Authors' Response to Reviewer 2

General Comment. In this manuscript Camargo and colleagues analyze the regional sea level budget (i.e., the sum of individually measured/modelled contributions) to satellite altimetry over the 1993 to 2016 period. They specifically focus on the effect of spatial averaging on the uncertainties in budget closure. For spatial averaging they incorporate an a priori pattern recognition (two different approaches) step, which identifies clusters of homogeneous regions that are then averaged for the budget analysis. They demonstrate that clustering generally improves the budget closure and works significantly better than just using larger blocks. They also demonstrate the importance of the inclusion of an ocean bottom pressure term to the sterodynamic component. Overall, this is a very well written paper using novel approaches with several interesting findings. I therefore have no major reservations regarding the publication of the paper in Ocean Science. Below I provide a couple of comments and suggestions.

Response:

Dear Reviewer,

Thank you for your feedback and positive review. We have addressed all the issues item by item as follows.

Kind regards,

Carolina Camargo, on behalf of the authors

Comment 1

I hope I did not overlook anything, but it seems that the authors compare geocentric sea level from satellite altimetry to relative sea level from the budget components, as their budget components also seem to contain crustal components of GRD terms due to contemporary mass change!? To my understanding one must either add those components to satellite altimetry, or only consider the geoid variations in the budget. The term has a substantial contribution to regional sea level according to Frederikse, Riva, et al. (2017)

Response: Indeed, altimetry sea level should not be directly compared to relative sea-level change. We understand the confusion of the reviewer, because we did not mention in Section 2.1 that the GRD fingerprints we use represent absolute/geocentric sea-level change. When solving the sea-level equation, both relative and absolute fields are computed. Here we used absolute sea-level change fields. To clarify this important issue, we added the following:

> For the GRD component, we use the estimates from Camargo et al. (2022), which includes the geocentric sea level response to changes on the Antarctic and Greenland ice sheets, glaciers and terrestrial water storage.

Line by Line Comments

Comment 1

Line 20: The inverse barometer contribution is missing here

Response: Apologies for the confusion. In this sentence we had mentioned only some examples of the processes responsible for the regional differences. But we agree that the inverse barometer is an important contribution leading to regional differences. Hence, we modified the line accordingly:

> Ocean dynamics, land ice mass changes and associated gravitational effects, vertical land movement and the inverse barometer effect are some of the processes responsible for these regional differences (e.g., Slangen et al., 2017; Stammer et al., 2013).

Comment 2

> Line 32: or for individual coastline stretches characterized by coherent variability (**Frederikse2016a**; Dangendorf et al., 2021; Frederikse et al., 2016). It has also been closed at a tide gauge level by Wang et al. (2021).

Response: References added as follows:

> The sea-level budget has also been analysed for individual coastline stretches characterized by coherent variability (Dangendorf et al., 2021; Frederikse et al., 2016; Frederikse, Simon, et al., 2017; Rietbroek et al., 2016), and at individual tide gauges (Wang et al., 2021).

Comment 3

> Line 69: I was wondering how the authors treated missing data due to the presence of sea ice at higher latitudes? This might also affect some of the budget misclosures/uncertainties mentioned farther below in the manuscript.

Response: Good point. Although we had not explicitly mentioned this in the manuscript, our analysis is constrained between 66°S to 66°N of latitude, as can be seen in the global maps. Therefore, the regions where the presence of sea ice might be an issue for satellite altimetry are not included. We now mention the latitudinal limits of the data:

> All data is regridded to 1°x1° map, selected within 66°S to 66°N of latitude, and combined into an ensemble mean, to avoid systematic errors.

Comment 4

Line 83: How does that compare the deep ocean contribution from Zanna et al. (2019)?

Response: Thank you for your question. The deep ocean contribution based on repeat hydrography estimates are comparable with the estimates from Zanna et al. (2019). However, while the trends from Purkey and Johnson (2010) are statistically significant, the reconstructed deep warming from Zanna et al. (2019) since 1992 is not. A comparison between the Purkey and Johnson (2010) estimates and the ones from Zanna et al. (2019) can be seen in Figure 1 of Zanna et al. (2019).

Comment 5

Line 85 following: As mentioned as a general comment, the approach seems to be inconsistent with respect to geocentric sea level as measured by satellites.

Response: As we clarified above, we used geocentric GRD fingerprints, which is then consistent with the sea level as measured by satellites.

Comment 6

Line 94: It might be good to provide a little more information here, given that this other paper is still under review. I was also wondering how the estimates differ from those in Frederikse et al. (2020)?

Response: Thank you for your comment. The paper from which we use the GRD estimates has now been published, hence we think that expanding on the method is not necessary. The main differences from the estimates of Frederikse et al. (2020) is the land mass data sets used as input for the sea-level equation, and the uncertainty characterization. For example, Frederikse et al. (2020) uses a GRACE based reconstruction for terrestrial water storage, while Camargo et al. (2022) uses two hydrological models for it. Also, in Frederikse et al. (2020), they use the spatial patterns of the mass loss over the ice sheets from GRACE to estimate the spatial pattern of mass change over the ice sheets prior to 2002. This approach is different than the ones form Camargo et al. (2022), in which the lack of spatial resolution of the data sets prior to GRACE are incorporated in the uncertainties. In practical terms, the main differences are seen in the uncertainty of fingerprints, while the central estimates (i.e., global mean sea-level change) and the fingerprint patterns are comparable. Additionally, the estimates from Frederikse et al. (2020) are of relative sea-level change, while the ones used here of geocentric sea-level change.

Comment 7

Line 174 following: I am wondering how sensitive the two approaches are to temporal filtering? Former assessments such as Thompson and Merrifield (2014) have focused on decadal scales (which is likely more relevant for trends). Did the authors test sensitivity to smoothing? Also, have the time series been deseasonalized before applying the clustering technique?

Response:

As the machine learning techniques are used to map coherent regions of similar time sea-level variability, they are expected to be sensitive to the time scales present in the input data set. That is why we decided to use the longest time series record we had, until December 2019, for the clustering, to better resolve the temporal variability and capture better the decadal variability relevant for trend analysis. We did test the clustering using time series until 2016 only, and saw that it was not strongly affected by it, as mentioned in Lines 133-135. We did not, however, perform a direct sensitivity test to temporal smoothing. Note that the inferred SOM temporal patterns of seal level are indeed smoothed during the training process, as neurons are updated according to the characteristic temporal scales of the sea level time series. As expected, if an specific time scale is removed from the input data before the training process (smoothing the time serie), the resulting pattern will not capture this scale. Note also that smoothing/smearing algorithms are needed to create altimetry gridded products from satellite tracks. As a result, sea level data used are already smoothed.

Yes, the time series have been deseasonalized before applying the clustering techniques, as stated in L135.

Comment 8

Line 207: Or atmospheric teleconnections. Not all of them are connected by coasts

Response: Thank you for your suggestion. Indeed, they can also represent atmospheric teleconnections. We added this to the sentence:

> areas adjacent to the 'ENSO-tongue' domain, both north and south are clustered together in domain 18 (light blue) or in domain 15 (moss green), indicating how the ENSO signal is propagated through the Pacific, possibly through coastally

trapped waves (Hughes et al., 2019) in the coastal domains (15), or via atmospheric teleconnections.

Comment 9

Line 231: does this mean a positive bias?

Response: We are not sure what the reviewer means with 'positive bias'. In the referred line, we mention how the residuals decrease when a coarser spatial scale (i.e., $\delta-$MAPS and SOM) is used, comparing to 1 degree resolution. If with the positive bias refers to the fact that in general the altimetry trends were larger than the sum of the budget components (i.e., more positive residuals), this is mentioned in L250. In fact this "bias" is reduced using the machine learning approaches.

Comment 10

Line 344: The authors might consider Calafat et al. (2013) and Dangendorf et al. (2014), who initially established that link

Response: We have added the references as suggested by the reviewer.

Comment 11

Line 349: Southern Hemisphere

Response: Corrected.

References

Calafat, F. M., Chambers, D. P., & Tsimplis, M. N. (2013). Inter-annual to decadal sea-level variability in the coastal zones of the Norwegian and Siberian Seas: The role of atmospheric forcing. *Journal of Geophysical Research: Oceans*, *118*(3), 1287–1301. https://doi.org/10.1002/jgrc.20106

Camargo, C. M. L., Riva, R. E. M., Hermans, T. H. J., & Slangen, A. B. A. (2022). Trends and uncertainties of mass-driven sea-level change in the satellite altimetry era. *Earth Syst. Dynam. Discuss.*, *13*, 1351–1375. https://esd.copernicus.org/preprints/esd-2021-80/

Dangendorf, S., Calafat, F. M., Arns, A., Wahl, T., Haigh, I. D., & Jensen, J. (2014). Mean sea level variability in the North Sea: processes and implications. *Journal of Geophysical Research: Oceans*, (119), 3868–3882. https://doi.org/10.1002/2014JC009901.Received

Dangendorf, S., Frederikse, T., Chafik, L., Klinck, J. M., Ezer, T., & Hamlington, B. D. (2021). Data-driven reconstruction reveals large-scale ocean circulation control on coastal sea level. *Nature Climate Change*, *11*(6), 514–520. https://doi.org/10.1038/s41558-021-01046-1

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V. W., Dangendorf, S., Hogarth, P., Zanna, L., & Cheng, L. (2020). The causes of sea-level rise since 1900. *Nature*, *584*(August). https://doi.org/10.1038/s41586-020-2591-3

Frederikse, T., Riva, R., Kleinherenbrink, M., Wada, Y., van den Broeke, M., & Marzeion, B. (2016). Closing the sea level budget on a regional scale: Trends and variability on the Northwestern European continental shelf. *Geophysical Research Letters*, *43*(20), 10, 810–864, 872. https://doi.org/10.1002/2016GL070750

Frederikse, T., Riva, R. E., & King, M. A. (2017). Ocean Bottom Deformation Due To Present-Day Mass Redistribution and Its Impact on Sea Level Observations. *Geophysical Research Letters*, *44*(24), 12, 306–12, 314. https://doi.org/10.1002/2017GL075419

Frederikse, T., Simon, K., Katsman, C. A., & Riva, R. (2017). The sea-level budget along the Northwest Atlantic coast: GIA, mass changes, and large-scale ocean dynamics. *Journal of Geophysical Research : Oceans*, (122), 5486–5501. https://doi.org/10.1002/2016JC012335.Received

Hughes, C. W., Fukumori, I., Griffies, S. M., Huthnance, J. M., Minobe, S., Spence, P., Thompson, K. R., & Wise, A. (2019). Sea Level and the Role of Coastal Trapped Waves in Mediating the Influence of the Open Ocean on the Coast. *Surveys in Geophysics*, *40*(6), 1467–1492. https://doi.org/10.1007/s10712-019-09535-x

Purkey, S. G., & Johnson, G. C. (2010). Warming of Global Abyssal and Deep Southern Ocean Waters between the 1990s and 2000s: Contributions to Global Heat and Sea Level Rise Budgets. *Journal of Climate*, *23*, 6336–6351. https://doi.org/10.1175/2010JCLI3682.1
deep steric

Rietbroek, R., Brunnabend, S.-E., Kusche, J., Schröter, J., & Dahle, C. (2016). Revisiting the contemporary sea-level budget on global and regional scales. *Proceedings of the National Academy of Sciences*, *113*(6), 1504–1509. https://doi.org/10.1073/pnas.1519132113

Slangen, A. B. A., Adloff, F., Jevrejeva, S., Leclercq, P. W., Marzeion, B., Wada, Y., & Winkelmann, R. (2017). A Review of Recent Updates of Sea-Level Projections at Global and Regional Scales. *Surveys in Geophysics*, *38*(1), 385–406. https://doi.org/10.1007/s10712-016-9374-2

Stammer, D., Cazenave, A., Ponte, R. M., & Tamisiea, M. E. (2013). Causes for Contemporary Regional Sea Level Changes. *Annu Rev Marine Sci*, *5*. https://doi.org/10.1146/annurev-marine-121211-172406

Thompson, P. R., & Merrifield, M. A. (2014). A unique asymmetry in the pattern of recent sea level change. *Geophysical Research Letters*, *41*(21), 7675–7683. https://doi.org/10.1002/2014GL061263

Wang, J., Church, J. A., Zhang, X., Gregory, J. M., Zanna, L., & Chen, X. (2021). Evaluation of the Local Sea-Level Budget at Tide Gauges Since 1958. *Geophysical Research Letters*, *48*(20), 1–12. https://doi.org/10.1029/2021GL094502

Zanna, L., Khatiwala, S., Gregory, J. M., Ison, J., & Heimbach, P. (2019). Global reconstruction of historical ocean heat storage and transport. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(4), 1126–1131. https://doi.org/10.1073/pnas.1808838115