Salinity Trends and Mass Balances in the Mediterranean Sea: Revisit the Role of Air-Sea Freshwater Fluxes and Oceanic Exchange

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Abstract. Understanding the drivers of salinity and mass variability in the Mediterranean Sea is critical for assessing regional climate impacts and interpreting long-term water cycle changes. Although previous studies have closed the Mediterranean's mass and salinity budgets within uncertainty ranges, the relative contributions of key boundary fluxes—surface freshwater fluxes (evaporation minus precipitation minus runoff) and Gibraltar exchange—remain unclear. Here, we analyze the Mediterranean budgets from 2003 to 2017 using the ECCO v4r4 ocean state estimate. Our results show that surface freshwater loss, averaging 1.80 ± 0.10 Sv, dominates salinity variability, while the net Gibraltar exchange contributes a smaller, yet essential, salt input of 0.30 ± 0.20 Sv. Despite the saltwater inflow, the Mediterranean exports salt through the strait at -1.48 ± 0.20 Sv due to density differences between Atlantic Water (AW) and Mediterranean Outflow Water (MOW), leading to an overall salinity increase of 0.29 ± 0.09 Sv over the 15-year period. These results are consistent with observed Mediterranean salinification trends and underscore the dominant role of surface evaporation in shaping the basin's long-term evolution. This study provides a physically consistent, basin-integrated benchmark for interpreting Mediterranean water cycle changes under continued climate forcing.

1 Introduction

The Mediterranean Sea is known to be sensitive to climate change due to its relatively small size and restricted exchange with the global ocean (Giorgi, 2006). This sensitivity is expected to manifest in changes of salinity distribution, consistent with an intensified hydrological cycle in response to global warming conditions (Held and Soden, 2006; Huntington, 2006; Durack et al., 2012; Greve et al., 2014). As a result, increased evaporation and reduced freshwater inflows in the Mediterranean region have already been observed, leading to notable changes in surface salinity (Myers and Haines, 2002; Skliris et al., 2014). These changes in salinity and water mass are not confined to the region alone—variations in the density and stratification of Mediterranean outflow can potentially affect broader global ocean circulation (Reid, 1979; Millot et al., 2006; Calafat et al. 2012; Ivanovic et al., 2014).

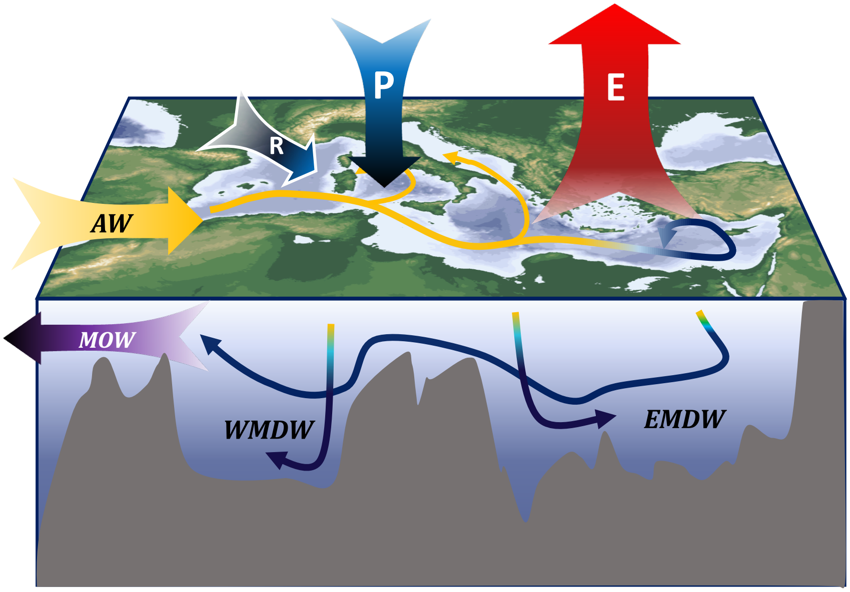

Figure 1 Schematic illustration of the Mediterranean basin and the main budget terms at the sea surface and the Strait of Gibraltar. Red, blue, and gray arrows represent the evaporation (E), precipitation (P) and river runoff (R) at the sea surface. Yellow arrows depict the inflow of Atlantic Water (AW), and purple arrows represent the outflow of Mediterranean Outflow Water (MOW). Not all branches of the sub-basin circulation are shown. The yellow-blue curves indicate the AW circulation pathways. The Eastern Mediterranean Deep Water (EMDW) and Western Mediterranean Deep Water (WMDW) formation sites are also indicated.

The salinity and mass variations in the Mediterranean basin are directly influenced by fluxes across the basin's boundaries (Figure 1). The two primary sources are air-sea interactions and water exchange with the North Atlantic through the Strait of Gibraltar. The freshwater flux mainly consists of evaporation (E) and precipitation (P), and drives the Mediterranean Sea dynamics by a persistent water deficit, resulting from the imbalance between high evaporation rates and relatively low precipitation. The river runoff (R) from major rivers and the Dardanelles Strait also contributes a measurable portion of the Mediterranean water budget (Jordà et al., 2017a). In particular, the Dardanelles Strait provides a smaller but non-negligible freshwater input from the Black Sea into the Mediterranean, equivalent to more than 10% of the Gibraltar Strait's net transport (Ünlülata et al., 1990; Jarosz et al., 2013).

The mass loss caused by strong net evaporation in the Mediterranean Sea is replenished by inflows from the North Atlantic through the Strait of Gibraltar. The circulation at the Strait of Gibraltar can be approximated as a two-layer system, with the upper layer carrying the relatively fresher Atlantic Water (AW) eastward, and the lower layer transporting saltier Mediterranean Outflow Water (MOW) westward at depths below 150 m. These two water masses are linked through the Mediterranean's internal thermohaline circulation and interact at sub-basin and mesoscale levels (Millot and Taupier-Letage, 2005), characterizing the overall dynamics of the Mediterranean basin (Tsimplis et al., 2008).

It is well established that the mass exchange through the Strait of Gibraltar significantly influences the Mediterranean Sea, particularly on the regional sea-level trend (Calafat et al., 2010; Pinardi et al., 2014). Unlike the global ocean, where 50–70% of total sea-level change is attributed to the steric component (Storto et al., 2019), the steric effect only accounts for about 20%

of sea-level changes in the Mediterranean basin (Calafat et al., 2012). The exchange through the Strait is also solely responsible for changes in the basin's salt content, as surface fluxes only alter freshwater content, not actual salt.

However, the role of the air-sea freshwater fluxes is often understated despite they directly reflect the change of water cycle. In the open ocean, the effects of air-sea interactions are more evident over the long term (Yu, 2011; Hasson et al. 2013). But in the enclosed basins like the Caspian Sea, evaporation could dominant the sea-level trends (Chen et al., 2017), and play a major role in modulating the local salinity levels (Kara et al. 2010). In the semi-enclosed Mediterranean, these effects are often masked by the replenishment at the Strait of Gibraltar, making it challenging to estimate how sensitive mass and salinity levels are to changes in air-sea freshwater fluxes.

While growing interest are found in using ocean salinity to quantify water cycle changes (Vinogradova and Ponte 2013, 2017; Nan et al. 2015), some researches also argue that air-sea freshwater fluxes should only be associated with salt transport when total mass transport of a region is zero (Tsubouchi et al., 2012; Schauer and Losch, 2019; Bladwell et al., 2021). This premise aligns well with the Mediterranean Sea where the water mass is well balanced (Fenoglio-Marc et al., 2012; Jordà et al., 2017a; García-García et al., 2022). However, substantial uncertainties still remain, making it challenging to quantify the relative contributions of different water exchange pathways (Schroeder et al., 2012; Jordà et al., 2017b). The water mass exchange at the Strait of Gibraltar was estimated 0.0323 ± 0.0018 Sv for the period 2005–2010, though longer timescale averages may offer smaller uncertainties (García-García et al., 2022). The greater challenge lies in determining the salt budget. Due to limited observations, the mean salt flux through the Strait of Gibraltar over the past four decades was estimated at $-1.5 \pm 6.5 \times 10^6$ kg/s, with uncertainties more than four times larger than the mean, despite an evident salinity increase in the Mediterranean region over the past decades (Jordà et al., 2017a). These fluxes at the boundaries of the Mediterranean basin also vary significantly across a wide range of spatial and temporal scales, making it more difficult to understand their variability and how they balance each other at this level (García-García et al., 2022).

In this study, we conduct an exploratory analysis using the dynamically consistent ocean state estimate produced by the Consortium for Estimating the Circulation and Climate of the Ocean (ECCO version 4; Forget et al. 2015). This state estimate provides a robust framework for investigating the Mediterranean's mass and salinity fluxes at basin-wide scales, offering valuable insights into the region's water cycle dynamics and its connections to surface and oceanic forcing. While ECCOv4's coarse resolution poses challenges for resolving finer-scale processes, such as subbasin circulation, it serves as a valuable tool for identifying large-scale trends and establishing a foundation for future research. Our approach focuses on diagnosing the mechanisms driving the temporal variability of mass and salinity budgets and understanding the links between the Mediterranean's exchanges with the atmosphere and the broader North Atlantic system.

Data and methods are described in Section 2. Section 3 presents the analysis of mass and salinity variability for the entire Mediterranean Sea, based on budget diagnostics with ECCOv4. In Section 4, we discuss model resolution, uncertainties, and potential implications to guide further detailed investigations. The study's conclusions are summarized in Section 5.

2 Data & Methods

2.1 ECCO Estimate and Its Evaluation

ECCO version 4 release 4 (v4r4) is an ocean state estimate that integrates the Massachusetts Institute of Technology General Circulation Model (MITgcm) (Marshall et al. 1997; Adcroft et al. 2004) with a wide array of observational data (Forget et al. 2015; ECCO Consortium et al. 2021). In this framework, observations are assimilated using an optimized least-squares method, ensuring dynamic and kinematic consistency without artificial heat or buoyancy sources (Heimbach et al. 2005; Wunsch et al. 2009; Wunsch and Heimbach, 2013). Argo temperature and salinity profiles and other CTD profiles from world ocean Database are used to constrain the ECCO v4r4 solution (Fukumori et al., 2017). At the sea surface, ECCO is constrained by forcing derived from the ERA-Interim reanalysis dataset (Dee et al., 2011). ECCO v4r4 spans the period 1992–2017, with a global domain and 50 vertical layers. Its resolution is 1° zonally and varies meridionally, from 1/3° at the equator to 1° at midlatitudes. For this study, we focus on the period from 2003 to 2017, during which the quality of observational data is significantly improved, enabling robust analysis of salinity, surface freshwater flux, and bottom pressure changes.

Although many previous studies have demonstrated that ECCO estimates reliably represent in situ measurements for salinity, sea level, and other variables (e.g., Stammer et al., 2004; Wunsch and Heimbach, 2007; Liu et al., 2019), this study seeks to further reduce uncertainties specifically associated with the Mediterranean Sea region. The salinity field is from the UK Met Office Hadley Centre EN4.2.2 (Good et al 2013). EN4 is an objectively-analyzed monthly dataset, covering the period from 1950 to 2016, with a horizontal resolution of 1 degree and a vertical resolution of 42 levels. It has been reported that EN4 displays some spurious salty bias after 2015 (Ponte et al., 2021; Liu et al., 2024). However, it has not been observed in the Mediterranean area (Liu et al., 2020).

The precipitation product used is the latest version, 2.3, from the Global Precipitation Climatology Project (Huffman et al. 2009). The GPCP product is created by combining various satellite and gauge-based datasets to form a coherent spatial and temporal representation. The evaporation data is obtained from the OAFlux (Yu et al. 2007), which is generated using an objective analysis method that integrates satellite and atmospheric reanalysis output, and calculates global surface fluxes using the state-of-the-art bulk flux parameterizations.

The study period (2003–2017) was selected to align with the onset of widespread Argo float deployments, which largely enhanced observational coverage and data quality in the Mediterranean Sea. While Argo data are not directly utilized in this study, they underpin the ECCO solution and contribute to the EN4 dataset, ensuring greater reliability and consistency in the input data during this period.

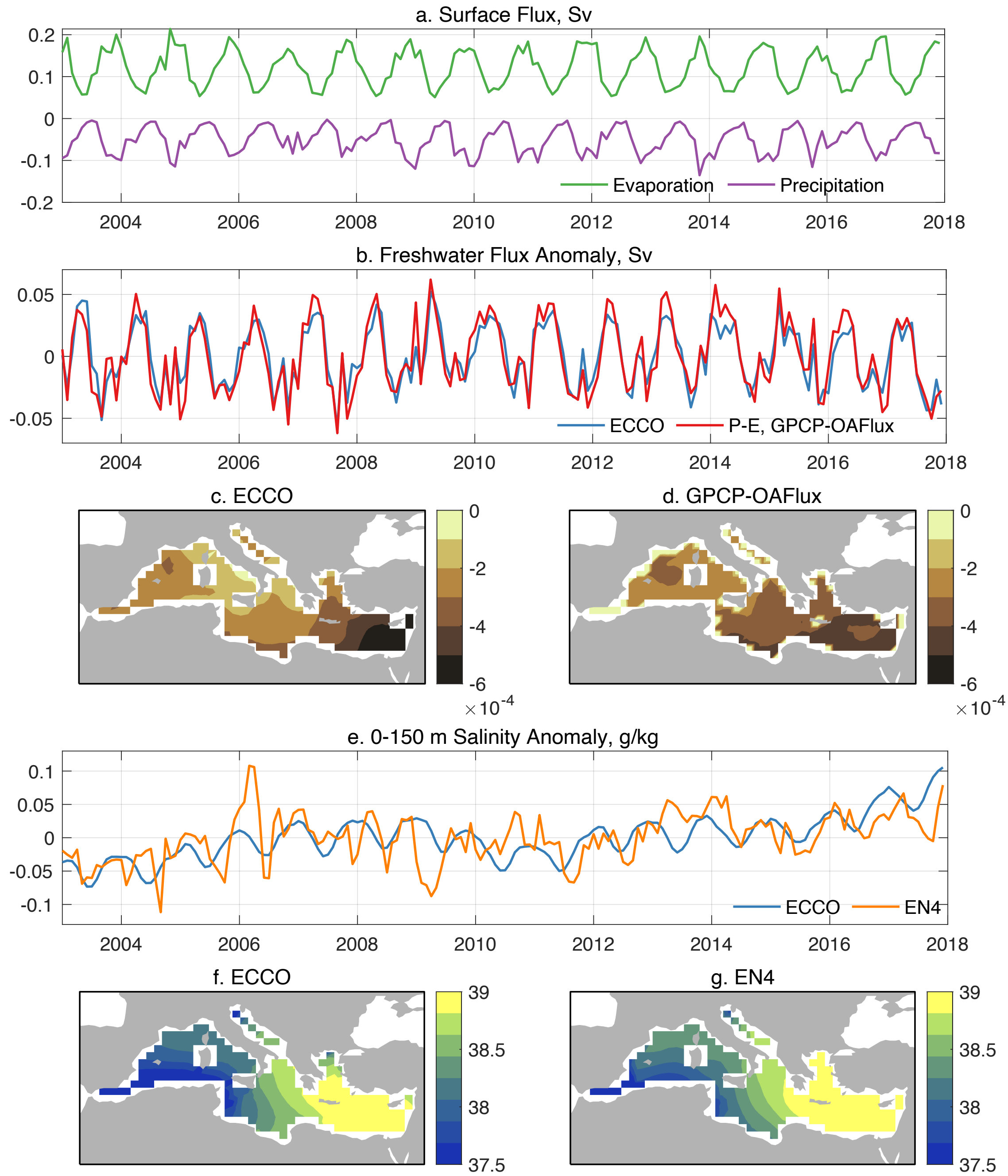

Figure 2 Timeseries and time-mean spatial patterns of freshwater flux and mean salinity (0–150 m) in the Mediterranean Sea, comparing ECCO outputs with other datasets. (a) timeseries of total evaporation and precipitation from ECCO; (b) timeseries of freshwater flux anomaly from ECCO and the reference flux derived from GPCP and OAFlux; (c&d) spatial patterns of surface freshwater flux; (e) timeseries of salinity anomaly from ECCO and EN4; (f&g) spatial patterns of salinity. All data are interpolated onto the ECCO grid.

The area-averaged timeseries from these datasets were compared with the monthly mean ECCO anomaly (Figure 2). Overall, the surface freshwater flux term of ECCO strong align with the observational *P-E*, with a correlation of 0.92 for surface freshwater flux and R^2 (the proportion of variance explained by the seasonal cycle) of 0.72. Discrepancies are observed, particularly during the winter months, where ECCO values are lower by 0.01–0.02 Sv compared to observational-based estimates. This discrepancy could come from the river runoff term *R*, which is incorporated into the total freshwater flux. In ECCO, river runoff is derived from observed seasonal climatology, applied as a mass flux over several surface grid cells near river mouths (Fekete et al., 2002; Stammer et al., 2004; Feng et al., 2021). Additionally, ECCO's freshwater flux estimates may also be influenced by precipitation biases in the ERA-Interim (Turuncoglu, 2015; Grist et al., 2016).

For salinity, ECCO shows good agreement with EN4, with a correlation of 0.70 and similar long-term trends of approximately 0.01 per year. However, differences arise at seasonal and shorter timescales. ECCO's seasonal cycle has an R^2 of 52%, which is substantially higher than EN4's (less than 20%). To provide further context, the temporal variability and long-term trend of ECCO's basin-mean salinity time series generally align with previously reported estimates (e.g., Jordá et al., 2017b; Llases et al., 2018). More recently, Aydogdu et al. (2023) presented an ensemble mean for the top 300 m of the water column, and despite this depth difference, the ECCO results fall within the spread of their multi-product uncertainty range.

The spatial patterns of the time-mean values are also compared. Overall, the time-mean patterns from ECCO align reasonably well with the observational data products. The correlation for freshwater flux and salinity patterns ranges between 0.6 and 0.7 ($p < 0.01$), respectively. Overall, ECCO captures the primary features of the observed oceanic variables in the Mediterranean Sea with reasonable accuracy (Fukumori et al. 2007; García-García et al. 2010; Soto-Navarro et al., 2010; Calafat et al. 2012). This gives us confidence in using ECCO for salinity and mass budget analyses in the region.

2.2 The Calculation of Salinity and Mass Budgets

Below we provide a brief summary of the salinity and mass budget analyses with the ECCO estimates. In general, our approach is very consistent with other budget analysis using ECCO (e.g., Tesdal & Abernathey 2021; Siddiqui et al. 2024), which benefit greatly from the provided diagnostic terms. Details on how to close the budgets are provided in Forget et al. (2015) and Piecuch (2017).

In the Mediterranean Sea, significant spatial differences are observed at the sub-basin scale (Bonaduce et al., 2016; Mohamed et al., 2019). This spatial variability is caused by the complex thermohaline changes and local circulation (Menna et al., 2012; Mauri et al., 2019; Menna et al., 2019; Poulain et al., 2021). Compared to other regional models (Escudier et al., 2021; Meli et al., 2023), ECCOv4r4's coarse resolution may limit its ability to confidently resolve these sub-basin and mesoscale processes, and it is unclear how precise the flux estimates must be to ensure accurate simulations and avoid potential model drifts. Additionally, narrow straits such as the Dardanelles are not explicitly resolved as lateral boundary fluxes in ECCO but are instead incorporated within the surface flux term, along with river runoff and other unresolved processes. This introduces some uncertainty in the precise partitioning of boundary inputs. Therefore, in this study, we focus on the Mediterranean basin as a whole, rather than attempting to resolve the sub-basin processes in detail. More discussion on the model resolution and uncertainty will be discussed in later section.

The budgets for the whole Mediterranean Basin can be described as a simple box model. The balance in the Mediterranean Sea budgets is between two boundary terms, the surface flux and the inflow through the Strait of Gibraltar. Since ECCO uses volume-conserving Boussinesq approximation (Greatbatch 1994; Marshall et al. 1997), at each grid, the equation for mass budget of the whole water column can be estimated as:

$$\rho_{sw}\frac{\partial P_b}{\partial t} \approx -\nabla(\rho_{sw}\boldsymbol{u}) + \rho_{fw}F_{fw} \qquad (1)$$

where P_b is the bottom pressure equivalent water thickness, $\boldsymbol{u}$ is the horizontal velocity, F_{fw} is the surface freshwater flux (P+R-E). For the benefit of discussion, we do not separate the individual sources of freshwater inputs (i.e., P+R are treated as a single term). ρ_{fw} and ρ_{sw} are the freshwater and seawater density, respectively.

The left-hand side represents the tendency term of bottom pressure, i.e., the rate of OBP change, the first right-hand side term is the convergence of seawater, and the second term marks the contribution of surface freshwater flux.

Given the Mediterranean Sea's semi-enclosed nature, when integrating equation 1 over the entire basin, the integral of the convergence term naturally equals to the net influx through the strait, and the integral of the second term represents the total freshwater flux at the sea surface. Vertical exchanges between surface and deep Mediterranean layers are implicitly represented in ECCO but not explicitly analyzed in this study.

At the Strait of Gibraltar, we divided the water column into two layers to estimate the inflow and outflow: the upper layer (0–150 m) represents the transport of the AW (eastward, Figure 3a), while the lower layer (150 m to ~320 m, model bottom) represents the MOW (westward, Figure 3b).

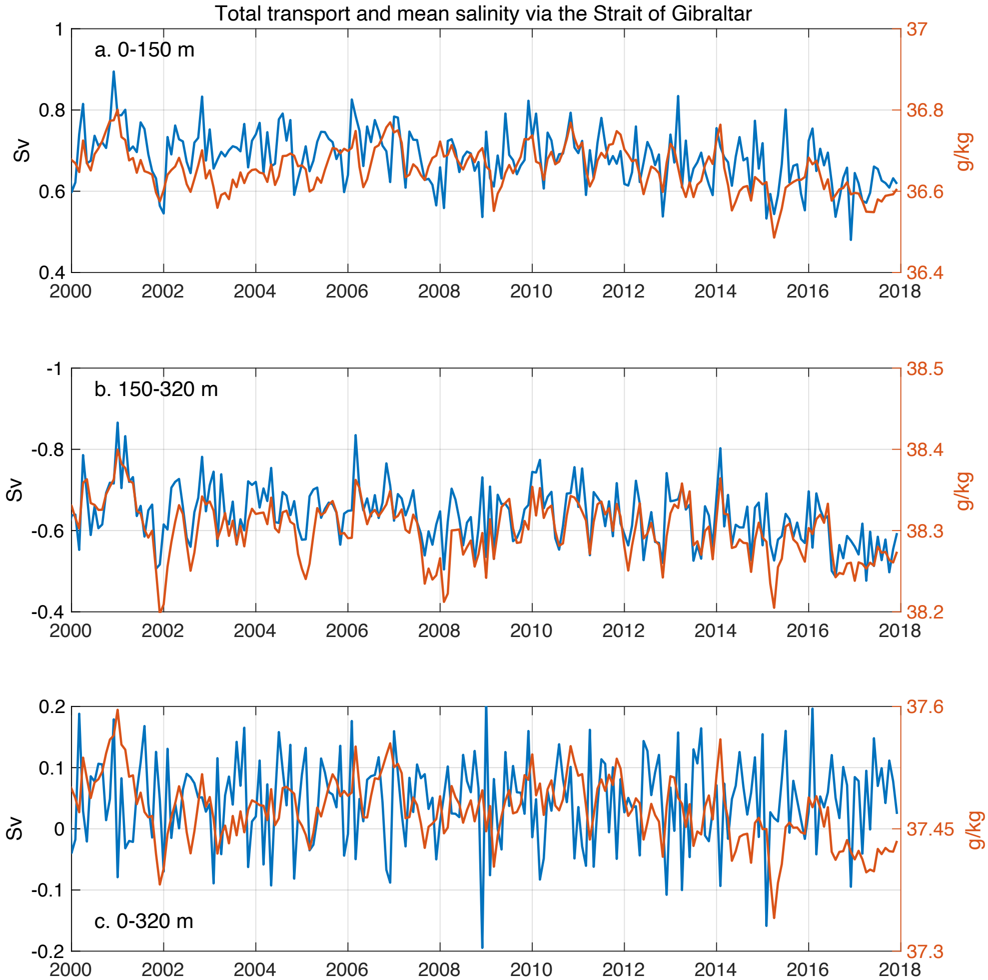

Figure 3 Net flux (blue, left axis) and mean salinity (red, right axis) at the Strait of Gibraltar. positive transport means eastward transport into the Mediterranean Sea. Notice the y-axis in panel (b) is inversed.

The salinity budget in the Mediterranean Sea is balanced in a similar form. The local salinity conservation can be simplified as:

$$\frac{\partial S}{\partial t} = -\nabla(S\boldsymbol{u}) + D_s + F_{fw}\,\tilde{S} \qquad (2)$$

where $\tilde{S}$ is the local surface salinity, and D_S represents the subgrid-scale processes parameterized as mixing (diffusive salt flux). The sum of the first two terms on the right-hand side describes the total flux of oceanic transport, which, when integrated over the entire basin, corresponds to the net influx of salinity through the strait.

The first term on the right-hand side, which represents the advection of salinity, includes two distinct physical processes that contribute to salinity changes (Piecuch, 2017): one process represents the overall dilution/concentration due to the convergence/divergence of the mass transport ($S\nabla \boldsymbol{u}$), while the other reflects the exchange of salt content carried by the advective flow ($\boldsymbol{u}\nabla S$).

It is important to note that ECCO-v4 solutions are based on the MITgcm model with the z* vertical coordinate system (Adcroft and Campin, 2004), which allows vertical grid-cell thickness to stretch or compress according to changes in sea surface height. Additionally, freshwater is added or removed as an explicit surface mass flux (Campin et al., 2008). This approach ensures that changes in salinity directly reflect mass input and removal, with the model naturally accounting for dilution and concentration effects. These characteristics support the physical consistency of ECCO estimates and justify our use of diagnosed mass fluxes in interpreting salinity variability.

The focus of this study is on the interannual variability of the fluxes. The non-seasonal signal is obtained subtracting the climatology from the original timeseries instead of a fitted annual sinusoid, since the annual variation is not always sinusoidal in shape (García-García et al. 2022). This approach is consistent with previous studies using ECCO to investigate Mediterranean Sea variability and phenomena associated with Gibraltar Strait transport (Fukumori et al., 2007; Menemenlis et al., 2007; Volkov and Landerer, 2015). These studies highlight a strong correlation between OBP and sea level on non-seasonal timescales, providing a more accurate representation of the relationship between mass (OBP) variations and volume (sea level) variations. By our estimation, the seasonal cycle accounts for less than 10% of the total variance in the mass flux, while the salinity component contributes slightly more, below 30%.

Here we express mass fluxes in Sverdrups (Sv) for consistency with common oceanographic practice. Salinity flux is represented in g/kg Sv, enabling direct comparison between mass and salinity fluxes.

3 Results

3.1 Non-seasonal Variability of Mass and Salinity Fluxes

In this section we present the estimates for each flux term of Eq. 1 and Eq. 2 applied to the entire Mediterranean Sea. Figure 4a presents the temporal variability of the Mediterranean Sea's mass budget from 2003 to the end of 2017. In general, the net influx at the Strait of Gibraltar (i.e., inflow plus outflow, labeled "*Strait*"), shows large month-to-month variability: its standard deviation is 2.4 times larger than the surface freshwater flux (labeled "*Surface*").

The mass tendency term, i.e., the sum of *Strait* and *Surface* terms, is labeled "*Total*" and mainly driven by the net influx at the Strait. The Pearson correlation coefficient between *Strait* and *Total* terms' timeseries is 0.96 ($p < 0.01$), while there is no significant correlation between *Total* and *Surface* terms ($r < 0.2$). The coefficient of determination (R^2) of *Strait* to *Total* term is 0.92, showing that the net influx explains nearly all of the variance in the total mass tendency. Previous studies have shown that the mass exchange through Gibraltar significantly impacts the Mediterranean, dominating the mean sea-level trend in the region (Calafat et al., 2010; Pinardi et al., 2014).

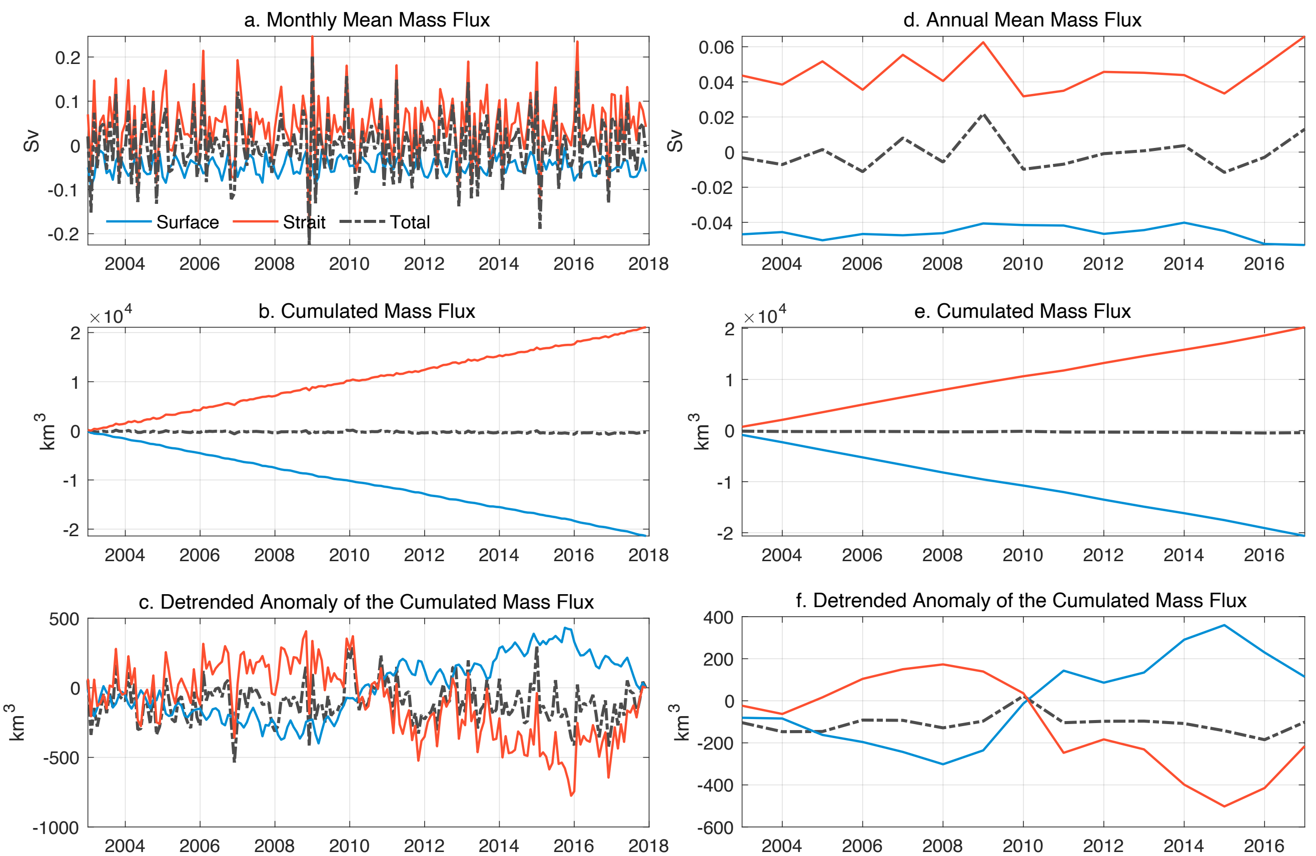

Figure 4 Mass fluxes in the Mediterranean Sea. (a) Monthly mean timeseries of Mass flux through the sea surface, Strait of Gibraltar, and the sum of both; (b) Temporally cumulated mass fluxes; (c) Same as b but detrended. (d-f) Same as a-c but with annual means.

The interannual variability of both the *Strait* and *Total* terms is evidently much smaller on a year-to-year scale compared to month-to-month fluctuations (Figure 4d). The transport through the Strait of Gibraltar exceeded 0.06 Sv in 2009 and 2017, while the lowest values occurred in 2010 and 2015, around 0.03 Sv. In contrast, the *Surface* term exhibits very limited interannual variability, with a range of only 0.01 Sv, reaching a maximum in 2014. Similar numbers have been previously reported in the literature; García-García et al. (2022) provided annual mean estimates of net exchange at the Strait of Gibraltar at 0.04 Sv in 2008, and 0.0224 Sv in 2010.

Linear trends of the fluxes were also estimated, showing a small upward trend in both the *Strait* and *Total* terms ($O(10^{-4}$ Sv per year)). However, these trends are not statistically significant as their 95% confidence intervals include zero. This indicates that the net transport through the Strait of Gibraltar, as well as the overall mass within the Mediterranean Sea, remained highly stable over the study period. On average, the total mass tendency is close to zero ($O(10^{-4}$ Sv)), and the net oceanic influx through the Strait of Gibraltar and the surface freshwater flux appear to be balanced almost simultaneously, with no noticeable lag.

We then examined the cumulative mass flux (Figure 4b) and the detrended timeseries (Figure 4c). The cumulative curves provide a clear visualization of long-term trends, where the slope corresponds to the time-averaged flux values. In contrast, the detrended time series isolates shorter-term variability, revealing patterns that are otherwise obscured by the dominant trend. Notably, the magnitude of the detrended series is approximately two orders of magnitude smaller than the cumulative fluxes. *Surface* and *Strait* terms exhibit nearly exact opposite variations, with the *Surface* term showing relatively smaller month-to-month fluctuations. This inverse relationship is expected, as the total mass of the Mediterranean Sea remains nearly conserved (Figure 4b).

A notable turning point occurs in the winter of 2010/2011. Prior to this, from 2003 to 2010, the surface flux shows a predominantly negative anomaly, followed by a subsequent seven-year period of positive anomalies. The *Strait* term exhibits the exact opposite pattern, with positive anomalies before 2010 and negative anomalies afterward. Notably, both fluxes tend to contribute to the removal of freshwater from the Mediterranean basin. Before 2010, the freshwater loss from surface fluxes exceeded the net inflow through the strait by approximately 100 km³. After 2010, the *Strait* term has a negative anomaly and reaches values as low as -500 km³, showing a larger deficit.

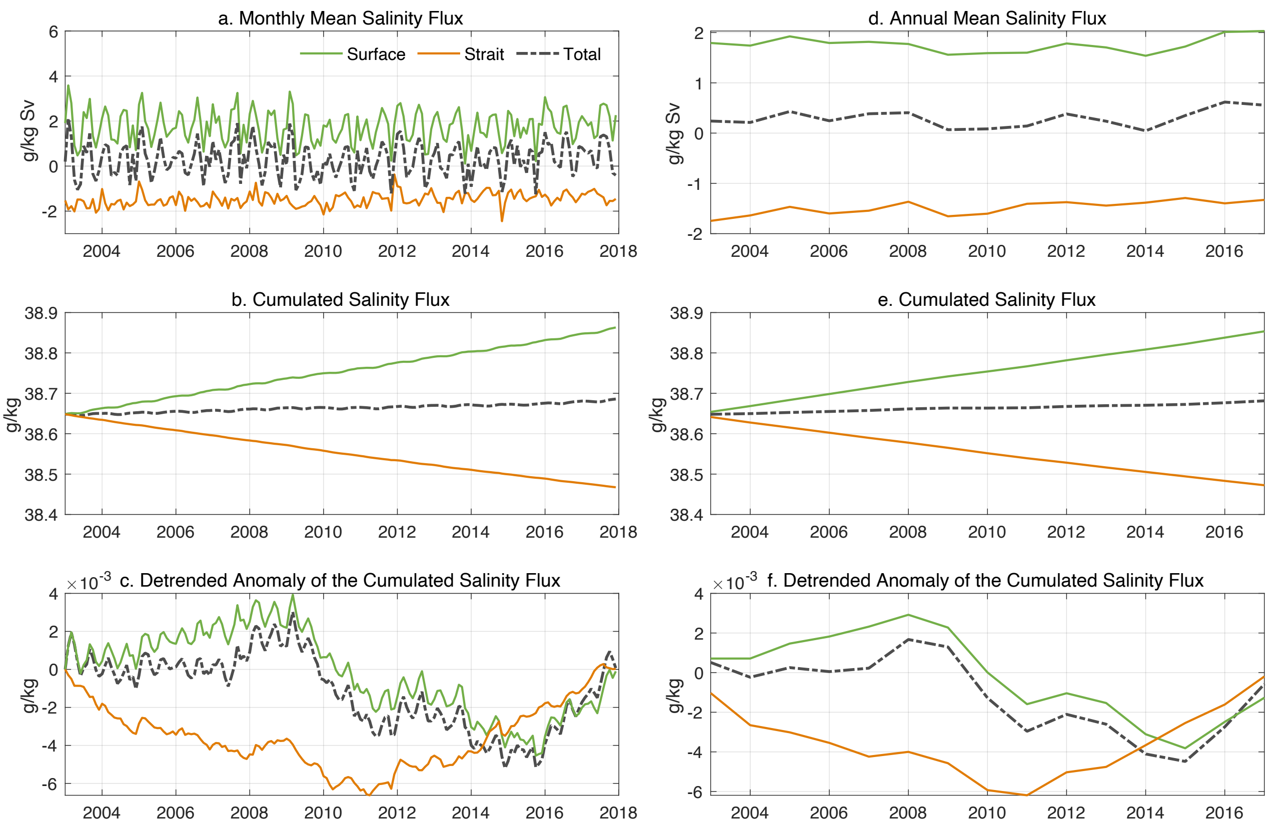

Figure 5 Salinity fluxes in the Mediterranean Sea. (a) Monthly mean timeseries of salinity flux through the sea surface, Strait of Gibraltar, and the sum of both; (b) Temporally cumulated salinity fluxes expressed as the equivalent of mean salinity change in the Mediterranean Sea; (c) Same as b but detrended. (d-f) Same as a-c but with annual means.

Figure 5 presents the salinity fluxes for the Mediterranean Sea. Unlike the mass budget, the *Surface* term exhibits considerably larger month-to-month variability in salinity, with a standard deviation 2.5 times greater than that of the *Strait* term. Moreover, the surface freshwater flux demonstrates a strong linear relationship with the total salinity tendency: the correlation between surface flux and *Total* salinity tendency is exceptionally high, exceeding 0.97 ($p < 0.01$) with an R^2 value of 0.95, indicating that air-sea fluxes alone account for nearly all observed salinity changes. In contrast, the net influx through the Strait of Gibraltar explains only 4% of the salinity variability, with a much weaker correlation of 0.25. This is because freshwater, which contains no salt, could substantially dilutes the denser, saltier Mediterranean waters when introduced, impacting the overall salinity dynamics within the basin.

A significant positive change was identified in the *Strait* term, with an estimated rate of 0.02 ± 0.01 g/kg Sv per year (Figure 5d), indicating a weakening of the net salinity flux. As illustrated in Figure 4, both the inflowing and outflowing water masses exhibit freshening trends over the analysis period. This concurrent decline in salinity across both layers results in a reduction in the mean salinity at the Strait of Gibraltar. Consequently, the net salinity flux through the strait decreases over time. This decline in the salinity gradient reduces the efficiency of salt export from the Mediterranean, assuming the net transport via the strait remain relatively stable (Figure 4d).

The observed freshening of the inflowing water has been attributed in some studies to Arctic ice melt and changes in North Atlantic circulation patterns (Dukhovskoy et al., 2019; Holliday et al., 2020). However, it is important to note that ECCO does not include tidal forcing, which has been shown to increase net salt export at Gibraltar by approximately 25% (Sanchez-Roman et al., 2018). This likely contributes to ECCO's relatively low estimate of salt export compared to tidal-resolving models. Other research also suggests that the salinity of North Atlantic waters may be increasing in recent decades (Bates & Johnson, 2020; Sukhonos et al., 2024). A recent study by Lu et al. (2024) further highlights the complexity of North Atlantic salinity trends at climate scales, noting that climate models tend to underestimate observed salinity increases in the Atlantic basin. These contrasting findings suggest that the salinity characteristics of North Atlantic are still subject to significant uncertainty and debate, warranting further investigation to clarify their role in shaping Mediterranean salinity trends.

In Figure 5b, we present the cumulative contribution of salinity fluxes to the mean salinity level in the Mediterranean Sea. Over the study period, the mean salinity of Mediterranean seawater shows a steady increase at a rate of approximately $2.2 \pm 0.2 \times 10^{-3}$ g/kg per year, translating to a total salinity increase of about 0.03 over 15 years. The air-sea freshwater flux, driven primarily by substantial net evaporation, contributes significantly to this trend. On its own, it would have raised the mean salinity by 0.2 over the period, with a rate of $14.0 \pm 0.2 \times 10^{-3}$ g/kg per year. In comparison, the contribution from the inflow through the Strait of Gibraltar is estimated at $-12.1 \pm 0.2 \times 10^{-3}$ g/kg per year, accumulating to a reduction of 0.17 over 15 years.

The detrended cumulative salinity timeseries are presented in Figure 5c. Prior to 2010, both terms exhibit positive salinity anomalies, while negative anomalies are prevalent in the years that follow. In contrast, the Strait term maintains a persistent negative anomaly throughout the period, reaching its lowest point in 2011. It is also out of phase with the other flux terms, highlighting its distinct behavior relative to surface-driven salinity changes.

3.2 Influence of Teleconnection Patterns on Salinity and Water Mass Transport

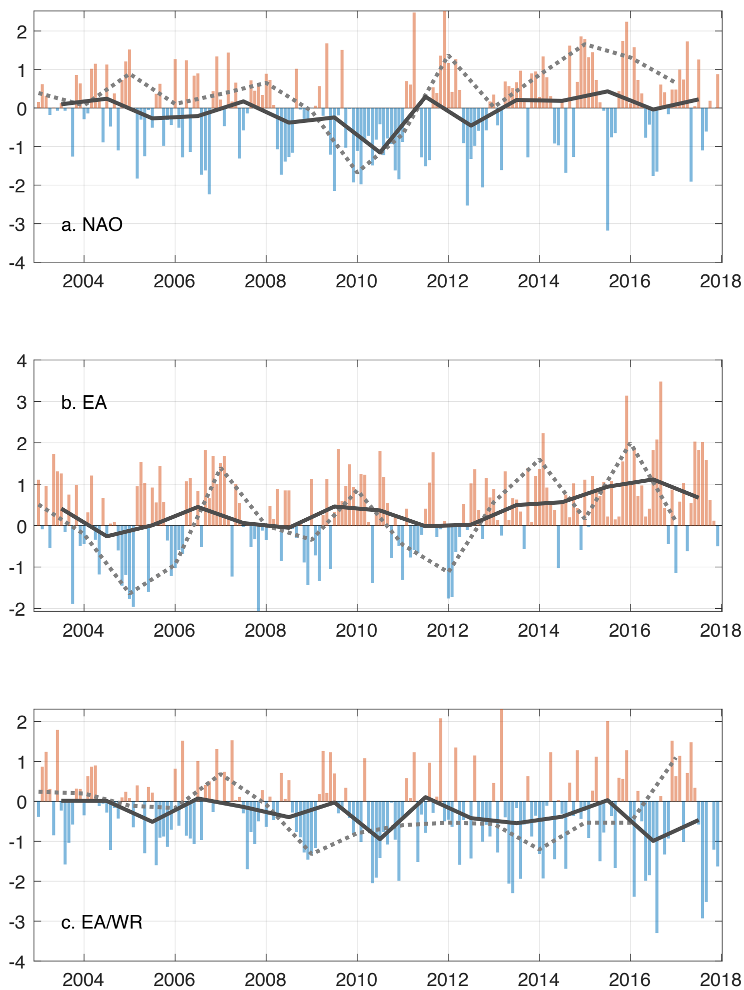

Figure 6 The standardized monthly climate index with the annual mean (black solid line) and the winter mean (gray dotted line). (a) NAO; (b) EA; (c) EA/WR. Winter means are calculated from December to February. Red bars represent months with positive values, while blue bars represent months with negative values.

In this section, we examine the influence of large-scale atmospheric teleconnection patterns on Mediterranean salinity variability and water mass exchange at the Strait of Gibraltar. Specifically, we consider the most prominent modes of atmospheric variability in the North Atlantic/Europe region, i.e., the North Atlantic Oscillation (NAO), the East Atlantic (EA) pattern, and the East Atlantic/Western Russia (EA/WR) pattern, which are known to modulate regional atmospheric pressure systems, wind forcing, air-sea fluxes, and hydrographic properties in the Mediterranean basin.

The NAO has a significant impact on both weather and oceanic circulation (e.g., Hurrell, 1995; Vigo et al., 2011). Particularly relevant to this study, it modulates wind patterns near the Strait of Gibraltar, affecting non-seasonal water mass transport and variations in Mediterranean sea levels (Fukumori et al., 2007; Menemenlis et al., 2007; Landerer and Volkov, 2013; Piecuch and Ponte, 2014).The NAO also influences the Mediterranean region across multiple timescales, from seasonal to interannual and decadal (Gomis et al., 2008; Tsimplis et al., 2008; Calafat et al., 2010; Calafat et al., 2012). These processes offer a framework for understanding the relationship between the NAO and the interannual variability of the observed timeseries of mass and salinity fluxes in the Mediterranean.

The NAO index reveals that the NAO remained in a positive-to-neutral phase from approximately 2003 to 2008, shifted to a negative phase from 2008 to 2011, and then returned to a positive phase afterward. We also calculated annual and winter seasonal averages for the NAO timeseries, as previous studies have shown that the NAO is particularly influential on Mediterranean weather patterns during the winter season (e.g., Castro-Díez et al., 2002).

Mariotti et al. (2002) found significant correlations between the NAO and both annual and winter averages of precipitation and net precipitation across the broader Mediterranean region. In our study, we also observed a significant correlation between the winter NAO and the air-sea mass flux shown in Figure 4d (blue), with a correlation coefficient of -0.51 ($p < 0.05$). Regarding salinity fluxes in Figure 5d, all annual fluxes show significant correlations with the winter NAO. Both the Surface and Strait terms are correlated with the winter NAO between 0.5 and 0.6 ($p < 0.05$), while the *Total* term, i.e., the sum of the *Surface* and *Strait* terms, correlates at 0.62 ($p < 0.01$).

The EA pattern, often considered the second mode of atmospheric variability over the North Atlantic, is characterized by a north-south dipole of pressure anomalies similar to the NAO but displaced southeastward (Barnston & Livezey, 1987; Wallace & Gutzler, 1981). It influences storm tracks and surface pressure fields across western and central Europe and the North Atlantic. Although the EA pattern has been associated with regional climate variability (e.g., evaporation and surface pressure, Zveryaev et al., 2012), our analysis reveals no significant correlation between the EA index and the Mediterranean salinity or water mass fluxes, whether based on annual mean or winter mean values.

In contrast, the EA/WR pattern exhibits a quasi-stationary wave-train pattern extending from the North Atlantic into western Russia, with centers of action over northern Europe and western Russia (Barnston & Livezey, 1987; Lim, 2015). This mode strongly affects the Mediterranean climate through its modulation of high-pressure anomalies and upper-level atmospheric flow (Krichak et al., 2002; Josey et al., 2011). In our results, the winter mean EA/WR index shows a strong and statistically significant correlation with both salinity flux ($r = 0.71$, $p < 0.05$) and mass flux ($r = 0.72$, $p < 0.05$) at the surface, suggesting that it may play a critical role in shaping the interannual variability of water mass transformation and transport in the basin.

3.3 Roles of Air-Sea Fluxes and Oceanic Exchange over 2003-2017

This section provides a summary of the estimated mass and salinity budgets, broken down by their components as represented in Eq.1 and Eq.2, along with associated uncertainties for the Mediterranean Sea over the period 2003–2017. Since these estimates are derived using ECCO, the budget calculations are inherently balanced. The budget diagram shown in Figure 7 is on the mass balance (top) and the salinity imbalance within the Mediterranean basin (bottom). Over this 15-year period, the long-term mean water mass change is calculated at 0.001±0.018 Sv, while the salinity change is estimated at 0.29±0.09 Sv. This reflects a balanced state in terms of mass, contrasted with a slight imbalance in salinity. These differences arise from the distinct roles of surface processes, which exchange freshwater, and oceanic exchange of saltwater through the Strait of Gibraltar.

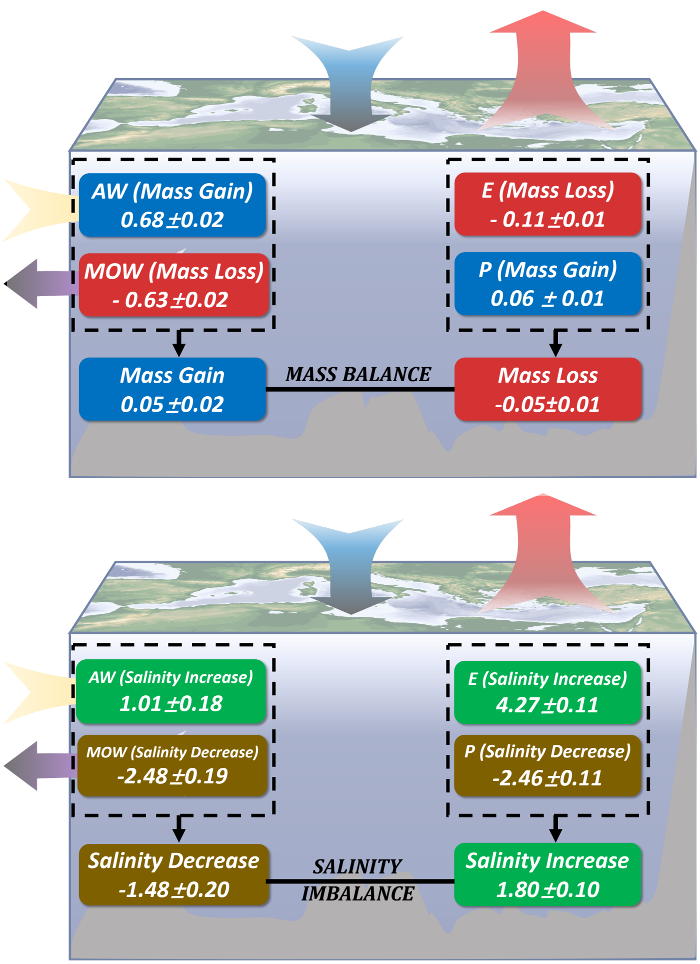

Figure 7 15-year mean mass (top) and salinity (bottom) budget for the Mediterranean Sea. Blue and red boxes mark the mass gain and mass loss, brown and green boxes mark the salinity increase and decrease, respectively. In each panel, the contributions from

air-sea fluxes are on the right, and the exchange through the Strait are on the left. The uncertainties are calculated as the standard error of the means, σ/√n, where σ is the standard deviation of the corresponding term and n = 15 for non-seasonal fluxes. Units are Sv.

Table 1 Estimates of the different components of the Mediterranean Sea mass and salinity with uncertainties for the period 2003–2017. Note that the salinity change is separated into contributions from changes in salt content, and changes in salinity due to dilution/concentration effect.

	Surface Fluxes			**Strait of Gibraltar**		
Processes	*E*	*P*	*Total*	*AW*	*MOW*	*Total*
Total Mass Change	**-0.11±0.01**	**0.06±0.01**	**-0.05±0.01**	**0.68±0.02**	**-0.63±0.02**	**0.05±0.02**
Salt Content Change				25.21±0.18	-24.91±0.19	0.30±0.20
Dilution/Concentration	4.27±0.11	-2.46±0.11	1.80±0.10	-24.21±0.15	22.43±0.16	-1.78±0.17
Total Salinity Change	**4.27±0.11**	**-2.46±0.11**	**1.80±0.10**	**1.01±0.18**	**-2.48±0.19**	**-1.48±0.20**

Starting with the mass budget, which is relatively straightforward: as outlined in the Data & Methods section, at each interface (air-sea and the Strait of Gibraltar) we can break the fluxes down into two primary processes. At the surface, these processes are evaporation and precipitation (including runoff). Evaporation results in a mass loss of -0.11±0.01 Sv, while precipitation adds a mass gain of 0.06±0.01 Sv. This leads to a net mass loss of -0.05±0.01 Sv from all air-sea freshwater fluxes.

At the Strait of Gibraltar, the two processes are the inflow of AW and the outflow of MOW. The inflow through the upper layer brings in 0.68±0.02 Sv of AW, while the outflow in the lower layer exports -0.63±0.02 Sv of MOW. The net result is a modest positive mass gain, on the order of one magnitude smaller than either of the individual flows. Overall, the Mediterranean Sea gains water mass through net inflow at an average rate of 0.05±0.02 Sv, which closely aligns with values reported in the literature. For instance, Jordà et al. (2017a) derived a similar number at 0.065±0.033 Sv from nearly 20 independent observational estimates.

Regarding the salinity budget, as noted previously, salt and salinity transport are only meaningful for understanding freshwater fluxes when the total mass transport within a closed region is zero (Tsubouchi et al., 2012; Schauer and Losch, 2019). This is an ideal condition in our case, as we have already established a mass balance within the semi-enclosed Mediterranean basin.

Meanwhile, evaporation increases the salinity level by removing freshwater, resulting in a concentration effect equivalent to 4.27±0.11 Sv. On the other hand, precipitation dilutes the seawater, leading to a salinity reduction of -2.46±0.11 Sv. Together, these air-sea fluxes contribute a net positive of 1.80±0.10 Sv.

In contrast to the surface processes, the salinity exchange through the Strait of Gibraltar operates in a more complex manner. As outlined in the methods section, salinity flux through the strait can be split into two main components: one term represents the advection of salinity due to mass transport ($\boldsymbol{u}\nabla S$), while the other captures changes in salinity caused by the differing salinity levels of the inflowing and outflowing water masses ($S\nabla \boldsymbol{u}$), which lead to salinification or dilution. Starting with the salt content transport $\boldsymbol{u}\nabla S$, ECCO estimate a net salt flux into the Mediterranean through this exchange at 0.30±0.20 Sv. This is driven by the exchange between the AW and the relatively saltier MOW at the Strait of Gibraltar. Specifically, the AW brings in 25.21±0.18 Sv of salt content, while the MOW carries out -24.91±0.19 Sv.

We then consider the dilution and concentration effects resulting from the introduction of AW and MOW at the Strait of Gibraltar, which is driven by the density differences between AW, MOW, and the average Mediterranean seawater. In this context, assuming the total salt content within the Mediterranean Sea remains constant, the addition of AW (with relatively lower salinity) and the removal of MOW (with higher salinity) lead to a net dilution effect due to changes in total mass and density; specifically, the water exchange at the Strait of Gibraltar would reduce the salinity by approximately -1.78±0.03 Sv due to a net dilution effect. After the adjustment, the net influence of the water exchange at the Strait of Gibraltar shifts from a net gain in salt content to an overall reduction in salinity, estimated at -1.48±0.20 Sv. This hilights the critical role of mass/density changes in the Mediterranean Sea's salinity budget, which significantly impact the balance of salinity in this semi-enclosed basin.

4 Conclusion and Discussion

This study revisits and presents a quantitative assessment of the Mediterranean Sea's mass and salinity budgets over the period 2003–2017 using the ECCO v4r4 ocean state estimate. By focusing on the two primary boundary terms—surface freshwater fluxes and the exchange through the Strait of Gibraltar—we diagnose the large-scale, basin-integrated processes that govern changes in the Mediterranean's salt and water content.

Our results highlight the dominant role of net evaporation in driving salinity increases across the basin. Surface freshwater loss, averaging approximately 1.80 ± 0.10 Sv, is only partially compensated by the saltwater inflow from the Atlantic, resulting in a net export of salt at -1.48 ± 0.20 Sv and a residual salinity gain of 0.29 ± 0.09 Sv over the study period. These values align well with estimates from previous studies (Calafat et al., 2010, 2012; Soto-Navarro et al., 2010; Jordá et al., 2017b; Llases et al., 2018), providing confidence in ECCO's basin-scale closure.

This work also reinforces recent arguments for adopting a salt budget framework—rather than relying solely on salinity—when interpreting long-term variability, as it removes the confounding effects of water mass changes (Schauer & Losch, 2019). The diagnosed salt trends offer a clearer attribution of the relative contributions from surface fluxes and boundary exchanges.

Despite its relatively coarse resolution, ECCO v4r4 provides a dynamically consistent, data-constrained estimate of the Mediterranean's basin-scale salt and freshwater budgets. While it cannot resolve mesoscale and submesoscale processes—particularly in narrow or complex regions like the Strait of Gibraltar (Soto-Navarro et al., 2010), the Strait of Sicily (Gasparini et al., 2004; Cotroneo et al., 2021), or Dardanelles Strait (Jarosz et al., 2013)—its global closure and physical consistency allow for long-term, basin-integrated trend estimation. Higher-resolution regional models such as the Med Sea Physics reanalysis (Escudier et al., 2021) and NEMO-MED12 better capture local dynamics, including Black Sea inflow (Potiris et al., 2024; Mamoutos et al., 2024), but are not optimized for large-scale/global budget closure. Our approach thus prioritizes a robust representation of large-scale exchanges—primarily surface evaporation and the Gibraltar flux—that dominate long-term salinity changes, in agreement with Mediterranean-wide salinification trends under climate forcing (Schroeder et al., 2016).

Uncertainties arising from ECCO's resolution, including excessive mixing and smoothed gradients in narrow passages, remain a key limitation for sub-basin interpretation. The absence of tidal forcing in ECCO v4r4 remains another key source of uncertainty in our salt budget estimates, as prior work (Sanchez-Roman et al., 2018) has shown that including tides can significantly increase net salt export by enhancing mixing and recirculation at the strait.

Additionally, discrepancies among reanalysis products in representing air-sea fluxes (Josey et al., 2011; Skliris et al., 2024) emphasize the need for multi-model comparisons. Future work should focus on integrating ECCO with higher-resolution models and independent observations to quantify these uncertainties, enhance confidence in diagnosed budgets, and refine our understanding of the Mediterranean's evolving water cycle.

While previous work established the roles of surface freshwater fluxes and Gibraltar exchange, our study leverages ECCOv4r4's unique framework—combining dynamic consistency, closed budgets, and assimilation of satellite and in situ observations—to traceably partition salinity variability. Rather than replacing high-resolution regional models, our work provides a physically consistent, observation-constrained baseline essential for interpreting Mediterranean salinity changes. By reconciling surface fluxes, Gibraltar exchange, and observed salinity trends, we clarify the relative influence of climate-driven surface forcing and advective processes, providing a foundation for future change attribution in this climatically sensitive basin. In summary, our findings contribute a consistent, basin-wide reference for interpreting ongoing and future changes in the Mediterranean Sea under continued climate forcing.

Data Availability

The gridded EN4 used in this work is accessible at http://hadobs.metoffice.com/en4. The OAFlux is accessible at https://oaflux.whoi.edu/, and the GPCP monthly analysis is available at https://psl.noaa.gov/data/gridded/data.gpcp.html. The ECCO ocean state estimate is accessible at https://ecco-group.org/. NAO, EA and EA/WR indices are obtained from https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml.

Author contributions

All coauthors defined the research problem and the conceptualization of the study. CL carried out the data analysis and produced the figures and first draft under the supervision of XL. All coauthors discussed the analysis and contributed to the writing of the final paper.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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References

Adcroft, A. and Campin, J.M.. Rescaled height coordinates for accurate representation of free-surface flows in ocean circulation models. Ocean Modelling, 7(3-4), pp.269-284, 2004.

Adcroft, A., Campin, J. M., Hill, C., & Marshall, J. Implementation of an atmosphere–ocean general circulation model on the expanded spherical cube. Monthly Weather Rev., 132, 2845-2863. doi:10.1175/MWR-3191.1, 2004.

Aydogdu, A., Miraglio, P., Escudier, R., Clementi, E., and Masina, S.: The dynamical role of upper layer salinity in the Mediterranean Sea, in: 7th edition of the Copernicus Ocean State Report (OSR7), edited by: von Schuckmann, K., Moreira, L., Le Traon, P.-Y., Grégoire, M., Marcos, M., Staneva, J., Brasseur, P., Garric, G., Lionello, P., Karstensen, J., and Neukermans, G., Copernicus Publications, State Planet, 1-osr7, 6, https://doi.org/10.5194/sp-1-osr7-6-2023, 2023.

Barnston, A. G., & Livezey, R. E.. Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Monthly weather review, 115(6), 1083-1126, 1987.

Bates, N. R. and Johnson, R. J. Acceleration of ocean warming, salinification, deoxygenation and acidification in the surface subtropical North Atlantic Ocean. Commun. Earth Environ., 1, 33. doi:10.1038/s41558-020-00859-4, 2020.

Bladwell, C., Holmes, R.M. and Zika, J.D., Internal salt content: A useful framework for understanding the oceanic branch of the water cycle. J. Phys. Oceanogr., 51(7), pp.2167-2179, 2021.

Bonaduce, A., Pinardi, N., Oddo, P., Spada, G., Larnicol, G., Sea-Level variability in the Mediterranean Sea from altimetry and tide gauges. Clim. Dyn., 47, 2851–2866, 2016. doi: 10.1007/s00382-016-3001-2.

Castro-Díez, Y., Pozo-Vázquez, D., Rodrigo, F.S. and Esteban-Parra, M.J., NAO and winter temperature variability in southern Europe. Geophys. Res. Lett., 29(8), pp.1-1, 2002.

Calafat, F.M., Chambers, D.P. and Tsimplis, M.N., Mechanisms of decadal sea level variability in the eastern North Atlantic and the Mediterranean Sea. J. Geophys. Res.: Oceans, 117(C9), 2012.

Calafat, F.M., Marcos, M. and Gomis, D., Mass contribution to Mediterranean Sea level variability for the period 1948–2000. Global Planet. Change, 73(3-4), 193-201, 2010.

Campin, J.M., Marshall, J. and Ferreira, D.. Sea ice–ocean coupling using a rescaled vertical coordinate z∗. Ocean Modelling, 24(1-2), pp.1-14, 2008.

Chen, J.L., Wilson, C.R., Tapley, B.D., Save, H. and Cretaux, J.F., Long-term and seasonal Caspian Sea level change from satellite gravity and altimeter measurements. J. Geophys. Res.: Solid Earth, 122(3), pp.2274-2290, 2017.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, D.P. and Bechtold, P., The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc., 137(656), pp.553-597, 2011.

Durack, P.J., Wijffels, S.E. and Matear, R.J., Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. Science, 336(6080), 455-458, 2012.

Dukhovskoy, D. S., Yashayaev, I., Proshutinsky, A., Bamber, J. L., Bashmachnikov, I. L., Chassignet, E. P., ... & Tedstone, A. J.. Role of Greenland freshwater anomaly in the recent freshening of the subpolar North Atlantic. Journal of Geophysical Research: Oceans, 124(5), 3333-3360, 2019.

ECCO Consortium, Fukumori, I., Wang, O., Fenty, I., Forget, G., Heimbach, P. and Ponte, R.M., Synopsis of the ECCO central production global ocean and sea-ice state estimate (version 4 release 4). Zenodo, 2021.

Escudier, R., Clementi, E., Cipollone, A., Pistoia, J., Drudi, M., Grandi, A., et al., A high-resolution reanalysis for the Mediterranean Sea. Front. Earth Sci., 9, 2021. doi: 10.3389/feart.2021.702285.

Fekete, B. M., Vörösmarty, C. J., and Grabs, W. *High-resolution fields of global runoff combining observed river discharge and simulated water balances*, Global Biogeochem. Cy., **16**, 15-11–15-10, 2002.

Feng, Y., Menemenlis, D., Xue, H., Zhang, H., Carroll, D., Du, Y. and Wu, H. *Improved representation of river runoff in Estimating the Circulation and Climate of the Ocean Version 4 (ECCOv4) simulations: implementation, evaluation, and impacts to coastal plume regions*, Geoscientific Model Development, **14**(3), 1801-1819, 2021.

Fenoglio-Marc, L., Rietbroek, R., Grayek, S., Becker, M., Kusche, J. and Stanev, E. *Water mass variation in the Mediterranean and Black Seas*, Journal of Geodynamics, **59**, 168-182, 2012.

Forget, G. A. E. L., Campin, J. M., Heimbach, P., Hill, C. N., Ponte, R. M., & Wunsch, C. *ECCO version 4: An integrated framework for non-linear inverse modeling and global ocean state estimation*, Geoscientific Model Development, **8**(10), 3071-3104, 2015.

Fukumori, I., Menemenlis, D., & Lee, T. *A near-uniform basin-wide sea level fluctuation of the Mediterranean Sea*, Journal of Physical Oceanography, **37**(2), 338-358, 2007.

Fukumori, I., Wang, O., Fenty, I., Forget, G., Heimbach, P., & Ponte, R. M. *ECCO version 4 release 3*, http://hdl.handle.net/1721.1/110380, Available at ftp://ecco.jpl.nasa.gov/Version4/Release3/doc/v4r3_summary.pdf, 2017.

García-García, D., Chao, B. F., & Boy, J. P. *Steric and mass-induced sea level variations in the Mediterranean Sea revisited*, Journal of Geophysical Research: Oceans, **115**(C12), 2010.

García-García, D., Vigo, M.I., Trottini, M., Vargas-Alemañy, J.A. and Sayol, J.M. *Hydrological cycle of the Mediterranean-Black Sea system*, Climate Dynamics, **59**(7), 1919-1938, 2022.

Giorgi, F. *Climate change hot-spots*, Geophysical research letters, **33**(8), 2006.

Gomis, D., Ruiz, S., Sotillo, M. G., Álvarez-Fanjul, E., & Terradas, J. Low frequency Mediterranean sea level variability: the contribution of atmospheric pressure and wind. Global and Planetary Change, 63, 215-229, 2008.

Good, S. A., Martin, M. J., & Rayner, N. A. EN4: Quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates. Journal of Geophysical Research: Oceans, 118, 6704-6716, 2013.

Greatbatch, R. J. A note on the representation of steric sea level in models that conserve volume rather than mass. Journal of Geophysical Research: Oceans, 99(C6), 12767-12771, 1994.

Grist, J. P., Josey, S. A., Zika, J. D., Evans, D. G., & Skliris, N. Assessing recent air-sea freshwater flux changes using a surface temperature-salinity space framework. Journal of Geophysical Research: Oceans, 121(12), 8787-8806, 2016.

Hasson, A. E., Delcroix, T., & Dussin, R. An assessment of the mixed layer salinity budget in the tropical Pacific Ocean. Observations and modelling (1990–2009). Ocean Dynamics, 63(2), 179-194, 2013.

Heimbach, P., Hill, C., & Giering, R. An efficient exact adjoint of the parallel MIT general circulation model, generated via automatic differentiation. Future Generation Computer Systems, 21(8), 1356-1371, 2005.

Held, I. M., & Soden, B. J. Robust responses of the hydrological cycle to global warming. Journal of Climate, 19(21), 5686-5699, 2006.

Holliday, N. P., Bersch, M., Berx, B., Chafik, L., Cunningham, S., Florindo-López, C., ... & Yashayaev, I. Ocean circulation causes the largest freshening event for 120 years in eastern subpolar North Atlantic. Nature communications, 11(1), 585, 2020.

Huffman, G. J., Adler, R. F., Bolvin, D. T., & Gu, G. Improving the global precipitation record: GPCP version 2.1. Geophysical Research Letters, 36(17), 2009.

Huntington, T. G. Evidence for intensification of the global water cycle: Review and synthesis. Journal of Hydrology, 319(1-4), 83-95, 2006.

Hurrell, J. W. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science, 269, 676-679, 1995.

Ivanovic, R. F., Valdes, P. J., Gregoire, L., Flecker, R., & Gutjahr, M. Sensitivity of modern climate to the presence, strength and salinity of Mediterranean-Atlantic exchange in a global general circulation model. Climate Dynamics, 42, 859-877, 2014.

Jarosz, E., W. J. Teague, J. W. Book, and Ş. T. Beşiktepe, Observed volume fluxes and mixing in the Dardanelles Strait, J. Geophys. Res. Oceans, 118, 5007–5021, doi:10.1002/jgrc.20396, 2013.

Josey, S. A., Somot, S., & Tsimplis, M. Impacts of atmospheric modes of variability on Mediterranean Sea surface heat exchange. Journal of Geophysical Research: Oceans, 116(C2), 2011.

Jordà, G., Sanchez-Roman, A., & Gomis, D. Reconstruction of transports through the Strait of Gibraltar from limited observations. Climate Dynamics, 48(3), 851-865, 2017.

Jordà, G., Von Schuckmann, K., Josey, S. A., Caniaux, G., García-Lafuente, J., Sammartino, S., ... & Macías, D. The Mediterranean Sea heat and mass budgets: Estimates, uncertainties and perspectives. Progress in Oceanography, 156, 174-208, 2017.

Kara, A. B., Wallcraft, A. J., Metzger, E. J., & Gunduz, M. Impacts of freshwater on the seasonal variations of surface salinity and circulation in the Caspian Sea. Continental Shelf Research, 30(10-11), 1211-1225, 2010.

Krichak, S., Kishcha, P. & Alpert, P. Decadal trends of main Eurasian oscillations and the Eastern Mediterranean precipitation. Theor. Appl. Climatol. 72, 209–220, 2002.

Landerer, F. W., & Volkov, D. L. The anatomy of recent large sea level fluctuations in the Mediterranean Sea. Geophysical Research Letters, 40(3), 553-557, 2013.

Llasses, J., Jordà, G., Gomis, D., et al. Heat and salt redistribution within the Mediterranean Sea in the Med-CORDEX model ensemble. Clim Dyn, 51, 1119-1143, doi:10.1007/s00382-016-3242-0, 2018.

Lim, Y. K.. The East Atlantic/West Russia (EA/WR) teleconnection in the North Atlantic: climate impact and relation to Rossby wave propagation. Climate dynamics, 44, 3211-3222, 2015.Liu, C., Liang, X., Ponte, R. M., Vinogradova, N., & Wang, O. Vertical redistribution of salt and layered changes in global ocean salinity. Nature Communications, 10(1), 3445, 2019.

Liu, C., Liang, X., Chambers, D. P., & Ponte, R. M. Global patterns of spatial and temporal variability in salinity from multiple gridded Argo products. Journal of Climate, 33(20), 8751-8766, 2020.

Liu, C., Liang, X., Ponte, R. M., & Chambers, D. P. "Salty Drift" of Argo Floats Affects the Gridded Ocean Salinity Products. Journal of Geophysical Research: Oceans, 129(9), e2023JC020871, 2024.

Lu, Y., Li, Y., Lin, P. et al. North Atlantic–Pacific salinity contrast enhanced by wind and ocean warming. Nat. Clim. Chang. 14, 723–731, 2024.

Mamoutos, I.G., Potiris, E., Androulidakis, Y., Tragou, E. and Zervakis, V., Evidence for reduced Black Sea water outflow to the North Aegean. Earth and Space Science, 11, p.e2024EA003674, 2024.

Marshall, J., Adcroft, A., Hill, C., Perelman, L., & Heisey, C., A finite-volume, incompressible Navier Stokes model for studies of the ocean on parallel computers. Journal of Geophysical Research: Oceans, 102(C3), 5753-5766, 1997.

Mauri, E., Sitz, L., Gerin, R., Poulain, P.-M., Hayes, D., Gildor, H., On the variability of the circulation and water mass properties in the Eastern Levantine Sea between September 2016–August 2017. Water, 11, 1741, doi: 10.3390/w11091741, 2019.

Meli, M., Camargo, C.M., Olivieri, M., Slangen, A.B. and Romagnoli, C., Sea-level trend variability in the Mediterranean during the 1993–2019 period. Frontiers in Marine Science, 10, p.1150488, 2023.

Menemenlis, D., Fukumori, I., & Lee, T., Atlantic to Mediterranean sea level difference driven by winds near Gibraltar Strait. Journal of Physical Oceanography, 37(2), 359-376, 2007.

Menna, M., Poulain, P.-M., Zodiatis, G., Gertman, I., On the surface circulation of the Levantine sub-basin derived from Lagrangian drifters and satellite altimetry data. Deep Sea Research Part I: Oceanographic Research Papers, 65, 46–58, doi: 10.1016/j.dsr.2012.02.008, 2012.

Millot, C. and Taupier-Letage, I., Circulation in the Mediterranean Sea. The Mediterranean Sea, pp.29-66, 2005.

Millot, C., Candela, J., Fuda, J.L. and Tber, Y., Large warming and salinification of the Mediterranean outflow due to changes in its composition. Deep Sea Research Part I: Oceanographic Research Papers, 53(4), 656-666, 2006.

Menna, M., Reyes-Suarez, N.C., Civitarese, G., Gačić, M., Poulain, P.-M., Rubino, A., Decadal variations of circulation in the central Mediterranean and its interactions with the mesoscale gyres. Deep Sea Research Part II: Topical Studies in Oceanography, 164, 14–24, doi: 10.1016/j.dsr2.2019.02.004, 2019.

Mohamed, B., Abdallah, A.M., Alam El-Din, K., Nagy, H., Shaltout, M., Inter-annual variability and trends of sea level and sea surface temperature in the Mediterranean Sea over the last 25 years. Pure and Applied Geophysics, 176, 3787–3810, doi: 10.1007/s00024-019-02156-w, 2019.

Myers, P.G., & Haines, K., Stability of the Mediterranean's thermohaline circulation under modified surface evaporative fluxes. Journal of Geophysical Research: Oceans, 107(C3), 7-1, 2002.

Nan, F., Yu, F., Xue, H., Wang, R., & Si, G., Ocean salinity changes in the northwest Pacific subtropical gyre: The quasi-decadal oscillation and the freshening trend. Journal of Geophysical Research: Oceans, 120(3), 2179-2192, 2015.

Piecuch, C.G., A note on practical evaluation of budgets in ECCO version 4 release 3. 2017.

Piecuch, C.G., & Ponte, R.M., Nonseasonal mass fluctuations in the midlatitude North Atlantic Ocean. Geophysical Research Letters, 41(12), 4261-4269, 2014.

Pinardi, N., Bonaduce, A., Navarra, A., Dobricic, S., Oddo, P., The mean sea level equation and its application to the Mediterranean Sea. Journal of Climate, 27, 442–447, doi: 10.1175/JCLI-D-13-00139.1, 2014.

Ponte, R.M., Sun, Q., Liu, C. and Liang, X., How salty is the global ocean: weighing it all or tasting it a sip at a time?. Geophysical Research Letters, 48(11), p.e2021GL092935, 2021.

Potiris, M., Mamoutos, I.G., Tragou, E., Zervakis, V., Kassis, D. and Ballas, D., Dense water formation in the North–central Aegean Sea during winter 2021–2022. Journal of Marine Science and Engineering, 12(2), p.221, 2024.

Poulain, P.M., Centurioni, L., Özgökmen, T., Tarry, D., Pascual, A., Ruiz, S., et al., On the structure and kinematics of an Algerian eddy in the southwestern Mediterranean Sea. Remote Sensing, 13, 3039, doi: 10.3390/rs13153039, 2021.

Reid, J.L., On the contribution of the Mediterranean Sea outflow to the Norwegian-Greenland Sea. Deep Sea Research Part A: Oceanographic Research Papers, 26(11), 1199-1223, 1979.

Sanchez-Roman, A., Jorda, G., Sannino, G., and Gomis, D.: Modelling study of transformations of the exchange flows along the Strait of Gibraltar, Ocean Sci., 14, 1547–1566, https://doi.org/10.5194/os-14-1547-2018, 2018

Schauer, U. and Losch, M., "Freshwater" in the ocean is not a useful parameter in climate research. Journal of Physical Oceanography, 49(9), 2309-2321, 2019.

Sukhonos, P., Gusev, A. and Diansky, N., Investigation of North Atlantic salinity long-term trends based on historical datasets. Journal of Marine Science and Engineering, 12(8), p.1404, 2024.

Schroeder, K., Garcìa-Lafuente, J., Josey, S.A., Artale, V., Nardelli, B.B., Carrillo, A., ... & Zodiatis, G., Circulation of the Mediterranean Sea and its variability. The Climate of the Mediterranean Region: From the Past to the Future, edited by: Lionello, P., Elsevier Insights, Amsterdam, 2012.

Siddiqui, A.H., Haine, T.W., Nguyen, A.T. and Buckley, M.W., *Controls on upper ocean salinity variability in the eastern subpolar North Atlantic during 1992–2017*. J. Geophys. Res.: Oceans, **129**(8), p.e2024JC020887, 2024.

Skliris, N., Marsh, R., Josey, S.A., Good, S.A., Liu, C., and Allan, R.P., *Salinity changes in the World Ocean since 1950 in relation to changing surface freshwater fluxes*. Clim. Dyn., **43**(3), 709-736, 2014.

Skliris, N., Marsh, R., Breedon, M. and Josey, S.A., *Accelerated Warming and Salinification of the Mediterranean Sea: Implications for Dense Water Formation*. J. Mar. Sci. Eng., **13**(1), p.25, 2024.

Soto-Navarro, J., Criado-Aldeanueva, F., García-Lafuente, J. and Sánchez-Román, A., *Estimation of the Atlantic inflow through the Strait of Gibraltar from climatological and in situ data*. J. Geophys. Res.: Oceans, **115**(C10), 2010.

Stammer, D., Ueyoshi, K., Köhl, A., Large, W.G., Josey, S.A., and Wunsch, C., *Estimating air-sea fluxes of heat, freshwater, and momentum through global ocean data assimilation*. J. Geophys. Res.: Oceans, **109**(C5), 2004.

Storto, A., Bonaduce, A., Feng, X. and Yang, C., *Steric sea level changes from ocean reanalyses at global and regional scales*. Water, **11**(10), p.1987, 2019.

Tesdal, J.E. and Abernathey, R.P., *Drivers of local ocean heat content variability in ECCOv4*. J. Climate, **34**(8), 2941-2956, 2021.

Tsimplis, M.N., Marcos, M., and Somot, S., *21st century Mediterranean sea level rise: steric and atmospheric pressure contributions from a regional model*. Global Planet. Change, **63**(2-3), 105-111, 2008.

Tsubouchi, T., and Coauthors, *The Arctic Ocean in summer: A quasi-synoptic inverse estimate of boundary fluxes and water mass transformation*. J. Geophys. Res., **117**, C01024, 2012.

Turuncoglu, U.U., *Identifying the sensitivity of precipitation of Anatolian peninsula to Mediterranean and Black Sea surface temperature*. Clim. Dyn., **44**(7), 1993-2015, 2015.

Ünlülata, Ü., Oğuz, T., Latif, M. A., & Özsoy, E. On the physical oceanography of the Turkish Straits. The physical oceanography of sea straits, 25-60, 1990.

Vigo, M.I., Sanchez-Reales, J.M., Trottini, M. and Chao, B.F., *Mediterranean sea level variations: analysis of the satellite altimetric data, 1992–2008*. J. Geodyn., **52**(3-4), 271–278, 2011.

Vinogradova, N.T., and Ponte, R.M., *Clarifying the link between surface salinity and freshwater fluxes on monthly to interannual time scales*. J. Geophys. Res.: Oceans, **118**(6), 3190-3201, 2013.

Vinogradova, N.T., and Ponte, R.M., *In search of fingerprints of the recent intensification of the ocean water cycle*. J. Climate, **30**(14), 5513-5528, 2017.

Volkov, D.L., and Landerer, F.W., *Internal and external forcing of sea level variability in the Black Sea*. Clim. Dyn., **45**(9), 2633-2646, 2015.

Wallace, J. M., & Gutzler, D. S.. Teleconnections in the geopotential height field during the Northern Hemisphere winter. Monthly weather review, 109(4), 784-812, 1981.Wunsch, C., and Heimbach, P., *Practical global oceanic state estimation*. Physica D: Nonlinear Phenom., **230**(1-2), 197-208, 2007.

Wunsch, C., Heimbach, P., Ponte, R.M., Fukumori, I., and ECCO-GODAE CONSORTIUM MEMBERS, *The global general circulation of the ocean estimated by the ECCO-Consortium*. Oceanography, **22**(2), 88-103, 2009.

Wunsch, C., and Heimbach, P., *Dynamically and kinematically consistent global ocean circulation and ice state estimates*. In International Geophysics Vol. 103, pp. 553-579. Academic Press, 2013.

Yu, L., *A global relationship between the ocean water cycle and near-surface salinity*. J. Geophys. Res.: Oceans, **116**(C10), 2011.

Yu, L., and Weller, R.A., *Objectively analyzed air-sea heat fluxes for the global ice-free oceans (1981–2005)*. Bull. Amer. Meteor. Soc., **88**(4), 527-540, 2007.

Zveryaev, I. I., & Hannachi, A. A.. Interannual variability of Mediterranean evaporation and its relation to regional climate. Climate dynamics, 38, 495-512, 2012.