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):

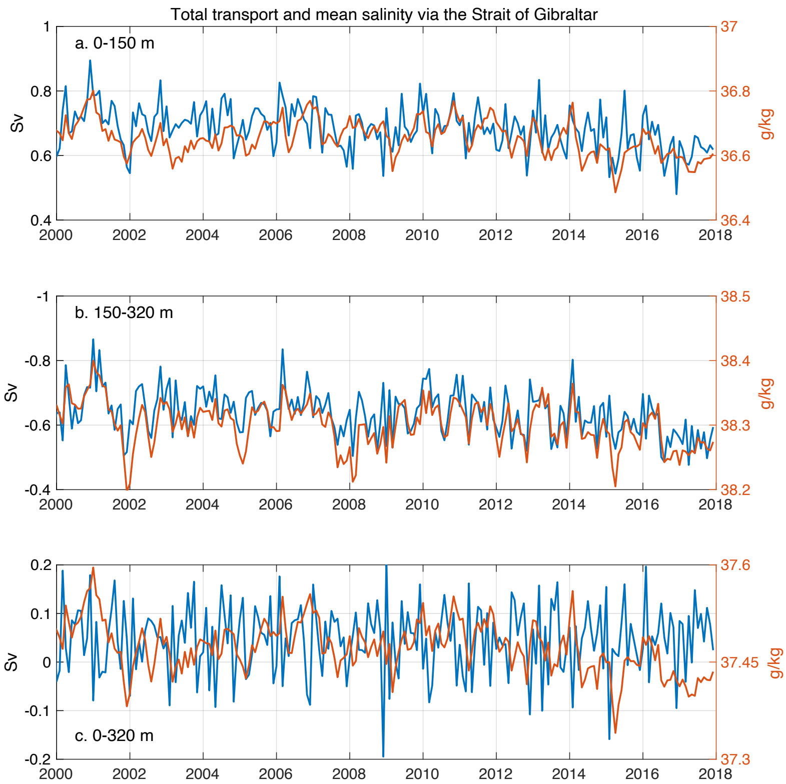

Figure R1 (New Figure 3) Net flux (blue, left axis) and mean salinity (red, right axis) at the Strait of Gibraltar. positive transport means eastward transport into the Mediterranean Sea. Notice the y-axis in panel (b) is inversed.

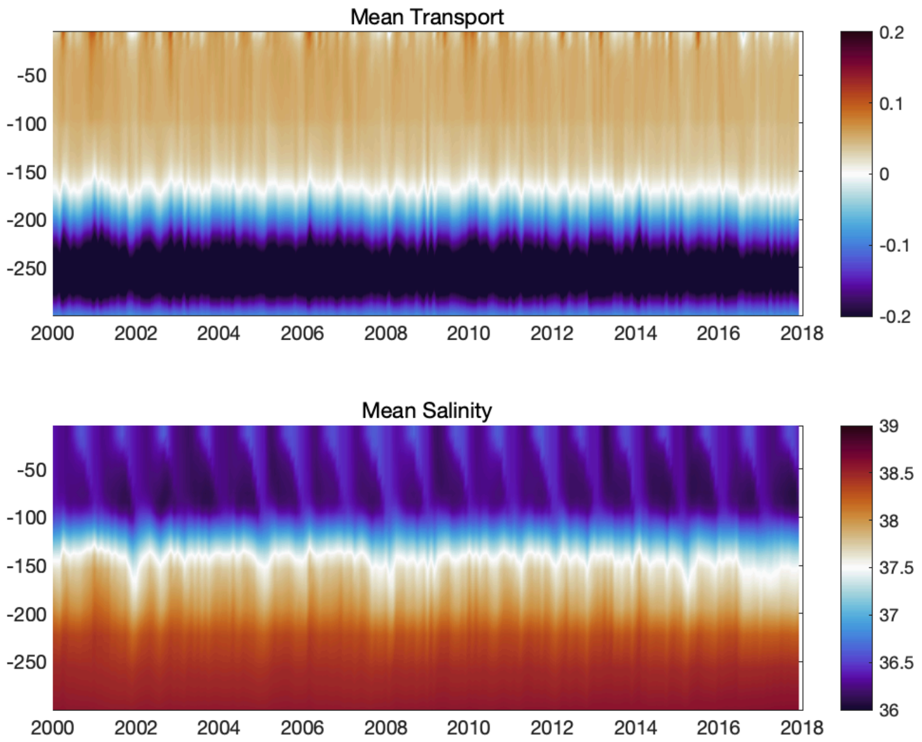

Figure R2 Net flux (top) and salinity (bottom) at the Strait of Gibraltar. Positive transport means eastward transport into the Mediterranean Sea.

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):

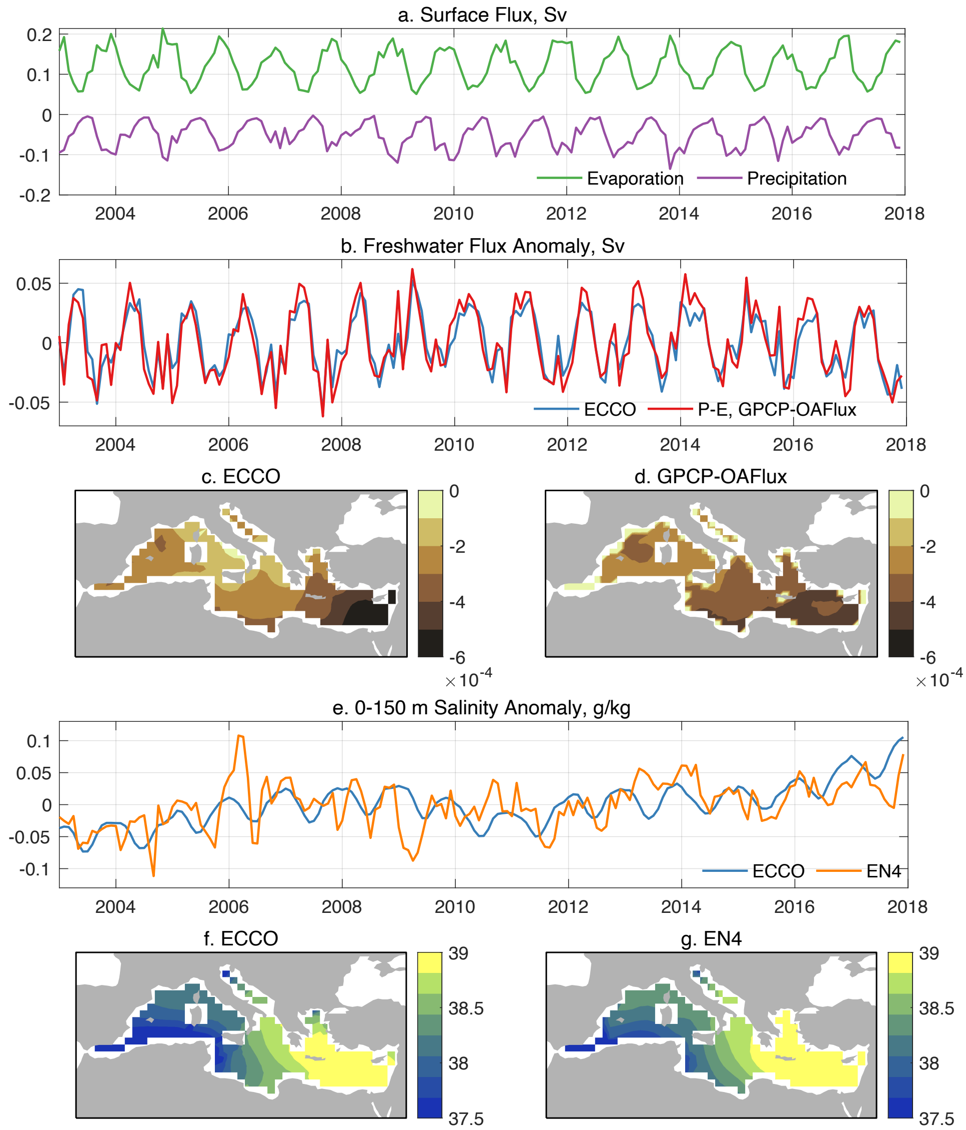

Figure 2 Timeseries and time-mean spatial patterns of freshwater flux and mean salinity (0–150 m) in the Mediterranean Sea, comparing ECCO outputs with other datasets. (a) timeseries of total evaporation and precipitation from ECCO; (b) timeseries of freshwater flux anomaly from ECCO and the reference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

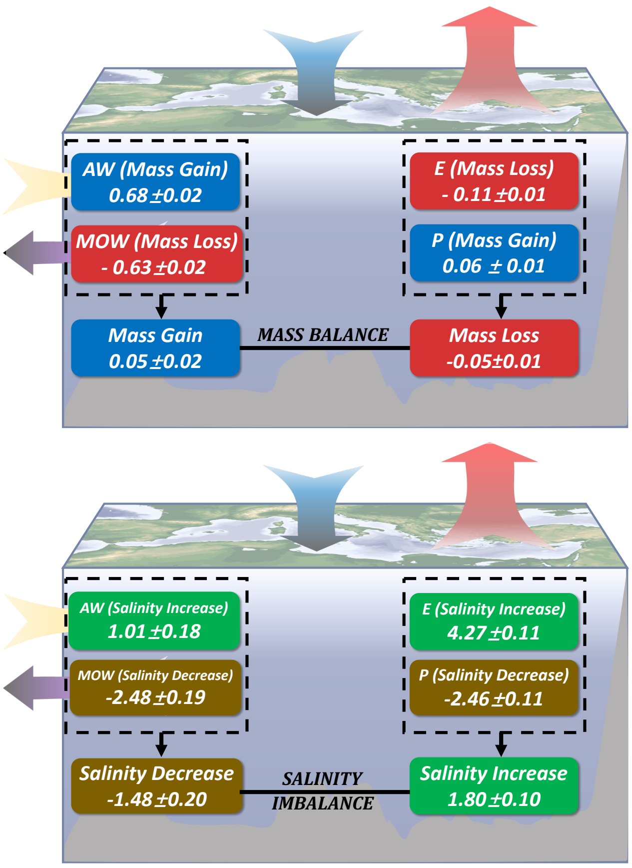

Figure 6 15-year mean mass (top) and salinity (bottom) budget for the Mediterranean Sea. Blue and red boxes mark the mass gain and mass loss, brown and green boxes mark the salinity increase and

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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