Observational-based quantification of physical processes that impact the evolution of global mean sea level

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Response to Reviewer #1

The basic premise of this manuscript is built around a distinction between a top-down and bottom-up approach to estimating sea level rise. This manuscript approaches the problem from the bottom up, examining the imbalance in mass and heat inputs to infer net sea level rise. One might alternatively refer to this, as a flux approach rather than a reservoir approach. The flux approach is exceedingly difficult since it requires accurate measurements of rainfall, evaporation, and storm-related heat gain and losses, all of which depend on transient or extreme events. Thus, as the author acknowledges, there is low probability of obtaining a closed budget through this approach. That could make this study seem like an unusual intellectual exercise, but that view would undersell the value of the manuscript. In fact the author avoids the global imbalance problem by working with fluxes that have been adjusted to remove long-term drift, using the fields to assess the impacts of mixing and advection, which can modify sea level, particularly through effects of cabbeling and thermobaricity. The exercise is valuable as a strategy for exploring the mechanisms underpinning sea level rise and for evaluating terms that need to be handled correctly in modeling studies. The maps in the manuscript provide a useful assessment of the relative importance of the less intuitive processes that contribute to the global sea level rise budget. In this sense, the manuscript is a valuable and thorough contribution to discussions of global sea level rise.

Thanks for this summary and analyses. I'm glad to see that the idea came across and I'm encouraged by the positive comments. I want to state that I'm impressed and grateful for the reviewer's effort to read and improve this paper. I apologize for the spelling mistakes.

The analysis framework appears sound. (I admit that I didn't check every step of the derivation.) The results provide a useful point of reference for evaluating contributors for sea level rise, and I think the results will be useful to journal readers. There are a number of details that should be addressed prior to publication.

1. The reference list is thorough but omits some recent studies that have been important to the global sea level rise discussion (e.g. Hamlington et al, Nature Communications Earth and Environment, 2024; Fasullo and Nerem, PNAS, 2018; Nerem et al, PNAS, 2018; Nerem et al, Earth's Future, 2022). It's not clear that all of these are relevant, but to my mind this body of work is relevant for framing what the "top down" approach for analyzing sea level rise.

Great! I found a place for all these references and more in the first 2 paragraphs of the introduction. Note the first paragraphs of the introduction are thoroughly rewritten.

2. Line 100. Equation (4) is described as deriving from equations (1) and (3). A direct substitution of (3) into (1) will not yield (4), so a bit of additional explanation is needed.

Ah yes, this was because I was only considering the first term on the right-hand side of equation 1. Then it does follows directly. So, I clarified this now to avoid confusion (L107). Thanks.

3. Line 196. “It also showcases”. It’s not clear that Equation (15) shows that sea level is constantly evolving---it shows that many terms contribute to sea level evolution. Perhaps there’s a better way to describe the fact that sea level is the result of many contributing factors.

Yes, I see your point. I have adapted the sentence and removed a part of it. See L205-L208.

4. Line 410. “densification upon mixing will keep the ocean from ever expanding”. This statement seems likely to be too strong. I think the intent is to say that densification upon mixing will counteract expansion due to nonlinear thermal effects.

It was meant as a more “romantic” way of saying the same thing. But this is not a novel, so I have now changed the sentence to be more scientific. Yet, part of it is still there. This is because somehow attention needs to be pointed towards the fact that this is not with respect to “normal expansion”. This expansion always happens, even when there is no net warming of the ocean. It is hard to get this message across, without first going into detail. I was hoping this way could be a good start, before the details come. I hope you consider the current way it is embedded in the text as an improvement.

5. Figures 1-8. The figures in this manuscript show global maps plotted over what appears to be the same domain. However, the aspect ratios of the figures vary substantially, in some cases even within the same figure (e.g. Figures 3 and 4). This makes it difficult for readers to compare the images. The maps should be redone with a single, consistent projection, even if that requires a white gap within the figure. In addition, colorbars are presented with inconsistent labeling (e.g. Figure 6)

Thanks for this comment. I have played around with the figures, colorbars, titles and aspect ratios. I think I have found a way that they all have the same aspect ratio throughout the whole manuscript. With all the other rearrangements as well, I think this has improved the presentation and paper.

6. Line 551-553. “Nonlinear thermal expansion and densification upon mixing go hand in hand, are of the same order of magnitude and of opposite sign, therewith compensating each other.” The manuscript earlier explains that thermobaricity is about an order of magnitude smaller than mixing-related densification. This point needs to be clarified so that readers can connect this sentence with material earlier in the paper to understand which terms correspond to thermal expansion and why this differs from the earlier thermobaricity/densification discussion where the terms are not the same order of magnitude.

Nonlinear thermal expansion and thermobaricity are not the same thing. Thermobaricity is related to the expansion coefficient being a function of pressure, while the nonlinear thermal expansion is related to the expansion coefficient being a function of, mainly temperature. Thermobaricity is an order of magnitude smaller than cabbeling. Nonlinear thermal expansion is of the same order as cabbeling. To address this, I made the following clarifications:

- L65, introduction.
- L157, section 2.3 clarifies the meaning of thermobaricity. But not in relation to nonlinear thermal expansion.

7. The appendices are intentionally derivation heavy. This makes them difficult to verify. Notably, the brevity of Appendix C is good, but makes it hard to unravel. It would be useful to explain the difference between z-hat and k. Both are presumably unit vectors. Are they in the same direction? The author should make sure that terms are clearly defined

Thank you for picking this up! This was indeed unnecessary clutter. I have gone through the appendix once again and tried to clarify where I could.

8. Minor points of grammar. The manuscript contains lots of typos, missing words, etc, and a revision should be carefully proofread. I have indicated issues that I noted, but I'm sure that there are more:

Wow, what an effort! And to think that, when I submitted it, I thought I got most mistakes. I thank the reviewer a lot for the effort to point at all these grammar problems. I fixed them all. I have really done my best, not to leave many new ones after the revisions.

Line 46: ", which raises" --> "and raise"
Line 46: "Result" --> "Results"
Line 68: "presented and derived" --> "derived" (More compact wording seems sufficient.)
Line 71: "amongs" --> "among"
Line 72: add comma after "(section 5)"
Line 84: "is studied" --> "are studied"
Line 88: "coined" --> "identified as" or omit "coined"
Line 88: "of Eq. 1" --> "in Eq. 1"
Line 98. No verb. Change equation (3) punctuation to be a comma, and change "Where" to "where"
Line 102. "conceptual" --> "conceptually"
Line 109. "therewith density. Mainly" --> "thus density, mainly".
Line 111. Missing period. "sensible heat fluxes" --> "sensible heat fluxes."
Line 118. "are due" v "is due"
Line 119. What does "O(meter)" refer to? Should this be "meter-scale eddies", or is there a different intended meaning?
Line 122. "eddies O(20-200 km)" --> "eddies of O(20-200 km)"

Line 140. “also creates” --> “we also create”
Line 141. “be interpret as interaction” --> “be interpreted as the interaction”
Line 142. “advantages” --> “advantageous”
Line 143. “of redistribution” --> “of the redistribution”
Line 146. “impact is” --> “impact”
Line 149. “naming” --> “terminology”
Line 150. “direction” --> “directions”
Line 161. “non-resolved” --> “unresolved”
Lines 161-162. “transportation” --> “transport”
Line 180. “leaves” --> “means”
Line 181. “defines” --> “defined”
Line 187. Comma after “0”.
Line 187. “interpret” --> “interpreted”
Line 196. “privde” --> “provide”
Line 200. Remove “based”. Rewrite to “This section describes a range of observational products that are needed …”
Line 203. Remove “based”
Line 216. “observational estimates” or “observation-based estimates”
Line 218. Would it be clearer to say “As the diffusivities obtained by Groeskamp et al. (2020 are static, they are ….”?
Line 220. “change at the mixed layer depth is applied” --> “change is applied at the mixed layer depth” (or maybe “at the base of the mixed layer”).
Line 223. Change to “even though they are known to be spatially inhomogeneous” or “even though they are known to vary spatially”
Lines 225-226. Inconsistent spelling of “parameterization”. What is the journal style?
Line 230. Maybe “while maintaining the mixed-layer depth as the separation ….”
Line 244. “interpret” --> “interpreted”
Line 252. “data is” --> “data are”
Line 254. “This data was” --> “These data were”
Line 365. “emphasis” --> “emphases”
Line 366. “of where” --> “in where”
Line 366. “stating” --> “demonstrating”
Line 367. “These results are comparable to, albeit a bit smaller, that found by Griffies and Greatbatch (2012)” ◊ “These results are comparable to results found by Griffies and Greatbatch (2012), albeit a bit smaller”
Lines 372-373 and Line 376. “(section 4.4)”. These references appear in section 4.4, so are presumably intended for a different section.
Line 374. “it will be cooler there” --> “sub-surface temperatures will be cooler,”
Line 374. “net smaller” --> “smaller net”
Line 381. “an change” --> “can change”
Line 384. “expansions” --> “expansion”
Line 385. “great ocean” --> “large ocean”?
Line 386. “of an order” --> “that are an order”
Line 400, Line 446. “don’t” --> “do not”
Line 404. “between in” --> “in”
Line 407, “of same order” --> “of the same order”
Line 414. “their” --> “the”; “is mostly” --> “are mostly”

Line 415. “by means of the different diffusivity parameterisations used” --> “by the different diffusivity parameterisations”
Line 394, Line 418, Line 420, Line 448, Line 484. “extend” --> “extent”
Line 418. “greater ocean basins” --> “major ocean basins” maybe
Line 418. Missing period at end of sentence.
Line 418. “The mesoscale diffusivity used, are” The intent is unclear, but I think this should say, “Mesoscale diffusivities are”
Line 421. “Location comparable to other studies considering cabbeling in the ocean”. No verb in sentence. What is the intended meaning?
Line 427. “completeness 5” --> “completeness in Fig. 5” (presumably)
Line 431-432. “Of the remaining two terms, it is only the "production term" Pstir that has a significant impact on GMSL rise” ◊ “Of the remaining two terms, only the "production term" Pstir has a significant impact on GMSL rise”
Figure 5 caption. “Thermobaricity” --> “thermobaricity”; “the different the” --> “the different”
Line 449. “different method” --> “different methods”
Line 449. “difference” --> “the difference”v
Line 453. “due to” --> “from” to maintain consistent structure within the sentence
Line 457. “positive and negative due to the divergence operator exist” --> “positive and negative change exist due to the divergence operator”
Line 513. “Parameterization” --> “Parameterizations”
Line 543. “can’t” --> “cannot”
Line 544. “distributed” --> “distribution”
Line 548. “has has” --> “has”
Line 553. No verb in the sentence starting “Albeit”. Instead, “Albeit” should be a connector to the previous sentence, using a comma: “other, albeit over....”
Line 558. “impact on” --> “impact”
Line 576. “are due” --> “due”
Line 604-605. Sentence beginning “Accounting for all” seems to be missing a verb.
Line 627. “assure” --> “assures”
Line 631. “With” should probably be a continuation of the previous sentence (i.e. “, with”)
Line 644. “expression” --> “expressions”
Line 695. “In addition use” --> “In addition, we use”
Line 733. “the the” --> “the”
Line 756. “definition” --> “definitions”