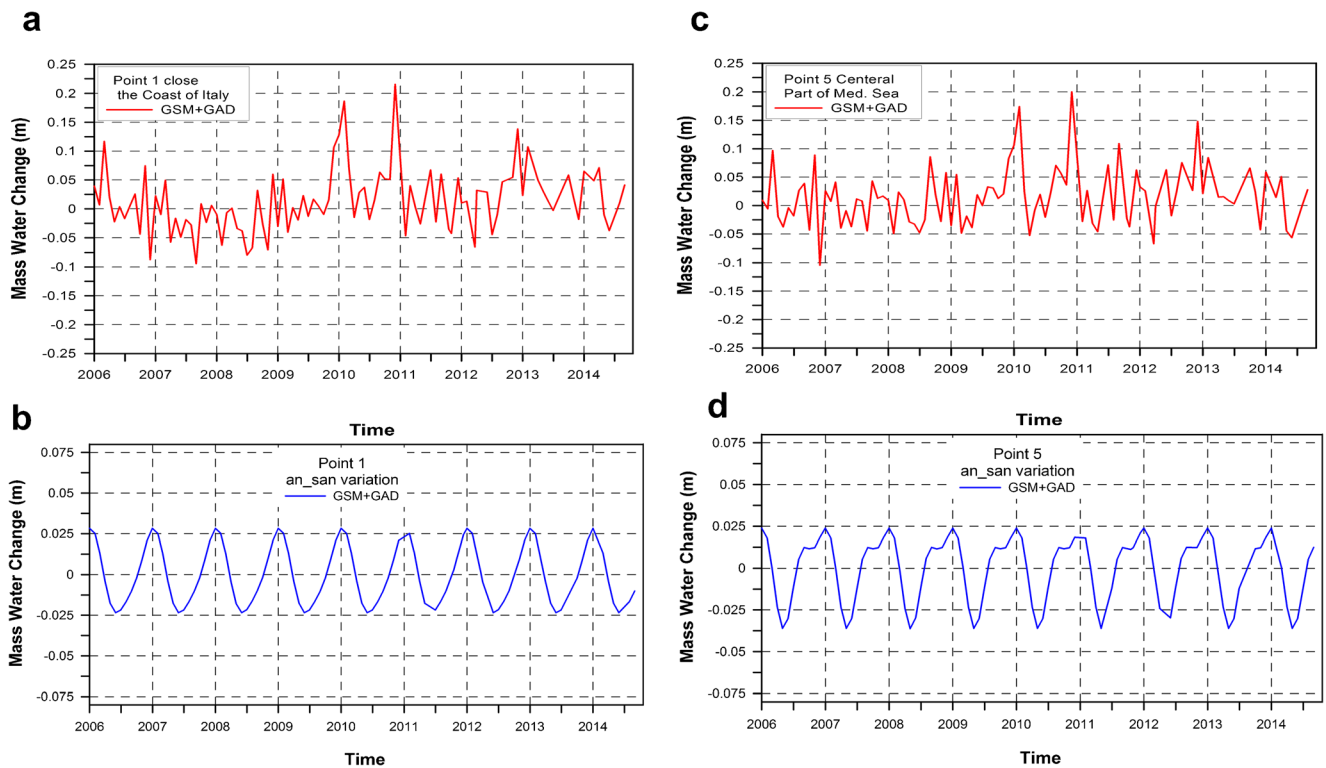


Fig. 11 (a) The time series of the TWS in point 1, (b) the time series of the TWS in point 5, (c) the annual and semiannual variation in the TWS in point 1, and (d) the annual and semiannual variation in the TWS in point 5

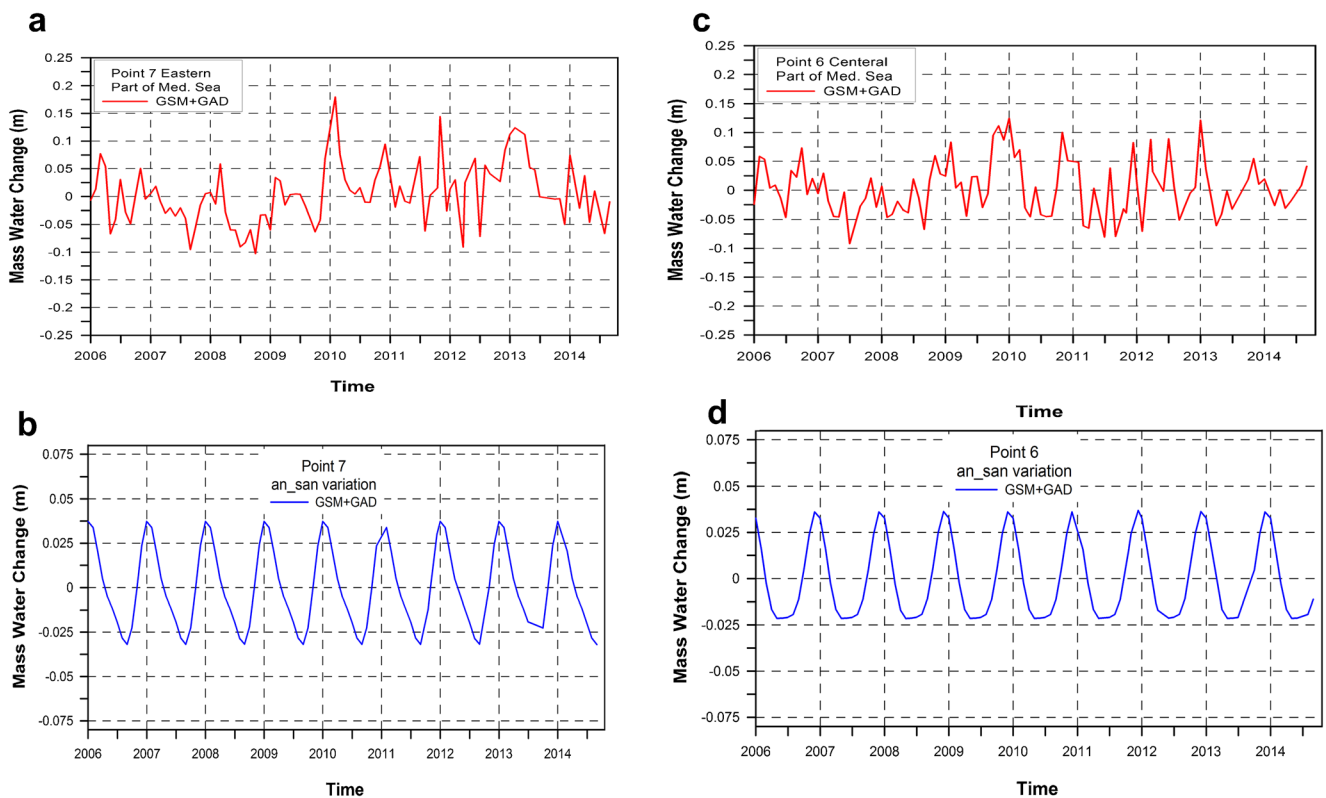


Fig. 12 (a) The time series of the TWS in point 7, (b) the time series of TWS in point 6, (c) the annual and semiannual variation in the TWS in point 7, and (d) the annual and semiannual variation in the TWS in point 6

Turkey based on ICGEM-Potsdam (Fig. 5) also indicated the same behavior. Most of the periods of maximum increase are similar in the two time series such as in January of 2006, March of 2010, and September of 2013. The annual amplitude of the TWS (Fig. 5c) was about 7 cm.

By comparing the TWS computed in point 4 in Turkey to the computed equivalent water height over the Kizilirmak basin in Turkey based on ICGEM-Potsdam as shown in Fig. 6, the point 4 is following the same behavior in Kizilirmak basin, where most of maximum increasing periods in time series of the TWS are similar to the crests in time series of equivalent water height for example in November of 2006, September of 2010, and September of 2011. The annual amplitude of the TWS (Fig. 6c) was about 8 cm.

The time series in point 8 (Fig. 7a and c) showed annual amplitude of the TWS of approximately 4 cm. We can see also from the computed TWS in the previous grid points that the GSM RI05a solutions filtered by Gaussian 300 and filtered by DDK4 have the same contribution in all-time series. So, there is no clear difference between the smoothing of the two filters.

The points of the southern part of Mediterranean Sea (points 9, 10, 11, and 12) revealed low annual and semiannual amplitude in the time series of the TWS. The point 9, which is located in the coastal area of Libya, indicated an annual amplitude of about 1 cm (Fig. 7b and d). On the other hand, point 10 showed an annual amplitude of about 3 cm (Fig. 8a and c). We suggest that the presence of the two points (9 and 10) in such arid region (i.e., the Sahara) and the lack of river basins in this area resulted in a minor annual change in the TWS computed over this part. Point 11 which is located at the Egyptian Nile Delta also showed low annual amplitude of about 1 cm (Fig. 8b and d). Even with the presence of the cultivated lands and ace in addition to the Nile River discharge, the effect of the surrounding desert areas (Western and Eastern deserts) predominates the TWS signal.

The time series of point 12 at Saudi Arabia showed an annual amplitude of about 3 cm (Fig. 9). The variation in the TWS at this point has a different trends compared to the other grid points in the south Mediterranean. The variation in the TWS followed the same trend of Tigris and Euphrates basin. It is clear from the points in southern Mediterranean Sea that the time series of TWS in the northern part is ranging between 4 and 8 cm due to the presence of basins and cultivated land where the other points of southern part have annual amplitude ranged between 2 and 3 cm due to the presence of large arid to semiarid areas like western desert in Egypt and Libya (Table 1).

Mass water variations in the marine part

The distribution of grid points in the marine part is shown on Fig. 10. Point 1 is located close to the coast of Italy and the points 5 and 6 are located in the middle of the Mediterranean Sea, while point 7 is located in the eastern part of the

Mediterranean Sea. The GSM solutions were used and additional the GAD solutions were involved to examine the oceanic circulation effect. The time series of the TWS at point 1 showed maximum values in January of 2010 and January of 2011, where the annual amplitude was about 2.5 cm (Fig. 11a and c).

The time series of the TWS at point 5 showed the same behavior (Fig. 11b and d), which indicates that this part of the Mediterranean Sea is affected by oceanic currents. The annual amplitude of the TWS was estimated as 2.5 cm. The time series of the TWS at point 6 in the middle of the Mediterranean Sea showed an annual amplitude of 2.9 cm and semiannual amplitude of 0.7 cm (Fig. 12 a and c). The TWS time series of point 7 in the eastern part of the Mediterranean Sea indicated an annual amplitude of 3 cm and semiannual amplitude of 0.9 cm with the maximum values were in January of 2010 and November of 2011 as shown in Fig. 12b and c.

Conclusion

The present study monitors the variations of the GRACE-derived TWS in the eastern Mediterranean region by comparing the GRACE-derived TWS for 12 points with the equivalent water height over different basins based on the International data Center of Global Earth Modeling-Potsdam (ICGEM). The TWS time series from the different points of the land part indicated that the annual amplitude of the points located in the northern part of Mediterranean Sea showed high values between 4 and 8 cm. This can be attributed to the presence of river basins and large green spaces. On the other hand, the points located in the southern part of the Mediterranean showed annual amplitude between 2 and 3 cm. This is due to the predominance of large deserts (i.e., the North African Sahara). Regarding points in the marine part, points 5 and 6 showed same maximum values in January of 2010 and 2011 which indicates that the middle part of the Mediterranean Sea is affected by strong oceanic currents. Generally, the findings indicated that the annual amplitude of land points is larger than the annual amplitude of marine points. The current study indicates that satellite gravity data is a valuable source of data in monitoring the change in total water storage and understanding the behavior of variation in the studied region.

Acknowledgements The present work has been conducted in cooperation with Physical and Satellite Geodesy Institute (PSGD), TU-Darmstadt, Germany. We thank the editor and reviewers for their instructive comments and suggestions, and our colleagues from Geodynamic Department, National Research Institute of Astronomy and Geophysics (NRIAG), Egypt.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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