Literature review

Jari Miglio

Abstract

This work was conducted as part of a literature review for the course "Physics of the Hydrosphere and Cryosphere" at the Università degli Studi di Milano. Its primary objective was to summarize the key findings of the referenced article and analyze the methodology employed. During the review, two typographical errors were identified. The first appears in Section "3.1 Non-seasonal Variability of Mass and Salinity Fluxes", where Figure 3a (instead of Figure 4a) correctly presents the temporal variability of the Mediterranean Sea's mass budget. The second error is in Section "3.3 Roles of Air-Sea Fluxes and Oceanic Exchange During 2003–2017", where, in Figure 6, the labels for evaporation and precipitation are inverted: evaporation, which represents mass loss, should correspond to the blue box, while precipitation, which represents mass gain, should correspond to the red box. Additionally, Section "2.2 The Calculation of Salinity and Mass Budget" requires further clarification, as the equations proposed for the mass and salinity balances in the Mediterranean basin are dimensionally inconsistent. A discussion of this issue is provided in the corresponding section of this review. All content in this literature review has been revised and approved by Professor Mauro Giudici.

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. Global warming has led to significant alterations in key physical quantities, such as surface salinity, which serve as indicators of the state of the Mediterranean's water masses. In particular, the overall increase in mean temperature has intensified the hydrological cycle, resulting in an increased evaporation rate and a reduction in freshwater inflows to the Mediterranean region. These changes have led to notable modifications in surface salinity.

The Mediterranean basin exhibits complex dynamics, with salinity and mass variations directly influenced by boundary fluxes, primarily air-sea interactions and water exchange with the North Atlantic through the Strait of Gibraltar. These two primary processes contribute to the basin's water balance in distinct ways:

1. Air-sea freshwater fluxes

   The freshwater flux is primarily composed of evaporation (E) and precipitation (P), driving the Mediterranean's persistent water deficit, which arises from the imbalance between high evaporation rates and relatively low precipitation. Additionally, river runoff (R) from major rivers contributes to the freshwater input, but its effect is significantly smaller compared to evaporation and precipitation. Despite its lower contribution, runoff is included in this study for completeness.

Surface fluxes only alter the freshwater content of the basin since they do not affect the total salt content and act as both mass and volume fluxes:

(a) As a mass flux, they can be measured through ocean bottom pressure (a decrease in mass due to net evaporation results in a drop in pressure, assuming other factors remain constant).

(b) As a volume flux, their impact is reflected in salinity changes (variations in water volume affect concentration, leading to changes in salinity).

These contributions arise from the strong coupling between the atmosphere and the hydrosphere.

2. Water exchange through the Strait of Gibraltar

The circulation at the Strait of Gibraltar can be approximated as a two-layer system:

(a) The upper layer carries relatively fresher Atlantic Water (AW) eastward into the Mediterranean Sea.

(b) The lower layer transports saltier Mediterranean Outflow Water (MOW) westward, at depths below 150 m.

These two water masses are interconnected through the Mediterranean's internal thermohaline circulation. The exchange through the Strait compensates for the mass loss caused by strong net evaporation and is the primary mechanism regulating the basin's salt budget.

Changes in air-sea freshwater fluxes, which reflect climate variability, have direct effects on both mass balance and salinity levels. However, in the semi-enclosed Mediterranean, these effects are often partially masked by the compensating exchange at the Strait of Gibraltar, making it challenging to provide precise estimations.

In this study, the authors 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). This model provides a robust framework for investigating the Mediterranean's mass and salinity budgets at a basin-wide scale. The analysis focuses on diagnosing the mechanisms driving temporal variability in mass and salinity and understanding the interactions between the Mediterranean Sea, the Atmosphere, and the broader North Atlantic system.

2 Data and Methods

2.1 ECCO evaluation

The model used in this study is an ocean state estimate, where observational data are assimilated while ensuring dynamic and kinematic consistency. Observations, such as Argo temperature and salinity profiles, are used to constrain the ECCO solution, which is obtained by integrating fundamental physical conservation laws. At the sea surface, ECCO is constrained by atmospheric forcing derived from the ERA-Interim reanalysis, a historical dataset providing a wide range of atmospheric parameters.

ECCO solutions span the period 1992–2017 and have a global domain with 50 vertical layers. The model resolution is relatively coarse, with a zonal (longitudinal) resolution of 1°, while the meridional resolution varies, ranging from 1/3° at the equator to 1° at midlatitudes. It is important to emphasize that the resolution of a model refers to the longitudinal and latitudinal spacing of the computational grid, which determines how finely the model discretizes the Earth's surface.

The study focuses on the period 2003–2017, chosen to coincide with the widespread deployment of Argo floats, which significantly improved observational coverage and data quality in the Mediterranean Sea. A comparison between ECCO model outputs and observational datasets, including time series and time-mean spatial patterns of freshwater fluxes, reveals a reasonable agreement (Figure 2 of the paper). Overall, ECCO effectively captures the primary features of oceanic variables in the Mediterranean Sea with reasonable accuracy, giving the authors confidence in its use for salinity and mass budget analysis in the region.

2.2 Calculation of Salinity and Mass Budgets

The Mediterranean Sea is characterized by complex thermohaline variability and local circulation patterns, which lead to significant spatial differences at the sub-basin scale. However, the relatively coarse resolution of ECCO may limit its ability to accurately resolve these finer-scale processes and consequently, the precision of sub-basin simulations remains uncertain. For this reason, this study focuses on the Mediterranean basin as a whole, rather than attempting to resolve localized sub-basin processes in detail.

The mass conservation principle governing the Mediterranean Sea's budget can be described using a simplified box model, with two primary boundary terms: surface fluxes and water exchanges through the Strait of Gibraltar. In the study, the mass budget equation for the entire water column is expressed as:

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

where P_b is the bottom pressure equivalent water thickness, $\mathbf{u}$ is the horizontal velocity, F_{fw} is the surface freshwater flux $(P + R - E)$, ρ_{sw} and ρ_{fw} are respectively the seawater and freshwater density. Some remarks are needed:

1. The left-hand side term represents a measure of sea mass variability, incorporating contributions from fluctuations in atmospheric sea level pressure, dynamic topography, and variations in the mass of the fluid column between the unperturbed surface and the seafloor. These factors collectively influence Observed Bottom Pressure (OBP) variability. Furthermore, OBP variability is strongly correlated with sea surface height (SSH) variability, which is also affected by atmospheric loading and the hydrological cycle. In summary, OBP can be considered a proxy for ocean mass variability, as well as for ocean circulation changes and variations in the Earth's gravity field. To illustrate this concept, let us consider a cylindrical water column extending from the seafloor to the sea surface, with a thickness H and surface area S. The notation used in this review differs slightly from that in the referenced article: here, P_b denotes the bottom pressure, while H retains the same meaning as what is called P_b in the article, representing the thickness of the water column. The bottom pressure at the seafloor can then be expressed as:

$$P_b = P_a + \frac{m_{sw}g}{S} = P_a + \rho_{sw}gH. \tag{2}$$

Hence the time variation of the sea bottom pressure is:

$$\frac{\partial P_b}{\partial t} = \frac{\partial P_a}{\partial t} + \frac{\partial(\rho_{sw}gH)}{\partial t} = \frac{\partial P_a}{\partial t} + \rho_{sw}H\frac{\partial g}{\partial t} + Hg\frac{\partial \rho_{sw}}{\partial t} + \rho_{sw}g\frac{\partial H}{\partial t} \tag{3}$$

$$\frac{1}{g}\frac{\partial P_b}{\partial t} = \frac{1}{g}\frac{\partial P_a}{\partial t} + \frac{\rho_{sw}H}{g}\frac{\partial g}{\partial t} + H\frac{\partial \rho_{sw}}{\partial t} + \rho_{sw}\frac{\partial H}{\partial t} \tag{4}$$

Neglecting the time variation of atmospheric pressure and seawater density we obtain:

$$\frac{1}{g}\frac{\partial P_b}{\partial t} \approx \rho_{sw}\frac{\partial H}{\partial t} \tag{5}$$

This computation aims to clarify the first term on the left-hand side of the equation. It should be interpreted as the product of seawater density and the time variation of the ocean's thickness. Alternatively, when neglecting variations in atmospheric pressure and seawater density, it represents the tendency term of bottom pressure per unit gravity, i.e., the rate of change of OBP (Observed Bottom Pressure).

The corresponding dimensions are:

$$[\rho_{sw}\frac{\partial H}{\partial t}] = \frac{\text{kg}}{\text{m}^3}\frac{\text{m}}{\text{s}} = \frac{\text{kg}}{\text{m}^2\text{s}} \tag{6}$$

and can be interpreted as:

$$\frac{\Delta M_{\text{in/out on the surface of Mediterranean basin in } \Delta t}}{\Delta t \cdot S} \tag{7}$$

2. The first term on the right-hand side represents the convergence of seawater fluxes and accounts for the time variation of seawater density due to water exchanges at the Strait of Gibraltar. The dimensional estimation of this term can be computed as follows:

$$[\nabla \cdot (\rho_{sw}\mathbf{v})] = \frac{1}{\text{m}}\frac{\text{kg}}{\text{m}^3}\frac{\text{m}}{\text{s}} = \frac{\text{kg}}{\text{m}^3\text{s}} \tag{8}$$

   Since the dimensions of this quantity are not consistent with the overall equation, equation (1) must be expressed in a formally consistent manner. To achieve this, equation (1) should either be considered in its integral form, summing up all contributions over the entire Mediterranean basin, or this term should be integrated over the entire thickness of the sea.

3. The second right-hand side term marks the contribution of surface freshwater fluxes and its dimension are perfectly coherent with the dimension of the left-hand side:

$$[\rho_{fw}F_{fw}] = \frac{\text{kg}}{\text{m}^3} \cdot \frac{\text{m}}{\text{s}} = \frac{\text{kg}}{\text{m}^2\text{s}} \tag{9}$$

   Thus, this term can be interpreted as the net mass of freshwater exchanged through air-ocean interactions per unit area and per unit time, i.e., the rate of mass exchange per unit surface area:

$$\frac{\Delta M_{\text{net in-out flow due to P+R-E}}}{\Delta t \cdot S} \tag{10}$$

   Integrating this term over the sea surface represents the total freshwater flux at the Mediterranean basin surface.

The article also offers a formula to calculate the salinity budget in the Mediterranean Sea, balancing in a similar form. The local salinity conservation can be simplified as:

$$\frac{\partial S}{\partial t} = -\nabla \cdot (S\mathbf{u}) + D_S + F_{fw}\tilde{S} \tag{11}$$

where S represents salinity, $\tilde{S}$ denotes local surface salinity, and D_S accounts for subgrid-scale processes, parameterized as diffusive salt flux. The units of the terms in this equation are psu/s, except for the last term, which has units of (psu $\cdot$ m)/s. For this reason, this formula should be regarded as a conceptual representation of physical processes rather than a fully rigorous mathematical expression. In particular, the first term on the right-hand side represents the advection of salinity, which includes two distinct physical mechanisms contributing to salinity changes: one process describes dilution/concentration effects due to the convergence/divergence of mass transport ($S\nabla \cdot \mathbf{u}$), the other represents the exchange of salt content transported by the advective flow ($\mathbf{u} \cdot \nabla S$).

For further insights into the ECCO model and its unit conventions, refer to the following resources: *ecco-v4-python-tutorial* and *ecco-group-evaluating-budgets*.

Since the study focuses on interannual variability of fluxes, the seasonal signal has been removed by subtracting the climatological mean (i.e., mean values over a specified reference time window) from the original time series.

A notable point is that both mass flux and salinity flux are represented in Sverdrups (Sv), allowing for a direct comparison between the two fluxes.

3 Results

3.1 Non-seasonal Variability of Mass and Salinity Fluxes

For the mass flux contributions, refer to Figure 3 of the article (noting that the authors made a typographical error by incorrectly referring to Figure 4a). The monthly mean mass flux exhibits significant month-to-month variability, particularly in the net flux through the Strait of Gibraltar, whose standard deviation is 2.4 times larger than that of the surface freshwater flux.

The mass tendency term variability (the sum of Strait and Surface contributions) is primarily driven by the Strait component, as indicated by a high Pearson correlation of 0.96 (compared to < 0.2 between the total mass tendency and surface term). Additionally, the coefficient of determination (R^2) of 0.92 suggests that Strait fluxes account for nearly all the variance in total mass tendency.

The interannual variability of the time series is much smaller, as expected for values computed as annual means. This is because averaging acts as a low-pass filter, removing higher-frequency fluctuations. Over the 2003–2017 period, the mean values reveal a net water mass gain in the Mediterranean Sea, with a net inflow of 0.05 ± 0.02Sv at the Strait of Gibraltar and a net water loss of -0.05 ± 0.01Sv due to air-sea freshwater fluxes. As a result, the total mass tendency remains close to zero on average, with the two primary fluxes appearing nearly balanced at all times.

This conclusion is further supported by an analysis of the cumulative mass flux time series, which quantifies the contribution of each flux component to overall mass gain or loss over time. The surface flux contribution exhibits a steady downward trend, decreasing at a rate of $-1390 \pm 18\text{km}^3$/year, whereas the net inflow through the Strait of Gibraltar contributes a mass gain at a slightly lower rate of $1368 \pm 20\text{km}^3$/year. These trends result in a very small and statistically insignificant net mass loss of $-22 \pm 24\text{km}^3$/year, indicating a near-equilibrium state, with the total water mass in the Mediterranean Sea remaining relatively stable from 2003 to 2017.

To better evaluate interannual variability in mass flux contributions, the cumulative mass flux time series was detrended. The results reveal that the surface and Strait terms exhibit nearly opposite variations, as expected given that the total Mediterranean mass remains nearly unchanged. Notably, both fluxes tend to contribute to freshwater removal from the Mediterranean basin.

For the salinity flux contributions, refer to Figure 4 of the article. In contrast to the mass budget, the surface freshwater flux term exhibits considerably larger month-to-month variability in salinity, with a standard deviation 2.5 times greater than that of the Strait of Gibraltar flux. The salinity tendency term is primarily driven by surface freshwater fluxes, as indicated by a high Pearson correlation of 0.97 and a coefficient of determination of 0.95. These values suggest that air-sea fluxes alone account for nearly all observed changes in salinity trends. This strong influence arises because freshwater (which contains no salt) dilutes the denser, saltier Mediterranean waters, significantly impacting the basin's overall salinity dynamics.

The interannual variability of the time series reveals a significant increasing trend in salinity flux at the Strait of Gibraltar, estimated at 0.02 ± 0.01Sv per year, while no significant trend is observed in the surface and total salinity fluxes. Since there is no substantial long-term change in the overall mass transport through the Strait of Gibraltar, this salinity increase is likely due to inflowing North Atlantic Water becoming saltier over time, as suggested by recent findings. The cumulative contribution analysis indicates that the mean salinity of Mediterranean seawater has been increasing steadily at a rate of approximately $2.2 \pm 0.2 \cdot 10^{-3}$ per year, corresponding to a total salinity increase of about 0.03 psu over the past 15 years.

The detrended cumulative salinity time series further highlights the dominant role of air-sea interactions in driving salinity variations, with an exceptionally high correlation coefficient (0.95) and $R^2 = 0.88$. The Strait of Gibraltar flux exhibits a phase shift relative to the other flux terms, underscoring its distinct role compared to surface-driven salinity changes.

3.2 Influence of NAO on Salinity and Water Mass Transport

The North Atlantic Oscillation (NAO) is one of the primary climate modes influencing Europe and the Mediterranean region, significantly impacting both weather patterns and oceanic circulation. It

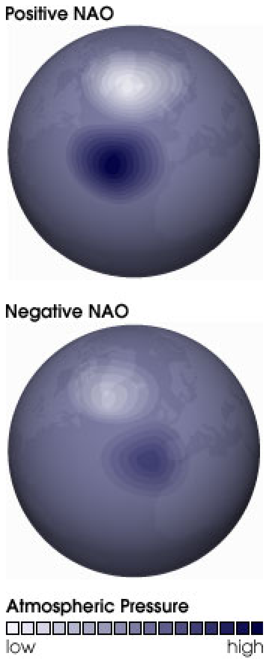

Figure 1: NAO Schematization, for more details, visit this link.

represents fluctuations in the sea-level atmospheric pressure difference between the Icelandic Low (a semi-permanent low-pressure center located between Iceland and southern Greenland) and the Azores High (a semi-permanent subtropical high-pressure system typically situated south of the Azores). Variations in the strength of the Icelandic Low and the Azores High control both the intensity and direction of westerly winds across the North Atlantic.

Since these westerly winds transport moist air toward Europe, fluctuations in their strength and direction account for weather variability across different timescales, ranging from seasonal to decadal. These processes provide a framework for understanding the relationship between the NAO and the interannual variability of the observed time series of mass and salinity fluxes in the Mediterranean.

By defining the winter NAO as the December-to-February mean of the monthly NAO index, several key relationships emerge, i.e. a significant correlation exists between the winter NAO and air-sea mass flux (Figure 3d), with a correlation coefficient of -0.51. Regarding salinity fluxes (Figure 4d), all annual flux components exhibit a significant correlation with the winter NAO: both surface fluxes and Strait fluxes correlate with the winter NAO between 0.5 and 0.6, and the total salinity flux has a correlation of 0.62. A possible interpretation of these results is as follows: since the winter NAO index is negatively correlated with the air-sea mass flux, a stronger NAO (i.e., stronger westerlies) leads to a reduction in air-sea mass flux. This implies an increase in net evaporation, as lower mass flux is associated with enhanced moisture loss from the Mediterranean. As a result, the salinity of the total fluxes increases, ultimately leading to a rise in the overall salinity of the Mediterranean Sea, as explained by the observed positive correlation between the winter NAO and salinity fluxes.

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

Thanks to the ECCO model, it is possible to decompose the contributions of mass and salinity fluxes into their fundamental components. By comparing Figure 6 with Table 1, an inconsistency in the figure is evident: the mass fluxes related to evaporation and precipitation are reversed.

Uncertainties are calculated as the standard error of the mean, given by $\sigma/\sqrt{n}$ where σ is the standard deviation of the corresponding term and $n = 15$ for non-seasonal fluxes.

3.3.1 Mass Budget Analysis

At the surface, 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 due to air-sea freshwater fluxes.

At the Strait of Gibraltar, two primary processes occur:

1. The inflow of Atlantic Water (AW) through the upper layer, bringing in 0.68 ± 0.02 Sv.
2. The outflow of Mediterranean Outflow Water (MOW) through the lower layer, removing -0.63 ± 0.02 Sv.

The net result is a modest positive mass gain, which is an order of magnitude smaller than either of the individual flows.

3.3.2 Salinity Budget Analysis

Evaporation increases salinity by removing freshwater, leading to a concentration effect equivalent to 4.27 ± 0.11 Sv, conversely, precipitation dilutes seawater, causing a salinity reduction of -2.46 ± 0.11 Sv. Together, these air-sea fluxes contribute a net positive effect of 1.80 ± 0.10 Sv on salinity. In contrast, salinity exchange through the Strait of Gibraltar operates in a more complex manner: the salinity flux can be decomposed into two main components:

1. Salt transport associated with mass flow ($\mathbf{u} \cdot \nabla S$). ECCO estimates a net salt flux into the Mediterranean through the Strait of 0.30 ± 0.20 Sv. The increase in salinity is primarily due to the stronger inflow rate of AW: although MOW is saltier than AW, the higher volume of inflowing AW results in a net salt import. Specifically:
   (a) AW imports 25.21 ± 0.18 Sv of salt.
   (b) MOW exports -24.91 ± 0.19 Sv of salt.
2. Volume and mass changes that cause salinification or dilution effects ($S\nabla \cdot \mathbf{u}$). Assuming that the total salt content within the Mediterranean remains constant, the higher inflow rate of AW compared to MOW results in a net dilution effect due to changes in volume and, hence, in density. The exchange at the Strait of Gibraltar reduces salinity by approximately -1.78 ± 0.03 Sv due to this net diluition effect.

After accounting for both components, the net influence of water exchange at the Strait shifts from a net gain in salt content ($\mathbf{u} \cdot \nabla S$) to an overall reduction in salinity ($\mathbf{u} \cdot \nabla S + S\nabla \cdot \mathbf{u}$) estimated at -1.48 ± 0.20 Sv.

These findings emphasize the critical role of volume and density changes in the Mediterranean Sea's salinity budget. The dynamic interplay between inflow and outflow fluxes significantly impacts the overall salinity balance in this semi-enclosed basin.

4 Discussion of ECCO Resolution and Uncertainty

The analysis focuses on basin-scale budgets rather than spatial patterns of trends or decadal means, acknowledging ECCO's limited resolution in accurately representing localized circulation and exchange processes. The model's coarse resolution also poses challenges in resolving vertical salinity variations, particularly within the complex intermediate and deep water masses of the Mediterranean. A direct comparison between ECCO outputs and higher-resolution datasets would help quantify uncertainties associated with resolution limitations and further refine our understanding of both regional and basin-wide trends.

While this study provides a valuable foundation, there is a clear need for further research to address these uncertainties, particularly through validation with higher-precision observational datasets.

5 Conclusion

This study provides a comprehensive assessment of the mass and salinity budgets in the Mediterranean Sea from 2003 to 2017, using the ECCO state estimate. By analyzing the contributions of the primary boundary fluxes — surface freshwater fluxes and saltwater exchange at the Strait of Gibraltar — the study reveals the complex dynamics governing mass and salinity variations in the Mediterranean. The analysis highlights the critical role of air-sea freshwater fluxes, which dominate long-term balance and variability, acting as both mass and volume fluxes.

One of the key findings of this study is the demonstration that the observed salinity increase in the Mediterranean basin is a steady and sustained process, primarily driven by long-term factors, such as the gradual rise in surface net evaporation and the influx of saltier Atlantic waters, rather than being the result of isolated, short-term events.

While these findings emphasize the limitations of ECCO's coarse resolution in resolving fine-scale processes, including the complex water exchange at Gibraltar, they nonetheless provide a robust baseline for understanding large-scale trends. Higher-resolution datasets could further refine these estimates and better capture the nuances of Mediterranean exchange dynamics.

By clarifying the role of air-sea fluxes in regulating water mass and salinity, this study illustrates how these processes drive regional steric (halosteric) adjustments and contribute to global ocean mass variations. Although temperature-driven changes remain the dominant factor behind global sea level rise, the findings underscore the critical yet often understated influence of air-sea fluxes in shaping both regional and global ocean trends.