Review for Salinity Trends and Mass Balances in the Mediterranean Sea: Revisit the Role of Air-Sea Freshwater Fluxes and Oceanic Exchange by Liu et al.

General Comments

Authors present an analysis of the salt and mass budget of the Mediterranean Sea accounting the air-sea water fluxes and exchanges through the Gibraltar Strait. They employ ECCOv4v4 in which a 1°x1° resolution configuration of MITgcm is constrained by observations using adjoint methods to maintain the dynamic and kinematic consistency. The study is conducted within the period 2003-2017 while the entire dataset extends back to 1992 that covers the altimeter era.

The article is well written and improved following the suggestions of the reviewers. While the authors insist to use only ECCO timeseries for consistency concerns, the problems related to the resolution of the model to address the questions remains unresolved. Furthermore, the assumptions that authors made to simplify the calculations are actually important to close the salt and water budget of the Mediterranean Sea.

We sincerely thank you for the positive feedback and for acknowledging the improvements made in the revised manuscript. We appreciate your recognition of our goal to use ECCO v4r4 for its physically consistent, observation-constrained framework, despite its known spatial resolution limitations.

We fully agree that ECCO's 1° resolution limits the model's ability to resolve fine-scale processes, particularly in narrow passages like the Dardanelles Strait. To address this, we have expanded our discussion in the revised manuscript (Sections 2 and 5) to more clearly acknowledge these limitations and their implications for interpreting our results. We also added further discussion and comparisons with higher-resolution studies as suggested (e.g., Sanchez-Roman et al., 2018; Aydogdu et al., 2023).

We hope these clarifications and additional discussions help resolve your concerns and improve the overall scientific rigor and transparency of the study.

I can only recommend the manuscript for publication after addressing the following issues with the hope that they help to improve the quality of the manuscript.

First, the Dardanelles Strait is completely ignored. It is known to have a net flux of 9000 m^3/s which is 0.009 Sv (Unluata et al. 1990) Compared to 0.04 Sv net transport in the Strait of Gibraltar, it has 20-25% of contribution to the water budget and cannot be ignored. In the most optimistic case, Jarosz et al. (2013) reports 0.005 Sv which is still about 10% of Gibraltar.

Thank you for highlighting the importance of the Dardanelles Strait in the Mediterranean water budget. Given ECCO v4r4's 1° horizontal resolution, the Dardanelles inflow is not explicitly resolved as a distinct boundary flux in the model output. However, its integrated effect is implicitly

accounted for within ECCO's internal mass balance, particularly within the surface freshwater flux term, which includes all unresolved sources and sinks (including runoff and small strait exchanges).

To acknowledge this limitation, we have added text in the Introduction (Line 40) and in Section 2: Data and Methods (Line 146), clarifying the absence of a separately diagnosed Dardanelles flux in ECCO and discussing its likely magnitude and contribution to overall budget uncertainty.

Secondly, the salinity estimates in Fig.2 could be compared with Aydogdu et al. (2023) in which four global ocean reanalysis (GREP), a high-resolution Mediterranean Sea Reanalysis and observational products are put together to estimate the ensemble mean and uncertainty. Sanchez-Roman et al., (2018) found that tides were found to increase the net salt transport through the strait by 25% and decrease the net heat transport by 10%. Therefore a model without tides will not represent the mixing and recirculation in the strait therefore will underestimate the salt flux. It would be interesting to see if ECCO falls into the uncertainty provided by other products.

I find it useful to have another table to compare the findings in this study with the ones in the literature cited in the text to have a summary of all.

Thank you for these very helpful suggestions.

Regarding comparison with Aydogdu et al. (2023), we appreciate the opportunity to contextualize ECCO's salinity estimates relative to their multi-product ensemble. We have now added a brief comparison in Section 2.1, where we describe basin-mean salinity and its trend. While ECCO's mean salinity and trend fall within the general spread of prior studies (e.g., Jordá et al., 2017b; Llases et al., 2018), we explicitly acknowledge that Aydogdu et al. (2023) provides more formal ensemble uncertainty ranges. ECCO's basin-mean salinity anomaly variability generally lie within the GREP ensemble spread. (Line 127)

Regarding the effect of tides, we fully agree that the absence of tidal forcing in ECCO v4r4 is a known limitation, particularly for constraining strait exchange processes. We have now added a short discussion of this point in the Discussion referencing Sanchez-Roman et al. (2018). (Line 257, 390)

Specific Comments

Introduction

L35 - and Dardanelles Strait.

Thanks for this observation. We have added the Dardanelles Strait to the list of boundary terms in the Introduction (Line 39) and now note that its contribution, while smaller than Gibraltar, is non-negligible (see also our response to the major comment on Dardanelles).

L38 - In Jorda et al. 2017 (their Table 11), the contribution of Dardanelles and rivers are 0.1 m/yr

and 0.2 m/yr respectively compared to 0.8 m/yr of Gibraltar. So I wouldn't say it is much smaller.

We agree. It is reworded to:

"The river runoff (R) from major rivers and the Dardanelles Strait also contributes a measurable portion of the Mediterranean water budget (Jordá et al., 2017b)." (Line 127)

L62 - I understand Sv in two ways 10^6 m^3/s as volumetric measure or 10^9 kg/s as mass measure. The authors use estimates of volume transport (e.g. 0.0323 ± 0.0018 Sv in L64) as mass budget. This seems to me confusing throughout the text.

We acknowledge your confusion regarding our usage of Sverdrup (Sv) units. Throughout the revised manuscript, we have clarified that we express fluxes in Sv (10^6 m^3/s) as a volumetric measure for consistency with oceanographic convention, while explicitly noting that these volume fluxes correspond to actual mass exchanges due to the ECCO's model's non-Boussinesq formulation. Clarification is included in Section 2.2 (Line 196).

L75 - Are there any considerations on the vertical exchanges with deep basin?

Our current analysis focuses on basin-integrated surface and boundary fluxes. Vertical exchanges between surface and deep layers are implicitly captured within ECCO's state estimate but are not explicitly diagnosed in this study. We have now added a clarifying sentence in Section 2 noting this limitation:

"Vertical exchanges between surface and deep Mediterranean layers are implicitly represented in ECCO but not explicitly analyzed in this study." (Line 163)

2 Data & Methods

L119 - River contribution was ignored previously but now attributed to 0.01-0.02 Sv of difference which is about 30-50% of Gibraltar net transport.

To clarify, river runoff was not ignored in our ECCO-based budget analysis. ECCOv4r4 includes river inputs via surface boundary forcing, and these are accounted for in our diagnosed surface freshwater flux (E-P-R). However, when we compared ECCO-derived E-P-R with external satellite-based E and P products (i.e., Figure 2b), we did not include runoff in the satellite estimates due to lack of consistent global runoff data in these products. This naturally results in a small systematic offset (~0.01–0.02 Sv) between ECCO and satellite-derived surface freshwater fluxes.

We also respectfully note that comparing this small offset (~0.01–0.02 Sv) to the long-term mean Gibraltar transport (~0.04 Sv) is not directly meaningful, as this anomaly appears only during certain months and represents a short-term flux discrepancy rather than a persistent or cumulative transport bias.

L140 - It could be at least compared.

As part of addressing the earlier comment, we have now added a comparison with Aydogdu et al. (2023) in Section 2 where basin-mean salinity is discussed (see also response to major comment on salinity comparison). (Line 129)

L157 - Why 320 m? Is this the depth of Mediterranean overflow?

The 320 m depth corresponds to the deepest sill depth at the Strait of Gibraltar that allows inflow and outflow exchange between the Atlantic and Mediterranean in ECCO's model. We have now clarified this in the methods section. (Line 166)

3 Results

Fig. 7 0.05 Sv of "mass gain" is a bit large compared to 0.038 Sv of Soto-Navarro et al. (2010) or other estimates.

We agree that our diagnosed net mass gain of 0.05 Sv is somewhat larger than the 0.038 Sv reported by Soto-Navarro et al. (2010) and other previous estimates. However, it is important to note that our estimate falls within the uncertainty range of ±0.02 Sv, which we explicitly state in the manuscript. This range encompasses the Soto-Navarro et al. value as well as other observational estimates.

We also emphasize that ECCO's estimate reflects a fully observation-constrained, dynamically consistent long-term mean for the 2003–2017 period, which could differ slightly from shorter or earlier observational periods due to interannual variability.

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