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Black Sea level variability and its driving factors in the last two decades

Zhiqiang Wen

wenzhiqiang211@mails.ucas.ac.cn

College of Earth and Planetary Sciences, University of Chinese Academy of Sciences
https://orcid.org/0000-0003-4004-6268

Peyman Saemian

University of Stuttgart

Fan Xu

Wenke Sun

Mohammad J. Tourian

University of Stuttgart https://orcid.org/0000-0002-4200-0848

Article

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Black Sea level variability and its driving factors in the last two decades

Zhiqiang Wen[1,2,*], Peyman Saemian[2], Fan Xu[3], Wenke Sun[1], and Mohammad J. Tourian[2]

1 College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, China.

2 Institute of Geodesy, University of Stuttgart, Stuttgart, Germany.

3 School of Mathematics and Maxwell Institute for Mathematical Sciences, The University of Edinburgh, Edinburgh, UK;

*Correspondence: wenzhiqiang211@mails.ucas.ac.cn

Abstract While global sea level rise is a major concern for coastal regions, understanding water level variability in inland seas like the Black Sea is crucial due to its sensitivity to river inflow, evaporation, and limited ocean connectivity. Using satellite altimetry and satellite gravity data from 2003 to 2023, this study analyzes the long-term and seasonal variations in the Black Sea water levels, as well as local sea level variability and its driving factors. The results indicate that the sea level in the Black Sea experiences a positive trend of 1.04 ± 0.39 mm/a. This comes, however, with a negative trend on a seasonal scale during winter (–1.14 ± 0.27 mm/a), which contrasts with the rising trends observed in other seasons. We found that the loading deformation induced by global mass redistribution contributes to 39% of the Black Sea level trend, leading to an overestimation of actual climate-induced sea level change by 0.41 mm/a. Additionally, reduced precipitation and river inflow increase salinity, driving the decline in steric sea level. On the other hand, it has also increased the water mass of the Black Sea, compensating for the steric sea level drop.

Keywords: the Black Sea; steric sea level rise; river discharge; GRACE; Altimetry; loading deformation.

Key Points:

(1) The Black Sea level rose by 1.04 ± 0.39 mm/year from 2003 to 2023;

(2) Loading deformation induced by global mass redistribution contributed 39% to the long-term trend of the Black Sea level rise;

(3) The rise in salinity of the Black Sea water leads to an increase in mass, which compensates for the decline in the steric sea level.

1 Introduction

Sea level change is a critical indicator of climate and environmental variability (Volkov and Landerer, 2015), influenced by both natural and anthropogenic factors (Church and White, 2011; Slangen et al., 2016; Dangendorf et al., 2017; Frederikse et al., 2020). With the intensification of global warming, sea level rise poses a significant threat to coastal regions and islands, leading to severe socio-economic challenges (Nicholls and Cazenave, 2010). While global sea level change reflects large-scale climate trends, regional sea level variations can differ substantially from the global average due to local factors (Chen et al., 2017). In some areas, processes like crustal subsidence and regional climate phenomena can amplify sea level rise beyond the global average (Oelsmann et al., 2024), while in others, tectonic uplift and post-glacial rebound may offset it entirely or even lead to a decline (Mazzotti et al., 2008).

The Black Sea, the world's largest inland sea, is located at the intersection of Europe and Asia, and connects to the Mediterranean via the Bosphorus Strait (Figure 1a). It features a deep southern basin with depths exceeding 2000 meters, and a relatively wide continental shelf in the northwestern region. Hydrologically, the Black Sea is influenced by the monsoon climate and receives inflow from several major rivers such as the Danube, Dniester, and Dnieper within its drainage basin (Karageorgis et al., 2009). Notably, nearly one-third of the sea's total water volume originates from freshwater inflow from the rivers over the European continent (Bakan and Buyukgungor, 2000). This large-scale freshwater input is strongly modulated by climatic factors, including precipitation, evaporation, and continental hydrology (Stanev and Peneva, 2001). These climate-driven changes in freshwater balance are linked to the Black Sea level variability.

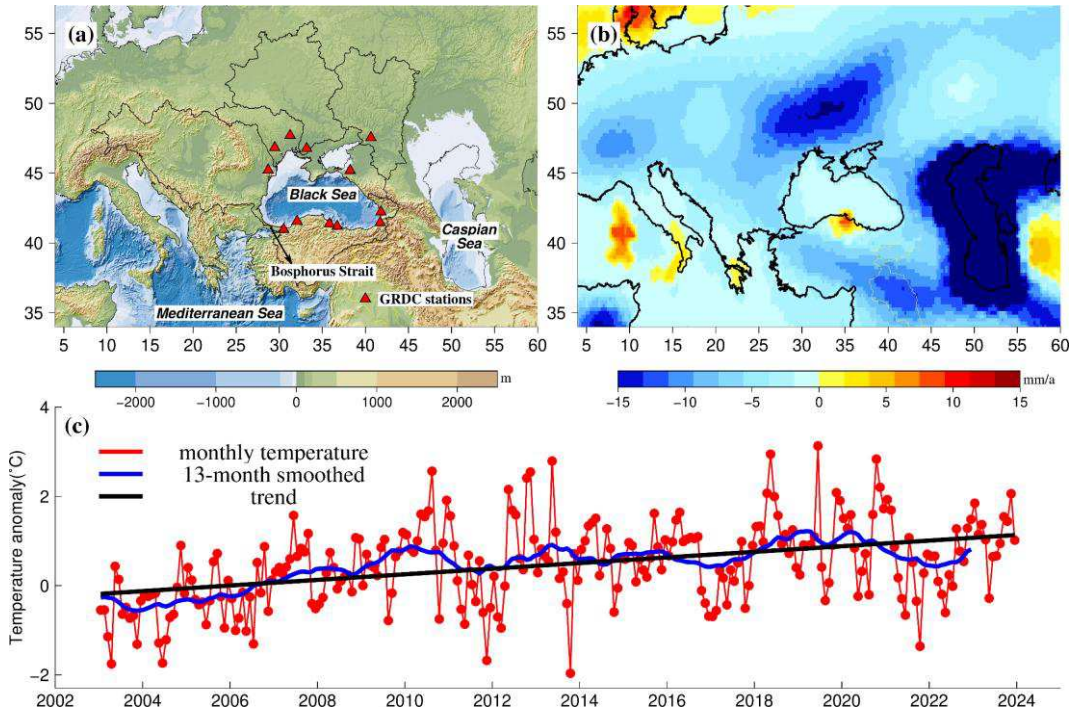


Figure 1. (a) The geographic overview of the study area, the Black Sea, including six coastal river basins; (b) the long-term surface mass change annual trends around the Black Sea from 2003 to 2023 as observed by GRACE; and (c) the sea surface temperature variations in the Black Sea over the same period.

Geometric sea level changes observed by satellite altimetry encompass solid Earth geophysical processes, such as GIA and loading deformation, which have not been fully explored in the Black Sea level studies. Previous research has indicated that from 1993 to 2014, global seabed subsidence caused by surface mass redistribution occurred at an average rate of 0.1 mm/a (Frederikse et al., 2017). This global-scale ocean bottom deformation is significant and comparable to estimates of deep steric sea level change (Vishwakarma et al., 2020). Wen and Sun (2025) investigated the contribution of loading deformation induced by mass changes in the Gulf of northern Australia using geodetic methods. However, due to the uncertainty inherent in altimetry data, the resulting influence on sea level estimates was considered negligible. Over the past two decades, the nearby Caspian Sea has experienced substantial water mass loss (Figure 1b), with a decline rate between 2002 and 2015 approximately 20 times greater than the rate of global sea level rise (Chen et al., 2017). Similarly, significant mass loss has also been observed in the northern Black Sea region. These large-scale mass redistributions induce measurable loading deformation of the Earth's surface, complicating the assessment of climate-driven sea level variations.

Apart from the loading-induced variations, river runoff plays a direct role in regulating sea level changes in the Black Sea by contributing to increases in ocean mass. The Black Sea receives inflow from several major rivers, with the Danube, Dniester, Dnieper, and Don being the largest contributors. The total annual river discharge into the Black Sea is approximately 364.9 km^3, with the Danube River, the largest tributary, contributing about 54% of the total freshwater input (Bondar, 2007). On the other hand, steric sea level also makes a significant contribution to sea level variations. Steric changes result from the thermal expansion of seawater and are typically estimated through steric calculations. From 2003 to 2023, sea surface temperature in the Black Sea has shown a continuous increase (Figure 1c). However, due to the limited availability of in situ temperature and salinity observations in the Black Sea, many steric sea-level estimates rely on reanalysis data. Novitskaya et al. (2023) reconstructed a steric sea level time series for the Black Sea from 2002 to 2016 by integrating satellite altimetry and gravity observations. Their results revealed a negative linear trend in steric sea level, with a rate of –0.59 ± 0.21 cm/a. This trend was independently validated by instrumental observations derived from Argo float CTD profiles, which confirmed the interannual variability of the reconstructed series. By applying the sea level budget equation, steric sea level variations can be estimated using a combination of satellite altimetry and GRACE observations.

Despite the progress made in understanding the drivers of the Black Sea level change, several critical gaps remain unaddressed. Existing studies have primarily focused on geometric sea level variations derived from altimetry, often without fully accounting for the underlying solid Earth processes such as loading deformation or glacial isostatic adjustment (GIA), which can bias sea level estimates. Furthermore, while river runoff and steric effects have been individually investigated, there is still a lack of integrated analyses that reconcile mass and steric contributions within a consistent sea level budget framework. The limited availability of in situ observational data in the Black Sea region further constrains the validation of satellite-based or reanalysis-derived estimates, adding uncertainty to trend assessments. Therefore, a comprehensive approach is needed that explicitly incorporates geophysical corrections, mass contributions, and steric effects to improve the accuracy of the Black Sea level change assessments.

To address the above issues, this study focuses on quantifying the contribution of loading deformation to sea level changes in the Black Sea using surface mass variation data from satellite

gravity observations. It further investigates the long-term and seasonal variations of sea level over the past 21 years (2003–2023) by integrating altimetry data and quantifying the regional mass balance using precipitation and evaporation data. Furthermore, the study separates the contributions of mass-related and steric components to provide a clearer understanding of the mechanisms driving sea level changes in the region.

2 Datasets and methods

2.1 Datasets

To investigate the characteristics of sea level changes in the Black Sea, this study utilizes sea level anomaly products from the Copernicus Climate Change Service (C3S), covering the period from January 1993 to December 2023. The data processing focuses on the stability and consistency of the sea level record, relying on a stable dual-satellite constellation. This dataset is specifically designed for monitoring long-term sea level evolution, supporting climate applications, and ocean/climate indicator analysis. The spatial resolution is 1/4° × 1/4°, and it has been corrected for ionospheric delay, electromagnetic bias, dry and wet tropospheric effects, solid Earth tides, pole tides, ocean tides, and inverse barometer effects. The altimetry data represent anomalies relative to the 20-year mean from 1993 to 2012.

The GIA correction for satellite altimetry is applied using the model from Peltier et al. (2018). Additionally, temperature and salinity data from the C3S Black Sea ocean reanalysis dataset (spatial resolution 0.025° × 0.025°, Lima et al., 2020) are used to estimate steric sea level. This study also employs four GRACE Mascon products from the Jet Propulsion Laboratory (JPL), CSR, GSFC, and ANU to constrain water mass changes in the Black Sea, covering the period 2003–2023. Data preprocessing includes restoring degree-1 coefficients (Swenson et al., 2008) and replacing C_{20} (Cheng et al., 2011) and C_{30} (Loomis et al., 2020) with values derived from satellite laser ranging (SLR). To study sea level changes, the GAD product is restored. And three GIA models from A et al. (2013), Peltier et al. (2018), and Caron et al. (2018) are used to remove post-glacial rebound (GIA) signals.

Furthermore, precipitation, evaporation, and river runoff data are used to analyze the drivers of sea level change. The study utilizes monthly mean reanalysis data from the ERA5 model, provided by Copernicus Climate Change Service (C3S) (Hersbach et al., 2023), with a spatial

resolution of 0.25° × 0.25° and covering the period 2003–2023. Basic information of all the datasets used in this study can be found in Table S1.

2.2 Methodology

2.2.1 Loading deformation

Global surface mass variations induce widespread loading deformation, significantly affecting geometric sea level changes, necessitating load correction. Assuming a surface mass redistribution $\Delta m(\theta', \varphi')$, the load displacement within the study area is calculated as follows:

$$U_{dis} = \iint \Delta m(\theta', \varphi') G(\alpha) \cos\varphi' d\theta' d\varphi' \quad (1)$$

Where Δm represents surface mass variation (in our case, from GRACE, global mass grids are used for integration), α is the angular distance between the load computation point and the load source, and $G(\alpha)$ is the load Green's function, typically derived from the PREM Earth model (Farrell, 1972).

2.2.2 Steric sea level

We analyze salinity and temperature (converted from potential temperature field) data from Copernicus Marine Service to integrate ocean density from the surface to depth of 2,000 m following Equation 2 from Gill and Niller (1973) for steric variation:

$$\Delta h_{steric} = \frac{-1}{\rho_0} \int_{-H}^{0} (\rho - \bar{\rho}) dz \quad (2)$$

2.2.3 Geometric sea level budget

The total sea level change observed by altimetry includes sea level variations caused by mass changes, steric sea level changes due to seawater density variations, and the effects of Earth's deformation.

$$SSH_{alt} = SSH_{mass} + \Delta h_{steric} + U_{dis} \quad (3)$$

3 Results

3.1 Long-term and seasonal variations in the Black Sea water level

Altimetry data estimates indicate that the overall sea level in the Black Sea exhibited an upward trend from 2003 to 2023 (solid blue line in Figure 2a), with a rate of 1.04 ± 0.39 mm/a, suggesting a stable sea level rise over the past two decades. However, this trend is not strictly linear, as there

are significant interannual fluctuations and short-term anomalies, such as a decline from 2005 to 2010, followed by rapid increases from 2010 to 2012 and after 2020. Beyond the long-term trend, this study further investigates the seasonal variations in sea level. Seasonal trends refer to the changes occurring in specific months throughout the study period (e.g., the spring trend is calculated using data from March to May of each year). The year is divided into four seasons: spring (MAM), summer (JJA), autumn (SON), and winter (DJF). Figures 2b–2e present the seasonal sea level trends in the Black Sea from 2003 to 2023.

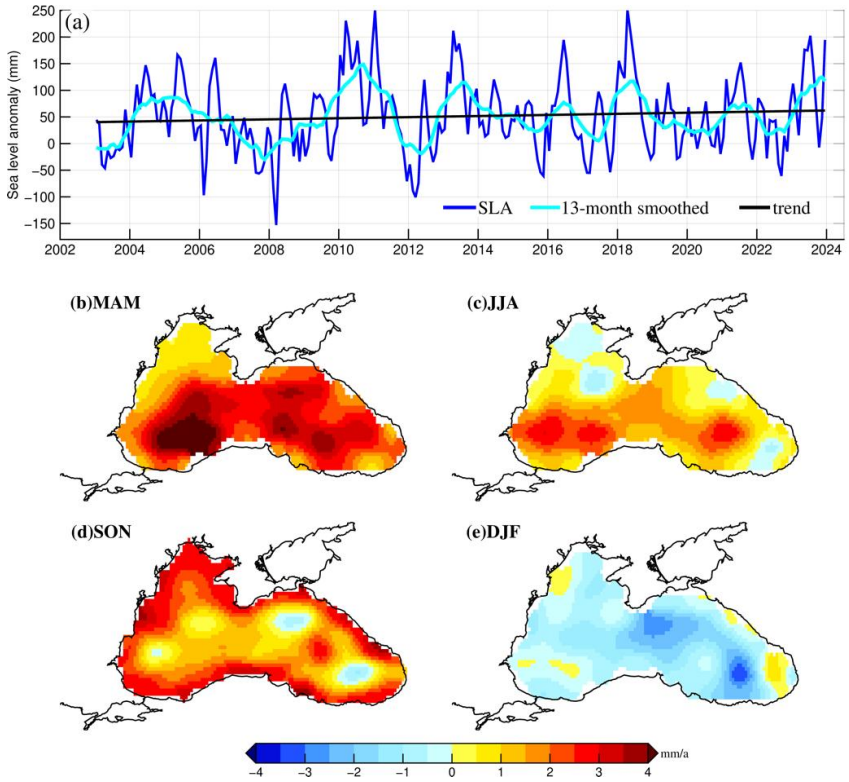


Figure 2. (a) Sea level changes in the Black Sea basin from 2003 to 2023 constrained by altimetry, with the cyan solid line representing the 13-month moving average of altimetry-based sea level; (b)–(e) represent the long-term seasonal sea level trends.

The seasonal variation of sea level in the Black Sea exhibits clear spatial and temporal heterogeneity (Figure b - e). Sea level trends are significantly positive in the central and western regions during spring (MAM) and autumn (SON), while summer (JJA) shows a slight overall increase with localized decreases. In contrast, winter (DJF) presents a pronounced decline (-1.14 ± 0.27 mm/a) across most of the basin, with the most substantial decrease occurring in the

southeastern region. These seasonal sea level changes correspond closely with variations in net precipitation (precipitation minus evaporation, P–E) and river runoff (Figure 3). During spring and autumn, P–E slightly increases. In spring, runoff decreases only marginally, whereas in autumn, the reduction in runoff is more significant, potentially offsetting the sea level rise induced by P–E. In winter, both P–E and runoff show substantial declines, likely contributing to the observed sea level drop during DJF. In summer, although P–E slightly increases, the marked reduction in runoff suggests that the total freshwater input is insufficient to sustain sea level rise. Overall, the seasonal variability of the Black Sea level is jointly regulated by changes in net precipitation and river discharge, with their relative contributions differing across seasons.

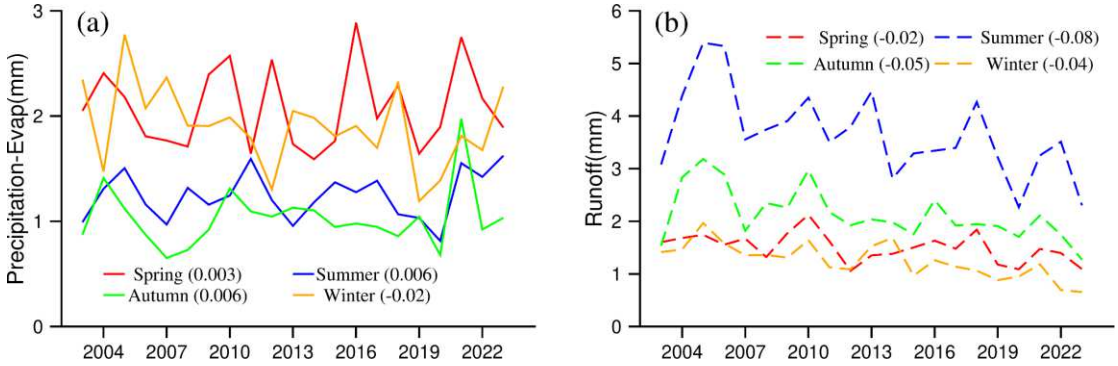


Figure 3. (a) Long-term seasonal trends in precipitation minus evaporation, and (b) long-term seasonal trends in runoff. Linear trend values for each season are indicated in the legends (in mm/year).

3.2 Contribution of loading deformation to the long-term sea level trend

Geometric sea level change is influenced by multiple factors, with solid Earth deformation playing a significant role. According to the studies of Rao and Sun (2022) and Wen et al. (2023), calculating loading deformation requires considering global mass variations. Therefore, we estimate the loading deformation in the Black Sea basin by integrating global mass changes constrained by GRACE with the Green's function integration method. Figure 4 illustrates the impact and spatial distribution of different Earth deformation factors on sea level change rates (mm/a) in the Black Sea region. Figure 4a presents the contribution of GIA, which exhibits an overall negative trend, indicating that GIA effects lead to gradual crustal subsidence in the region. Using the GIA model from A et al. (2013), Peltier et al. (2018), and Caron et al. (2018), the regional mean crustal subsidence rate is estimated at –0.33 ± 0.03 mm/a, contributing slightly to sea level decline in the

Black Sea. Figure 4b represents loading deformation, showing an overall positive trend with a regional mean of 0.41 ± 0.03 mm/a. This indicates that elastic deformation induced by water mass redistribution contributes to a net uplift of the sea surface. This effect is particularly pronounced in the eastern Black Sea, adjacent to the Caspian Sea, where substantial water loss from the Caspian Sea has exerted a significant influence on the surrounding region.

Figure 4c displays the spatial distribution of sea level change rates derived from satellite altimetry over the period 2003–2023, highlighting a pronounced overall upward trend. However, the rate of sea level rise exhibits notable spatial variability. Elevated rates exceeding 2 mm/a are particularly evident in the southern basin, especially in the southwestern and coastal regions, indicating a sustained increase in sea level in recent years. According to Kubryakov et al. (2017), from 1993 to 2014, the sea level rise rate in the Black Sea's coastal and shelf areas was approximately 1.5–2 times that of the basin center. However, our results show the opposite pattern, with the deep basin experiencing a higher sea level rise rate (1.08 ± 0.40 mm/a) compared to the northern coastal and shelf regions (0.85 ± 0.39 mm/a) during 2003–2023.

Figure 4d presents the net sea level change rate after correcting for GIA and loading deformation, showing a continued sea level rise (0.97 ± 0.40 mm/a). However, compared to the uncorrected trend in Figure 3c, the rate of rise is slightly adjusted, particularly in the eastern coastal and northern narrow sea regions, where the trend is significantly weakened. This indicates that GIA and loading deformation have a substantial impact on sea level changes. GIA accounts for 32% of the altimetry-based sea level change, while loading deformation contributes 39%, meaning that a total of 71% of the observed sea level change is due to GIA and loading deformation. Without correcting for these effects, satellite altimetry would overestimate the actual sea level change by 0.07 mm/a. Overall, sea level variations are jointly influenced by GIA and loading deformation, and removing these signals is essential for obtaining a more accurate estimate of climate-driven sea level changes.

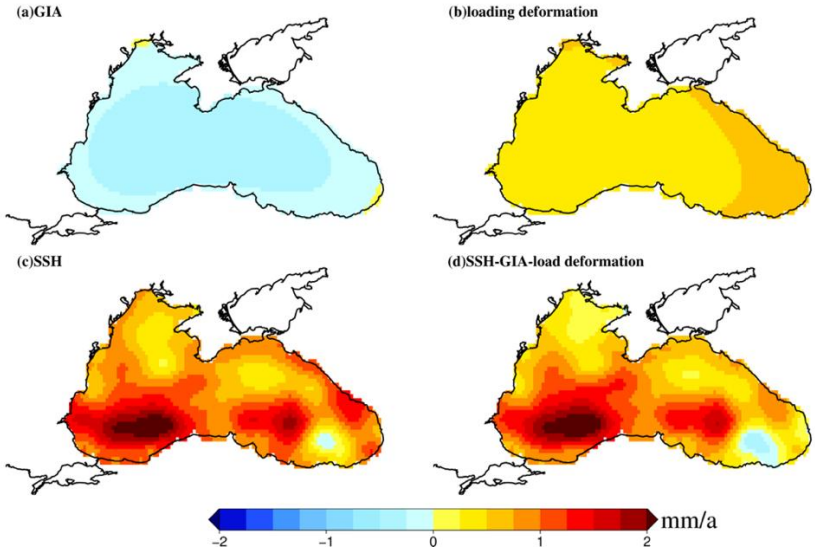


Figure 4. Long-term trends in the Black Sea from 2003 to 2023, including (a) GIA, (b) loading deformation induced by surface mass changes, (c) sea level changes derived from altimetry, and (d) sea level trend after removing GIA and load deformation.

3.3 Mass increase compensating for the decline of steric sea level

We used ERA5 reanalysis products to find that the net precipitation (precipitation minus evaporation) in the Black Sea region is decreasing (Figure 5a), while in-situ observations indicate that runoff is also continuously declining (Figure 5b). This reduction in freshwater input has led to an increase in seawater salinity. Based on temperature and salinity data provided by EN, we calculated the steric sea level changes induced by these factors and separated their contributions. The results show that the steric sea level in the Black Sea is decreasing at a rate of –3.42 ± 0.2 mm/a using EN4.2.2 and –3.29 ± 0.1 mm/a using C3S products, with the increase in salinity being the dominant factor (Figure S1), which is consistent with the conclusions of Novitskaya et al. (2023).

In addition to steric sea level changes, sea level variations in the Black Sea are also influenced by changes in water mass. To assess this component, we estimated the mass change trend using four GRACE mascon solutions provided by CSR, JPL, GSFC, and ANU. However, noticeable discrepancies exist among the results from these products (see Figure S2 and Table 1), with trend estimates varying across the four datasets. Considering that extensive in-situ observations of temperature and salinity in the Black Sea have been conducted in recent years, providing high reliability for large-scale spatial trends (Grayek et al., 2015; Atanas and Violeta, 2022). By subtracting the mass change from altimetry data, we obtained the steric sea level trend (Figure 5c).

Steric sea level trends from JPL and ANU products agree with reanalysis results, showing a decrease. In contrast, the CSR and GSFC mascon products may not have effectively corrected for the leakage of negative land signals around the Black Sea. Therefore, we ultimately adopted the mean of ANU and JPL mascon estimates, deriving a mass change trend of 1.73 ± 0.39 mm/a in the Black Sea from 2003 to 2023.

Table 1. GRACE-derived Mass trend and steric sea level in the Black Sea from 2003 - 2023

Products	Ocean mass (mm/a)	Steric sea level (mm/a)
CSR mascon	–1.58 ± 0.20	2.87 ± 0.47
JPL mascon	2.08 ± 0.37	–0.78 ± 0.40
GSFC mascon	–0.82 ± 0.39	2.13 ± 0.42
ANU mascon	1.38 ± 0.13	–1.82 ± 0.33

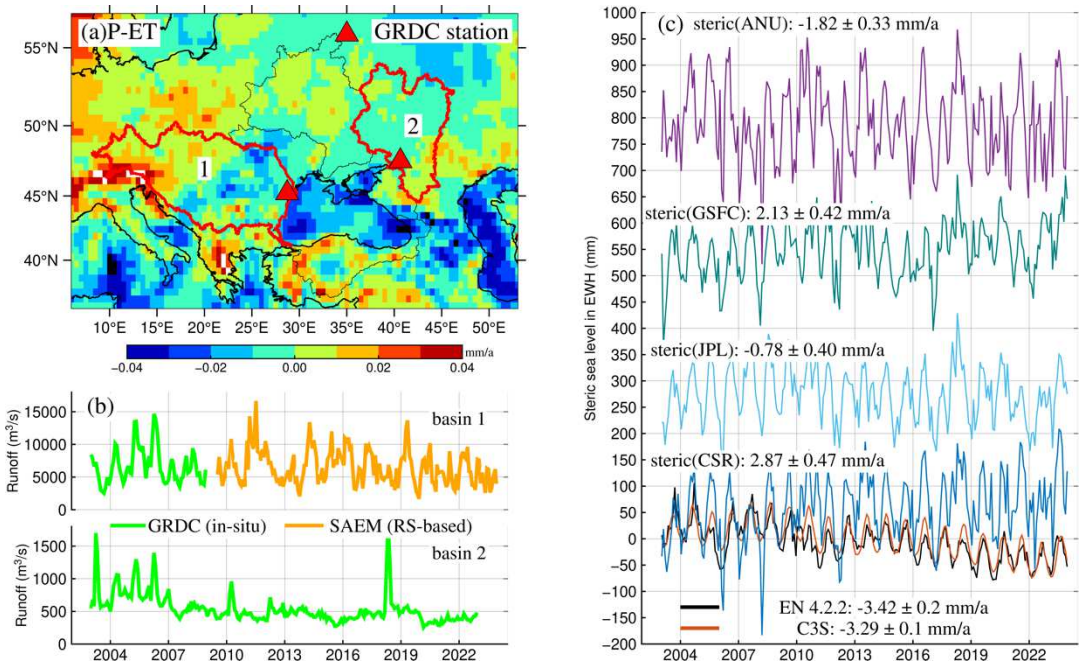


Figure 5. Long-term trends from 2003 to 2023: (a) precipitation minus evaporation in the Black Sea and (b) Runoff (in-situ and remote-sensing-based (SAEM, Saemian et al. (2024)) observed at two hydrological stations; (c) Sea level changes computed from temperature and salinity from different datasets, and mass change derived by subtracting the steric component from altimetry measurements.

Furthermore, by using altimetry data corrected for GIA and loading deformation, and subtracting the contribution of water mass, we derived a steric sea level change of -0.77 ± 0.55 mm/a. Our estimated steric sea level trend is smaller than that computed from reanalysis data; however, considering that Argo floats in the Black Sea are primarily distributed in the deep basin,

the reanalysis data may overestimate the thermal-saline expansion effect, particularly in the shallow waters of the northwest continental shelf. Overall, the increase in Black Sea water mass is mainly due to the reduced freshwater input from declining freshwater inflow and precipitation, which leads to increased salinity and, consequently, a decrease in the steric sea level. Additionally, Mamoutos et al. (2024) found, based on Argo floats and satellite-derived sea surface temperature (SST) and chlorophyll observations, that the volume of Black Sea water in the surface layer of the northern Aegean Sea has sharply decreased recently. This suggests that high-density water is accumulating in the Black Sea, further increasing the overall water mass and compensating for the decrease in the steric sea level.

3.4 Extreme Sea Levels in the Black Sea

Although the Black Sea water level showed relatively stable growth from 2003 to 2023, exceptionally high sea levels were observed in certain years. Figure 6 illustrates the relationship between Black Sea water level, water mass variation, the NAO index, and the Aegean Sea wind field. In Figure 6a, the overall sea level in the Black Sea remained stable between 2003 and 2023 but exhibited significant anomalies in 2010 and 2018, which are closely related to the NAO (Notably, the corresponding annual mean NAO indices were –0.89 in 2010 and 0.92 in 2018.). The average sea level anomalies during these two years reached 148.7 mm and 105.3 mm, respectively. The average sea level anomalies during these two years reached 148.7 mm and 105.3 mm, respectively. To avoid the gap between GRACE and GRACE-FO, we choose the period from June to December in both 2010 and 2018. In 2010, the NAO reached a strong negative phase, corresponding to an intensification of northward winds over the Aegean Sea (Figure 6b). This reduced mass outflow from the Black Sea, leading to sea level rise. This mechanism confirms the hypothesis that the NAO regulates changes in the Aegean Sea wind field, subsequently influencing the Black Sea water level, consistent with the findings of Volkov and Landerer (2015). In contrast, 2018 corresponded to a strong positive phase of the NAO, associated with enhanced southward winds over the Aegean Sea, which would typically increase mass outflow from the Black Sea. During the negative NAO phase in 2010 (June to December) and the positive phase in 2018 (June–December), the steric sea level was the dominant contributor to sea level variability in the Black Sea region (table 2), indicating that the mass-related changes induced by wind forcing were minimal during both periods.

Table 2. Proportion of steric sea level in total sea level derived from JPL and ANU mascon- constrained estimates.

Products	June to December 2010	June to December 2018
JPL mascon	65%	59%
ANU mascon	67%	83%

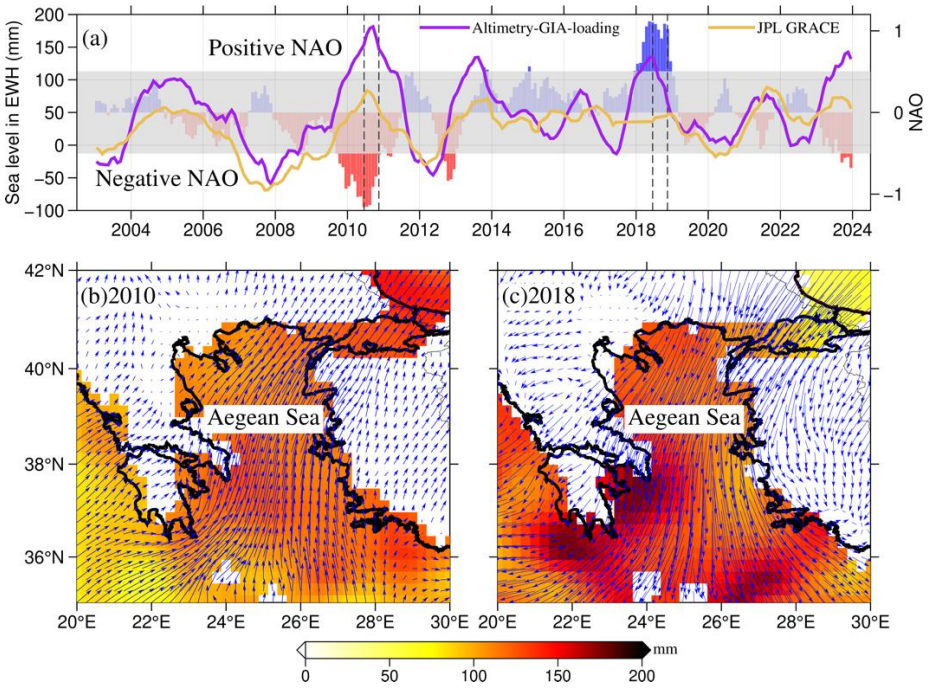


Figure 6. (a) Sea level changes derived from altimetry and ocean mass variations constrained by GRACE in the Black Sea region from 2003 to 2023 (with a one-year moving average). The NAO index is overlaid to highlight positive (blue) and negative (red) phases. The shaded area represents the ±0.5 threshold used to classify NAO phases. Vertical dashed lines indicate the years 2010 and 2018, which are selected for detailed spatial analysis; (b) and (c) show the annual mean wind field over the Aegean Sea and the annual mean sea level (background) for 2010 and 2018, respectively. Both years correspond to periods of extreme sea level, associated with different phases of the NAO.

4 Discussion and conclusion

The increase in the salinity of the Black Sea has a significant impact on both the decrease in steric sea level and the increase in water mass. Increased salinity raises seawater density, which in turn leads to a decrease in steric sea level. At the same time, because the water mass in a given

volume increases, the mass component of sea level in the Black Sea exhibits an upward trend. These dual effects—decreasing specific volume and increasing mass—are often coupled, and distinguishing their contributions requires precise observational data and data assimilation techniques.

As a semi-enclosed basin, the Black Sea's hydrological cycle is highly sensitive to precipitation, runoff, and evaporation. An increase in salinity may indicate a reduction in freshwater input, which not only affects the specific volume of the surface water but may also alter the two-layer exchange flow between the Black Sea and the Mediterranean, thereby impacting the region's overall heat and salt balance. In addition, since Argo floats are mainly distributed in the deep basin, the impacts in shallow shelf areas might be underestimated. Therefore, there is a need to enhance the observations of seawater temperature and salinity in the shallow continental shelf areas of the Black Sea.

In this study, we systematically investigated the sea level changes in the Black Sea from 2003 to 2023 using multiple remote sensing observations. The main conclusions are as follows:

（1）During the study period (2003-2023), the sea level in the Black Sea rose at a rate of 1.04 ± 0.39 mm/a. Notably, a seasonal analysis reveals a decreasing trend during winter (–1.14 ± 0.27 mm/a), which contrasts with the rising trends observed in other seasons.

（2）GIA and loading deformation induced by global mass redistribution have a significant impact on the Black Sea's sea level, with 71% of the observed sea level change attributable to GIA and loading deformation.

（3）The increase in salinity of the Black Sea water predominantly drives the steric sea level change. Increasing salinity leads to a reduction in steric sea level due to increased water density. However, this process is accompanied by an increase in total water mass, which partially compensates for the steric sea level decline.

（4）Extreme sea level events occurred in the Black Sea in 2010 and 2018. During the negative phase of the North Atlantic Oscillation (NAO) from June to December 2010, and the positive phase over the same period in 2018, steric sea level was the dominant contributor to total sea level variability in the region.

Data Availability Statement

In situ runoff data: https://portal.grdc.bafg.de/applications/public.html?publicuser=PublicUser#dataDownload/Stations. Wind field data：https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview. GIA model: https://www.atmosp.physics.utoronto.ca/~peltier/data.php; SEAM runoff data: https://darus.uni-stuttgart.de/dataset.xhtml?persistentId=doi:10.18419/DARUS-4475. GRACE/GRACE-FO Mascon data are available at http://grace.jpl.nasa.gov.

Acknowledgments

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