RC1: 'Comment on egusphere-2025-857', Anonymous Referee #1, 08 Apr 2025

This is an interesting paper which use the ECCO4 reanalysis to examine the relative contributions of Gibraltar Straits exchanges and surface fluxes to variability in the mass/salinity budgets of the Mediterranean Sea. It's relatively well written but could do with some further analysis in a few places as noted below.

We sincerely thank the reviewer for the thoughtful comments and suggestions, which have helped us significantly improve the clarity and rigor of the manuscript. In response, we have carefully revised the text to better frame the study's objectives, clarified the treatment of volume and mass fluxes, removed or corrected ambiguous statements, and strengthened the conclusions to more accurately reflect the analyses presented. We believe these revisions have improved the overall quality and focus of the paper, and we are grateful for the opportunity to address the reviewer's valuable feedback.

line 128-132. ECCO appears to do well despite it's relatively coarse resolution. Could the authors comment further here on whether they think the 1 deg ECCO resolution is sufficient for their analysis? Also include some discussion of what aspects of their study are likely to become more accurate if a ¼ or 1/12 deg model were available.

We appreciate the reviewer's question. While higher-resolution models are often preferred for regional studies, ECCOv4r4's 1/3 to 1° resolution is well-suited for our basin-scale mass and salinity budget analysis in the Mediterranean Sea. ECCOv4r4 assimilates observational data (e.g., satellite altimetry, Argo floats, and hydrographic profiles) to constrain large-scale fluxes, as demonstrated in global and regional salt budget studies (Forget et al., 2015; Fukumori et al., 2017). ECCO and MITgcm have also been specifically utilized for Mediterranean studies (Fukumori et al., 2007; Menemenlis et al., 2007; Volkov and Landerer, 2015). Critically, ECCO's outputs align with prior in-situ estimates of Gibraltar exchange, which is a well-known challenging process to model, reinforcing its reliability for our analysis.

However, our choice of ECCOv4r4 stems from its unique strength as a state-of-the-art ocean state estimate that rigorously satisfies conservation laws while optimizing consistency with assimilated observations. This is essential for salinity budget studies, where salt transport interpretations require a closed mass balance within a semi-enclosed basin (Tsubouchi et al., 2012; Schauer and Losch, 2019). ECCO's adjoint-method framework ensures physically consistent budgets (ECCO Consortium et al., 2021), enabling us to disentangle the competing roles of surface fluxes and strait exchange with minimal systematic drift.

We acknowledge ECCO's limitations, as highlighted in prior literature. For instance, mesoscale and submesoscale processes in the Mediterranean (e.g., mesoscale eddies, sub-basin currents) are parameterized rather than explicitly resolved in ECCOv4r4, which may smooth short-term variability in regional dynamics (Escudier et al., 2016; Hernández-Lasheras et al., 2021). Similarly, ECCO's 1° resolution limits its ability to fully resolve fine-scale basin circulation features (e.g., the Levantine Intermediate Water formation zones) and highly localized runoff signals (Ludwig et al., 2009). In contrast, ¼° models like those in Hernández-Molina et al. (2021) better resolve coastal freshwater plumes and strait dynamics. However, our focus on basin-integrated budgets minimizes these impacts: river discharge contributes <5% to total freshwater flux (Ludwig et al., 2010), and decadal salinity trends are dominated by evaporation and Gibraltar exchange—processes ECCO captures robustly at its resolution.

To improve clarity, we have combined and tightened the discussion in Sections 4 and 5 (line 355-389), explicitly framing ECCO's resolution trade-offs within the context of basin-scale budget studies. The core advance of our work lies in its framework for diagnosing salinity-freshwater interactions in semi-enclosed seas. While future high-resolution models could refine specific processes like strait dynamics or coastal mixing, our analysis provides an observationally constrained, physically consistent baseline essential for interpreting such efforts.

Line 158. The authors choose a depth of 150m to separate the AW and MOW without any justification. So, can they include some further ECCO based results to support this choice? Is there any time dependence in the separation depth?

The 150 m depth threshold was selected based on ECCOv4r4's vertical structure of horizontal transport at the Strait of Gibraltar (Figure R1 and R2):

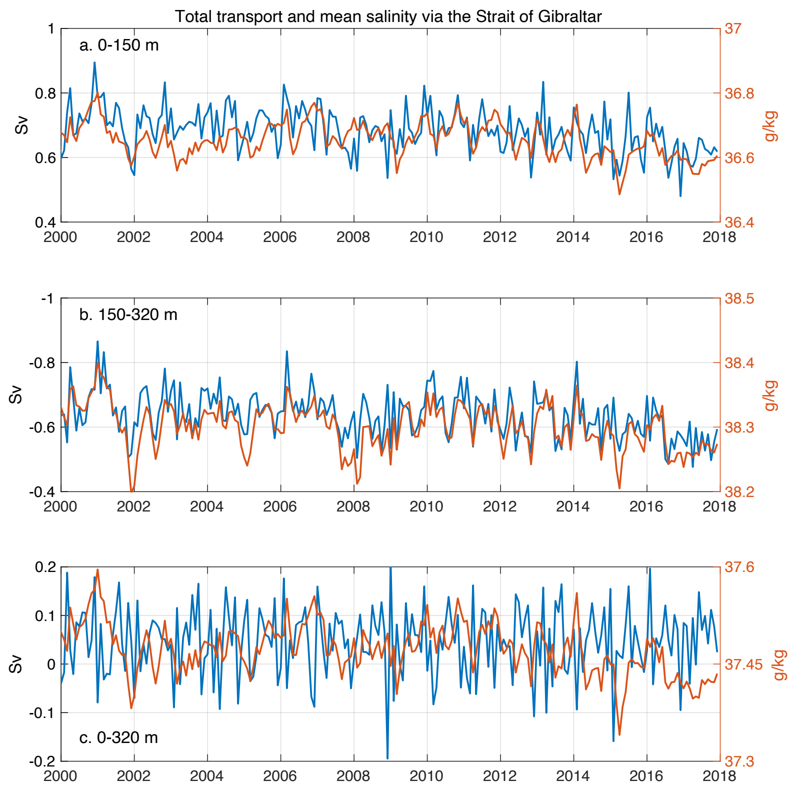

Figure R1 (New Figure 3) Net flux (blue, left axis) and mean salinity (red, right axis) at the Strait of Gibraltar. positive transport means eastward transport into the Mediterranean Sea. Notice the y-axis in panel (b) is inversed.

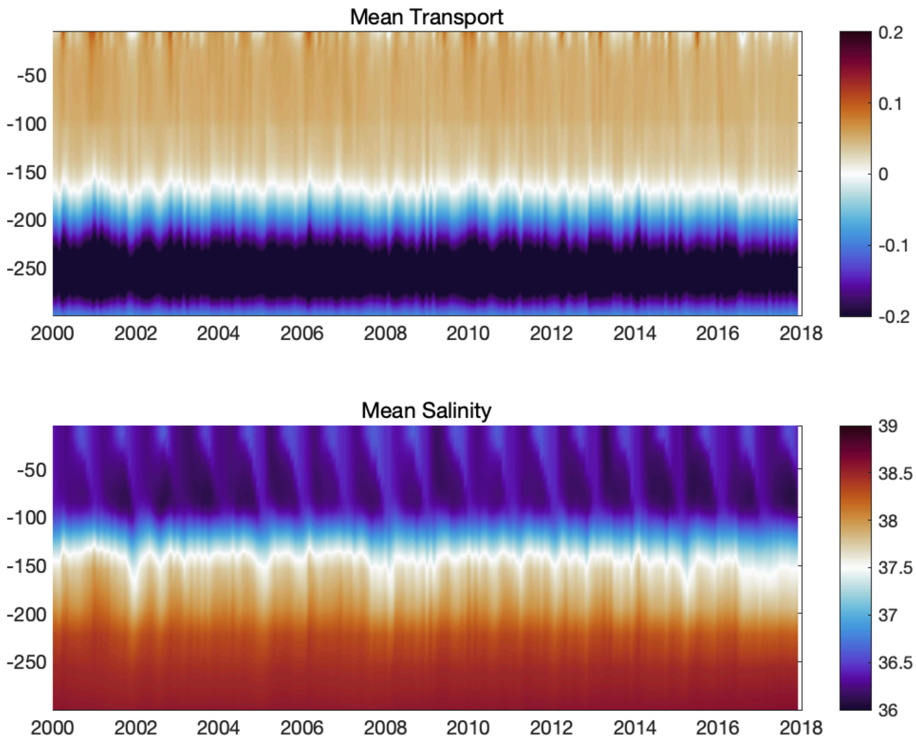

Figure R2 Net flux (top) and salinity (bottom) at the Strait of Gibraltar. Positive transport means eastward transport into the Mediterranean Sea.

ECCOv4r4 shows a clear reversal in time-mean velocity direction near 150 m. Above 150 m, velocities are eastward (i.e., Atlantic Water inflow), while below 150 m, velocities are westward (i.e., Mediterranean Outflow Water), generally consistent with observational evidence (e.g., Soto-Navarro et al., 2010). The 150 m depth also shows a sharp transition between fresher AW (salinity < 36.5 g/kg) and saltier MOW (salinity > 37.5 g/kg) in ECCO's monthly mean profiles. (Line 156-158)

Line 160-165. The authors chose to work at whole basin level rather than sub-regions. However, they could carry out an intermediate analysis by splitting the whole basin into two sub-basins i.e. E & W Med separated by the Strait of Sicily. Could they include some discussion of whether such an approach is likely to yield further insights to those already presented?

While analyzing sub-basins (e.g., Eastern vs. Western Mediterranean) could indeed offer finer insights into regional salinity dynamics, as previously mentioned, ECCOv4r4's 1° resolution limits the robustness of such subdivisions. For example, The Strait of Sicily is a narrow (~150 km wide) channel with complex circulation influenced by mesoscale eddies and alternating currents (Gasparini et al., 2004; Cotroneo et al., 2021). At 1° resolution (~110 km grid spacing), ECCOv4r4 cannot resolve critical features like the Atlantic Tunisian Current or the Maltese Front, leading to oversimplified exchange estimates. These features are parameterized in ECCO, which shows excessive mixing and smoothed gradients.

While higher-resolution model (e.g., 1/12° NEMO-MED12) could better resolve these regional processes, our whole-basin framework provides a foundational understanding of how evaporation and Gibraltar exchange dominate salinity trends, consistent with studies showing Mediterranean-wide salinification as a first-order response to climate forcing (Schroeder et al., 2016).

We added a paragraph (lines 370-383) in the revised discussion section discussing the trade-offs of sub-basin partitioning in coarse-resolution models.

Line 218. The Surface and Strait terms are noted to exhibit near exact, opposite variations. However, the process by which this is achieved is not noted here. So, please discuss. Is this a real balance or an artefact of the ECCO model?

The anticorrelation between surface freshwater fluxes and net Gibraltar exchange reflects a real physical balance driven by the Mediterranean Sea's semi-enclosed nature and volume conservation, with residuals primarily attributable to observed sea level change (Line 220-222):

As shown in Eq 2, in a semi-enclosed basin like the Mediterranean, volume conservation requires:

$$\frac{\partial V}{\partial t} = Q_{Gibraltar} + (E + P - R),$$

where V is basin volume, Q is net Gibraltar transport (inflow – outflow), and E−P−R is surface freshwater flux. Over our 15-year study period, the near-opposite variations between surface and strait terms arise because increased evaporation (or reduced precipitation/runoff) drives compensatory Atlantic Water inflow to balance mass loss (Tsimplis et al., 2008; Soto-Navarro et al., 2010).

ECCOv4r4's adjoint method ensures rigorous budget closure, but small residuals reflect real volume changes (i.e., $\frac{\partial V}{\partial t} \neq 0$) captured by satellite-observed sea level trends (Calafat et al., 2012).

Line 243. 'this is likely because the inflowing North Atlantic water is becoming saltier over time, which is consistent with some recent findings.' Please include a time series of the 0-150m mean salinity to show whether this statement is supported by more detailed analysis of ECCO.

Thanks for pointing out. The original interpretation of the results appears to be incorrect. As shown in Figure R1, both the inflowing Atlantic Water (upper branch) and the outflowing Mediterranean Water (lower branch) exhibit freshening trends over the analysis period. This simultaneous decrease in salinity across both layers leads to a reduction in the mean salinity at the Strait of Gibraltar. As a consequence, the net salinity flux through the strait—typically negative due to the Mediterranean exporting salt—also weakens over time. This trend is correctly captured in Figure 5d, which shows a decreasing magnitude of the net salinity flux. The decline in the salinity gradient across the strait reduces the efficiency of salt export, assuming transport volumes remain relatively constant. This interpretation is consistent with basic conservation principles and reflects the physical response of the strait's exchange dynamics to large-scale salinity changes in the basin. It is revised accordingly

(Lines 241-253).

Line 246. 'The air-sea freshwater flux, driven primarily by substantial net evaporation, contributes significantly to this trend.' A further time series needs to be included showing E and P separately to support this statement.

We have updated Figure 2 to include separate time series for E and P over the Mediterranean basin during 2003–2017 (panel a):

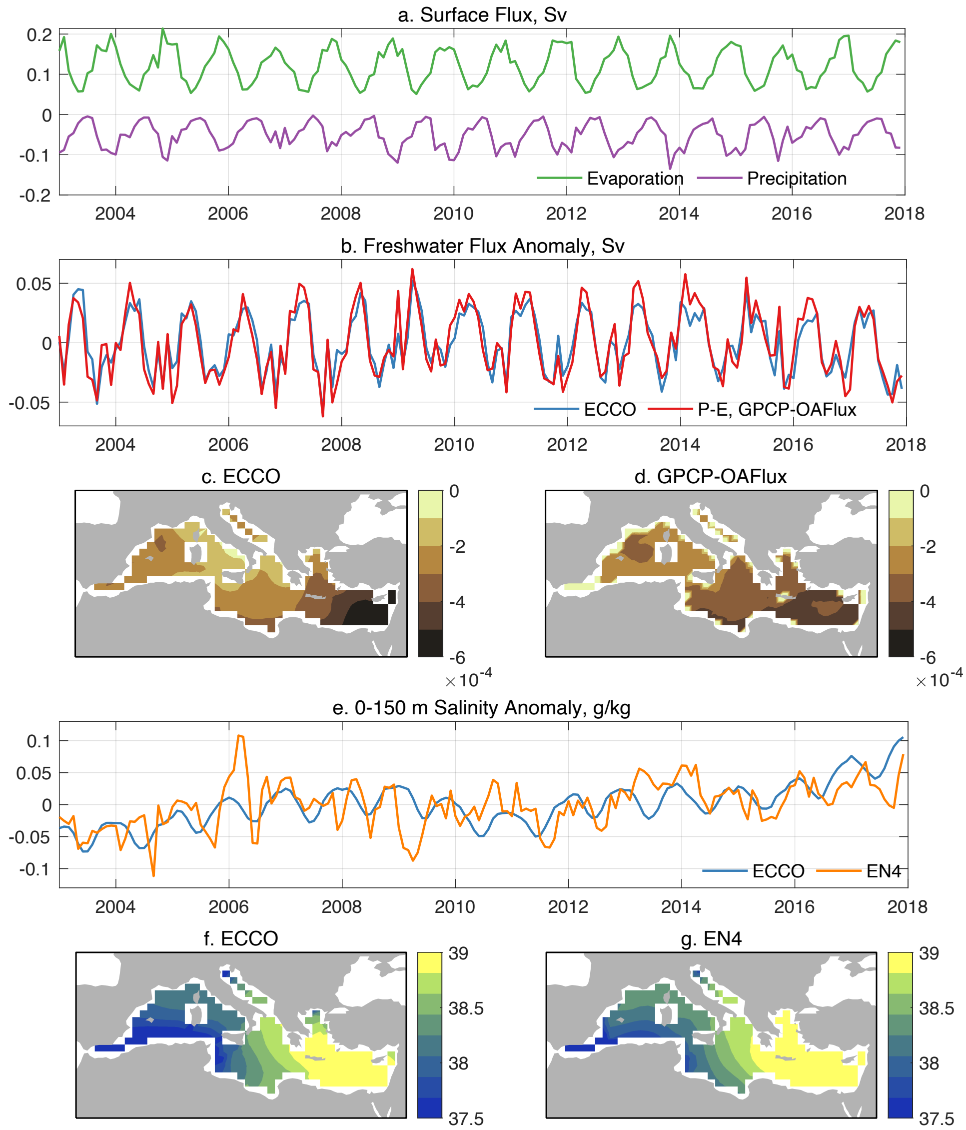

Figure 2 Timeseries and time-mean spatial patterns of freshwater flux and mean salinity (0–150 m) in the Mediterranean Sea, comparing ECCO outputs with other datasets. (a) timeseries of total evaporation and precipitation from ECCO; (b) timeseries of freshwater flux anomaly from ECCO and the reference 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.

Sec 3.2. The results on the NAO are interesting but other modes of variability, particularly the EAP and EA/WR patterns are known to influence the Mediterranean. So, the authors need to extend their analysis here to include the EAP and EA/WR in order to provide a complete picture (even if these modes turn out not to have strong correlations with the air-sea mass flux and salinity). Indices for the EAP and EA/WR are available from the same site as employed for the NAO: https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml.

We thank the reviewer for this valuable suggestion. We have expanded our analysis to include the East Atlantic Pattern (EAP) and East Atlantic/West Russia (EA/WR) pattern. In short, EAP is not correlated with the timeseries of mass/salinity fluxes in any case. However, correlation with EA/WR is established with the surface term of salinity flux (0.71) and mass flux (-0.72). The results/analysis are presented in Line 291-302.

Fig.6 The E & P salinity numbers in the boxes appear to be incorrect (wrong way round) compared to the values in the Table and main text.

Thanks for pointing it out. The labels for evaporation (E) and precipitation (P) in Figure 6's salinity boxes were inadvertently swapped during figure preparation. We have revised the figure to ensure its consistency with Table 2 and the text:

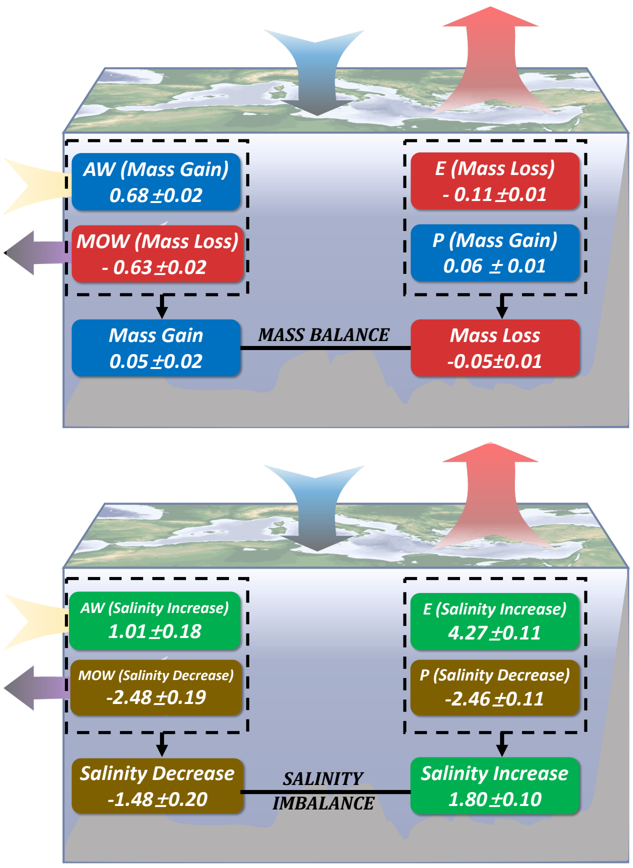

Figure 6 15-year mean mass (top) and salinity (bottom) budget for the Mediterranean Sea. Blue and red boxes mark the mass gain and mass loss, brown and green boxes mark the salinity increase and

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, $\sigma/\sqrt{n}$, where σ is the standard deviation of the corresponding term and $n = 15$ for non-seasonal fluxes. Units are Sv.

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RC2: 'Comment on egusphere-2025-857', Anonymous Referee #2, 09 Apr 2025

Review of "Salinity trends and mass-balances in the Mediterranean Sea: the role of air-sea freshwater fluxes and oceanic exchange" by Liu et al.

Using output from the ECCOv4r4 model for the Mediterranean Sea over a 15-year period (2003–2017), the authors analyze the region's mass and salinity budgets. They conclude that surface freshwater fluxes dominate salinity variability, while the exchange through the Strait of Gibraltar plays a key role in maintaining the overall mass balance. They report a salinity increase of 0.29 ± 0.09 Sv (units unclear) over the study period.

However, both of these findings—that salinity variability is mainly driven by air-sea fluxes and that the mass balance is maintained through the Gibraltar exchange—are well-established in the literature and do not represent novel results. The potential novelty of the study lies in the use of a global circulation model to revisit these questions. Yet, this approach has a significant limitation: the necessarily low spatial resolution of the ECCO model in the Mediterranean, a basin known for its rich mesoscale activity, which the model cannot resolve. As a result, the authors are constrained to a basin-integrated approach that effectively reduces the Mediterranean to a "box," as acknowledged in line 145. Unfortunately, this limits the originality of the analysis.

We thank the reviewer for highlighting the importance of contextualizing our work within the existing literature on Mediterranean salinity dynamics. While prior studies have established the roles of surface freshwater fluxes and Gibraltar exchange in regulating Mediterranean mass and salinity balances, as the reviewer pointed out, this study seeks to deepen this understanding through ECCOv4r4's unique framework. Unlike regional models or observational syntheses, ECCO's adjoint-based state estimation assimilates satellite altimetry, Argo profiles, and in situ salinity data to enforce closed mass and salt budgets, ensuring dynamic consistency between surface forcing, strait exchange, and steric adjustments. This approach eliminates spurious trends inherent to open-boundary models or mismatched flux products, allowing us to partition salinity variability into surface-driven and advective contributions with traceable sources and sinks.

The reviewer rightly notes that ECCO's 1° resolution precludes resolving Mediterranean mesoscale activity, but this "limitation" is in fact a deliberate strength for our large-scale climatic analysis. By aggregating fluxes over the entire basin, we isolate the roles of evaporation, precipitation, and Gibraltar exchange—processes that dominate interannual and decadal variability—while filtering out mesoscale eddies that contribute uncertainty to budget closure over short periods (days to weeks) and finer scales. For example, the counterintuitive salinity reduction caused by Gibraltar's density-driven exchange asymmetry is an important implication that is often ignored in box-model studies (e.g., Tsubouchi et al., 2012) and could only be quantified through ECCO's rigorous conservation laws.

Critically, our work does not seek to replace results obtained from high-resolution regional models or in-situ estimates (the title is also revised accordingly), but to provide a foundational baseline for their interpretation of the associated physical process. ECCOv4r4 rigorously satisfies conservation laws while optimizing consistency with assimilated observations. This is essential for salinity budget studies, where salt transport interpretations require a closed mass balance within a semi-enclosed basin (Schauer and Losch, 2019). ECCO's adjoint-method framework ensures physically consistent budgets (ECCO Consortium et al., 2021), enabling us to disentangle the competing roles of surface fluxes and strait exchange with minimal systematic drift.

By reconciling Mediterranean salinity trends with observationally constrained surface and strait fluxes, we address the relative roles of climatic forcing (e.g., NAO-associated air-sea interaction) versus advective adjustments—a prerequisite for attributing future changes in this climatically vulnerable basin.

In summary, the novelty of our work lies not in discovering that surface fluxes and Gibraltar exchange matter, but in rigorously quantifying how they interact within a closed, observationally informed system. This advances the field from qualitative mechanistic understanding to quantitative attribution, a critical step for improving Mediterranean salinity projections in climate system. The revised discussion is at line 382-389.

In addition to this general concern, there are several major and minor issues (detailed below) that prevent me from recommending this manuscript for publication in its current form.

Section 4 – "Discussion of ECCO resolution and uncertainty" This section is not a true discussion. The authors merely point out that the ECCO model's resolution is insufficient to capture key oceanographic processes in the Mediterranean Sea and that other numerical models—indeed, they do exist—may be better suited for this purpose. They also mention that further efforts are needed to address this gap. However, the question then arises as why did the authors not attempt to use one of these more appropriate models in their own analysis? Moreover, despite the title, there is no attempt to quantify the uncertainties discussed. As it stands, this section reads as a series of general, largely uncritical remarks that add little value to the manuscript. It could be omitted altogether without any loss.

We thank the reviewer for their constructive critique. Like we stated above, we believe that ECCO's adjoint-method framework ensures physically consistent budgets, enabling us to disentangle the competing roles of surface fluxes and strait exchange with minimal systematic drift.

ECCO was chosen not despite but because of its global data assimilation framework, which ensures closed mass/salt budgets—a prerequisite for attributing salinity trends to surface vs. strait processes. Regional models, while resolving finer dynamics, often rely on open boundary conditions that introduce spurious signals. We concede that mesoscale-rich processes (e.g., Levantine eddies) are unresolved but argue these average out over our 15-year focus.

That does not mean that other oceanic/regional model could not accomplish the task in a similar measure, and we are more than willing to continue explore this topic with higher-resolution models.

We agree that the original Section 4 lacked critical depth and have restructured its content to integrate meaningfully into the revised Discussion and Conclusions. See lines 356-389.

Section 5 – "Conclusions" The statement that "we reveal the complex dynamics that govern Mediterranean's mass and salinity variations" is misleading, as the manuscript contains no dynamic analysis whatsoever. Similarly, the claim that the findings contribute to a "broader understanding of sea level dynamics in the Mediterranean" through "regional steric (halosteric) adjustments" is not supported by the content—no such approach is developed or discussed in the paper. Most of the conclusions presented in this section do not reflect the actual analyses or results shown in the manuscript, and should be rewritten to more accurately represent the study's scope and findings.

Thanks for the critique. It is correct that the original Conclusions overstated the study's scope without sufficient support. We have rewritten this section entirely to focus on the core contribution of our work: leveraging ECCO's physically consistent state estimate to reconcile Mediterranean salinity budgets. See lines 356-389.

Salinity flux in Sv. In line 182, the authors state: "Since salinity is a unitless measure, we also express salinity flux in Sv in comparing both types of fluxes." I must admit I do not understand what 1 Sv of salinity flux means. The authors should provide a clearer explanation of how this unit is defined, as well as how it relates to conventional salinity units.

We thank the reviewer for highlighting this ambiguity. To clarify: salinity flux represents the transport of salt mass through a boundary. While salinity itself is unitless (expressed in g/kg or psu), salinity flux must account for both the salinity concentration and the volume transport.

In the revised manuscript, salinity flux has units of g/kg·Sv, which quantifies the rate of salt mass transfer and equivalent salinity change due to volume change.

This revision ensures consistency with oceanographic conventions (e.g., Zika et al., 2009; Griffies et al., 2016) and eliminates potential confusion.

Line 55. What exactly do the authors mean by "volume fluxes"? Are they referring to variations related to thermosteric effects? Since salinity is expressed in g/kg, it is influenced by mass fluxes—not volume changes unless these are accompanied by changes in mass. It's unclear how pure volume changes, without any mass input or output, would affect salinity. This needs clarification.

We thank the reviewer for raising this important point. Most ocean general circulation models employ the Boussinesq approximation, which assumes incompressibility and conserves volume rather than mass. This simplification neglects density variations in the momentum equations except where they contribute to buoyancy, which is generally acceptable for large-scale ocean modeling. However, it implies that volume fluxes are tracked rather than true mass fluxes, and additional care is needed when interpreting salinity or freshwater budgets in terms of actual mass transport.

While the term "mass flux" can be associated with bottom pressure changes in some contexts, "volume flux" is more appropriate for describing sea level variations as well as freshwater exchanges, such as evaporation, precipitation, and runoff. These fluxes alter salinity through dilution or concentration effects. For instance, a freshwater input of 1 Sv into the basin dilutes the existing salt content, reducing salinity, while evaporation acts as a negative volume flux, removing freshwater and increasing salinity through concentration.

We acknowledge that purely volumetric changes—such as thermosteric expansion—do not alter salinity. However, the fluxes analyzed in this study represent actual mass exchanges, including surface freshwater fluxes and the Gibraltar transport, both of which directly influence the basin's mean salinity. To avoid ambiguity, we rewrite the method section (Lines 173-178), refrain from using the term "volume flux" and instead explicitly describe how mass changes translate into salinity variations (e.g., Lines 340-342), including how these fluxes are quantified and incorporated into the salinity budget.

Lines 66–67. The sentence reads: "The water mass exchange at the Strait of Gibraltar was estimated at 1 ± 3 mm/yr…" These units are unusual (even, incorrect) for water mass exchange and add confusion to the manuscript, which also use Sv and km3/year for the same variable.

It has been revised to 0.0323 ± 0.0018 Sv to align with conventions and the manuscript's other analyses (Line 63).

Figure 3b (and 3e). These panels show the cumulative mass over time derived from the integration of the mass flux (Figure 3a and 3d), which is given in units of Sv. The slope of the cumulative curve corresponds to the time derivative, which essentially takes us back to the flux shown in Figure 3a (or 3d). In fact, the slope is simply the time-averaged value of the flux in Figure 3a (or 3d). Why is this point being made in such a roundabout way? Also, why express the slope in km^3/year instead of using Sv, as in Figure 3a? For instance, –1390 km^3/year corresponds to -0.044 Sv, a value that can be easily inferred from Figure 3d.

The slope of the cumulative curves does represent the time-averaged flux values. The primary purpose of these panels was to highlight the detrended variability in the bottom panels (3c and 3f), which reveals climatological signals not apparent in the monthly flux curves. We've revised the text to clarify this intention and removed redundant discussion of the slope interpretation (Lines 216-222).

Figure 4. Much of the above comment also applies here. In this figure, it is unclear how the questionable units of Sv for salinity flux (Figures 4a, 4d) translate into actual salinity values in Figures 4b and 4e. Regarding the discussion in lines 230–239: if the total salinity flux (black line) is the sum of the surface freshwater flux (green), which varies considerably month to month, and the relatively steady salinity flux through the Strait (red), then the black and green lines must be highly correlated. This should be not a new and relevant finding of the study.

The salinity level of Figure 4b is calculated in a similar way as Figure 3b but divided by the entire basin. It represents the mean salinity level of the Mediterranean Sea if one (or more) flux term is considered. We've modified the figure to better show the relationship between salinity flux (in g/kg·Sv) and actual salinity changes (g/kg). The discussion about the correlation between total and surface fluxes has been removed.

Line 240. The manuscript refers to a trend of "0.02 ± 0.01 Sv per year." Does this correspond to the trends shown in Figures 4a and 4d? Please clarify this point explicitly.

The trend of 0.02 ± 0.01 Sv/year corresponds specifically to the surface freshwater flux trend shown in Figure 4a. We've added explicit clarification in the revised text (Line 241).

Line 242. The authors suggest that the significant increase of salinity found in "the Strait" term is a consequence of an increase of the salinity of the Atlantic inflow through the Strait of Gibraltar. However, other studies point to the opposite trend—namely, freshening of the inflow—driven by melting Arctic ice. This apparent contradiction should be addressed or, at least, mentioned.

Thanks for pointing that out. The original interpretation of the results appears to be incorrect. As shown in Figure R1, both the inflowing Atlantic Water (upper branch) and the outflowing Mediterranean Water (lower branch) exhibit freshening trends over the analysis period. This simultaneous decrease in salinity across both layers leads to a reduction in the mean salinity at the Strait of Gibraltar. Consequently, the net salinity flux through the strait—typically negative due to the Mediterranean exporting salt—also weakens over time. This trend is correctly captured in Figure 5d, which shows a decreasing magnitude of the net salinity flux. The decline in the salinity gradient across the strait reduces the efficiency of salt export, assuming transport volumes remain relatively constant. This interpretation is consistent with basic conservation principles and reflects the physical response of the strait's exchange dynamics to large-scale salinity changes in the basin. It is revised accordingly (Lines 247-253).

Lines 281–284. There is a reference to Figures 2d and 2f, but these sub-panels do not appear in Figure 2. It's unclear what time series or pattern is being referred to in this sentence. The "cosine-like pattern" is not evident. Please clarify what is meant here, and where this pattern is supposed to appear.

The paragraph in question has been removed due to redundancy and the incorrect figure reference.

Figure 6. Are the labels in this schematic accurate? It is confusing to see evaporation (E) labeled as a mass gain and precipitation (P) as a mass loss—this seems reversed. Also, a "salinity increase of –2.46" is contradictory in terms—it would imply a decrease. Finally, the numbers in Figure 6 and Table 1 suggest a net salinity increase of 1.80 – 1.48 = 0.32, yet the text states 0.29. This discrepancy should be resolved for consistency.

We've carefully revised the schematic to correct the labeling of evaporation (E) and precipitation (P) fluxes, fix the sign convention for salinity changes, and reconcile the net salinity increase calculation.

All values are now consistent with the tables and the main text.

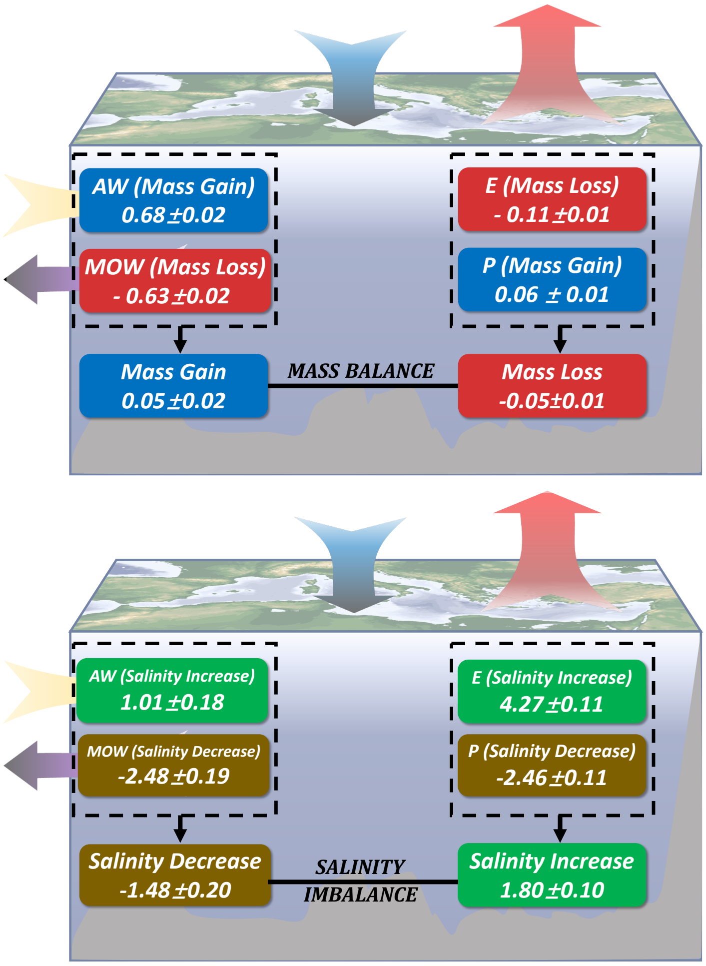

Figure 6 15-year mean mass (top) and salinity (bottom) budget for the Mediterranean Sea. Blue and red boxes mark the mass gain and mass loss, brown and green boxes mark the salinity increase and decrease, respectively. In each panel, the contributions from air-sea fluxes are on the right, and the exchange through the Strait are on the left. The uncertainties are calculated as the standard error of the means, $\sigma/\sqrt{n}$, where σ is the standard deviation of the corresponding term and n = 15 for non-seasonal fluxes. Units are Sv.

References:

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