

Response to reviewer 3

This is a review comment on the manuscript by Caley et al submitted to *Climate of The Past*.

In this paper, the authors present a calibration effort of sea surface water density and $\delta^{18}\text{O}$ analyzed in mixed layer dwelling planktonic foraminifera from core top samples. This is a laudable effort as sea water density is a key parameter driving and responding to oceanographic changes. Agreeing with the comments made by the other reviewer, I will focus on some caveats of the calibration effort. These caveats limit the applicability of the calibration equation in extreme climates of the past. Hence, this limitation needs to be clearly spelled out.

- It stands out that in the high salinity regions (Med Sea, Arabian Sea, Red Sea, upwelling region off NW Africa) the estimated density is less sensitive to an increase in $\delta^{18}\text{O}$. This is clearly visible in Fig 1 (poly1_hier) when an increase of $\delta^{18}\text{O}$ by 3 per mill is not accompanied by a substantial predicted density change. This issue is further highlighted in Figure 3 (lower panel), where the residual density (predicted minus observed) shows a strong correlation with salinity changes. This means that the salinity role in shaping the predicted density is underestimated.

Though less severe, this issue is also observed in low salinity regions such as the Gulf of Guinea (eastern equatorial Atlantic) and the Bay of Bengal (Northern Indian Ocean).

The implication of these observations/caveats is that the current density- $\delta^{18}\text{O}$ calibration (as presented in this paper) is less reliable for the density reconstruction of past extreme climates. For instance, high $\delta^{18}\text{O}$ values driven by large ice volume, dry climate or ocean basin characterized by anti-estuary circulation, like the current Mediterranean Sea and Red Sea). Similarly, in warming climate and wet climate (small ice sheet and large riverine runoff), this calibration is likely to provide density estimates with a large uncertainty.

While the calibration effort presents a step forward, the authors need to clearly emphasize the serious issues spelled out above. Consequently, the concluding statement made in lines 465-475 is too optimistic and needs some moderation.

We are grateful for the constructive feedback provided by the reviewer 3 that helps to significantly improve our manuscript and allow us to clarify the applicability of the calibration equation in extreme climates of the past. Below, we present our response to the comment raised. A final version of our point-by-point response will be given at the end of the discussion phase with responses to all reviewers' comments.

Reviewer comments are shown in red color, with our responses in black.

We highlight the high salinity regions mentioned by reviewer 3 in the $\delta^{18}\text{Oc}$ -density calibration on Figure a (with regions = Med Sea, Arabian Sea, Red Sea, upwelling off NW Africa).

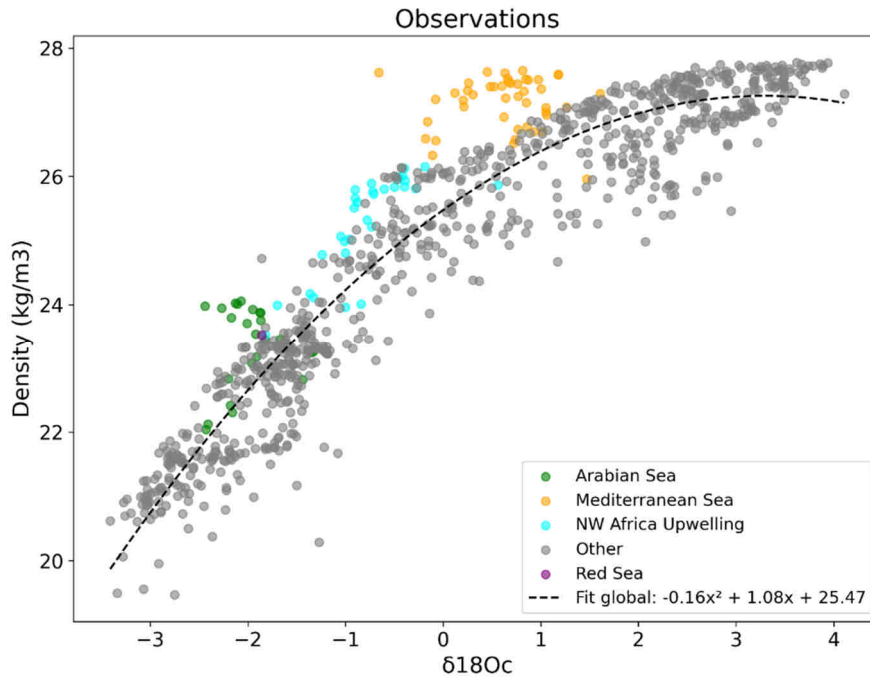


Figure a: $\delta^{18}\text{Oc}$ -density relation for late Holocene core-top samples against observed density. We highlight in colors the high salinity regions mentioned by reviewer 3 (Med Sea, Arabian Sea, Red Sea, upwelling region off NW Africa).

Contrary to what is stated by the reviewer 3, these regions do not correspond to the portion of our calibration curve that is less sensitive to an increase in $\delta^{18}\text{Oc}$ (“**increase of d18O by 3 per mill is not accompanied by a substantial predicted density change**”). In fact, except for some parts of the Mediterranean Sea, these regions are not regions where we observe the maximum ocean density.

In addition, we do not consider that Figure 3 shows a “**strong**” correlation between the residual density and salinity changes. $R^2 = 0.2$ is a weak correlation. Also, this pooled foraminifera species correlation integrates various species. The correlation coefficients with SSS vary for the individual species: $R^2 = 0.17$ for *G. ruber*, $R^2 = 0.12$ for *T. sacculifer*, $R^2 = 0.54$ for *G. bulloides*, $R^2 = 0.15$ for *N. incompta*, and $R^2 = 0.32$ for *N. pachyderma* as discussed in the text. So, probably other factors than SST and SSS influence these residual structures that persist and some of them could indirectly be associated with gradients in SSS. For example, negative residuals are observed in the Benguela, Canary, Peru and North Arabian regions (Fig. 1). All these coastal areas correspond to upwelling systems and previous work already suggested that foraminifera species could have a preference for nutrient-rich waters with high turbidity. This is particularly true for the seasonal species *G. bulloides* (Peeters et al., 2002; Gibson et al., 2016). The negative density residuals in these upwelling regions may reflect this habitat preference (Fig. 1), as we discussed in the text.

The portions of the calibration curve that can be described by “when an increase of d18O by 3 per mill is not accompanied by a substantial predicted density change” correspond to some high latitudes regions (Nordic Seas and Austral Ocean), as also discussed in the response to reviewer 2. This is because we are close to the maximum of density observed today.

What is the explanation of this decrease in linearity of the relation between $\delta^{18}\text{O}_c$ and surface ocean density in Nordic Seas and Austral Ocean regions? When density is already high, temperature changes have a smaller effect. Cold water is already dense, so cooling it further doesn't increase density as much (see TS diagram on Figure b). Consequently, we observe a sensitivity decreases. The rate of change of density with respect to T flattens out, meaning the system becomes less responsive to temperature changes. Small changes in temperature and salinity no longer cause significant shifts in density. This behavior is linked to the non-linearity of the seawater equation of state.

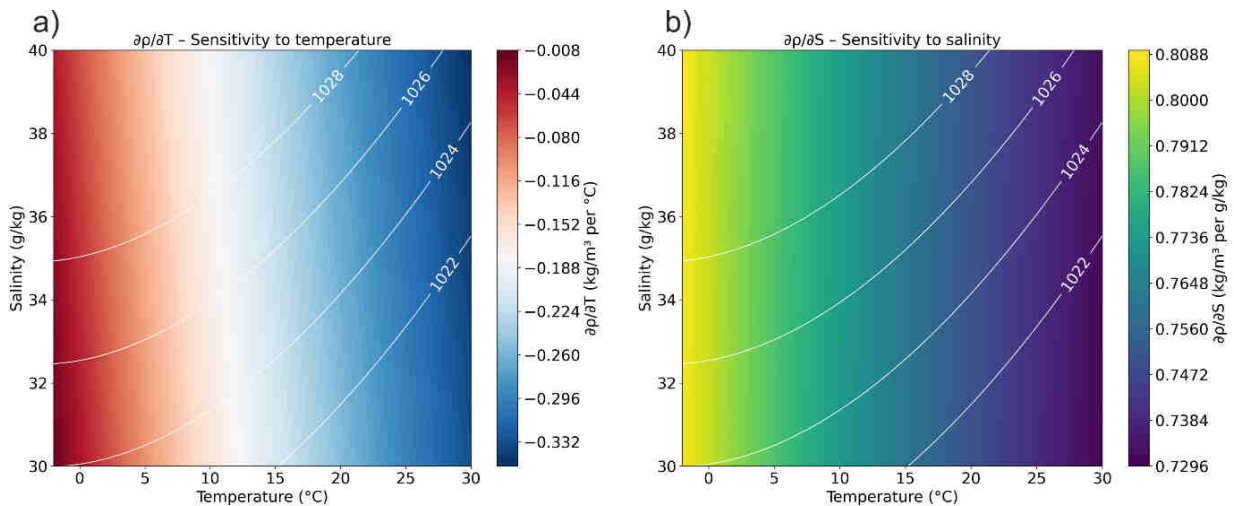


Figure b: TS diagram for Surface Ocean with the derivative $\partial\rho/\partial T$ in (a) and $\partial\rho/\partial S$ in (b). The derivative $\partial\rho/\partial T$ and $\partial\rho/\partial S$ represents the change in density per degree of temperature or per one salinity unit respectively. In surface waters, and at low temperatures (e.g., -2 to 2 °C), water is already dense and a temperature change has little effect: $\partial\rho/\partial T$ approaches zero. $\partial\rho/\partial S$ remains positive and relatively stable, often between 0.6 and 0.8 kg/m³ per g/kg, though it may increase slightly with salinity. Its effect becomes dominant in cold waters, where $\partial\rho/\partial T$ is weak. Both diagrams include isopycnals (lines of constant density) and have been computed with the Gibbs SeaWater (GSW) Oceanographic Toolbox of TEOS-10.

This process does not affect the $\delta^{18}\text{O}_c$ (quasi-linear fractionation with temperature at low temperature (see for example Mulitza et al., 2003)) and this is why we observe that an increase of $\delta^{18}\text{O}_c$ by 3 per mill is not accompanied by a substantial change in predicted density in Nordic Seas and Austral Ocean. Even if this part of the regression is less predictive, the estimated values of density are correct and are not expected to change strongly as ocean density approaches its upper limits.

In the climate model world, we found some uncertainties, in the Nordic seas, in the model simulations we conducted at the LGM because of the difficulty to simulate this region (see response to reviewer 2), together with ocean dynamic effect induced by the mean ocean salinity increase due to ice volume increase in regions of sea ice and deep water formation (see response to point 1 of reviewer 1). We therefore recommend in our paper to not apply the calibration to this region.

Regarding the fact that the calibration could be less reliable for the density reconstruction of past extreme climates. Concerning “high $\delta^{18}\text{O}_{\text{c}}$ values driven large ice volume”, a global correction can be applied to account for the effect of ice volume increase on $\delta^{18}\text{O}_{\text{sw}}$ and salinity, and in turn on density (see our response to reviewer 1’s point 1 for detailed explanations). Because it is an additional global correction, it will not change the range of values in our present day calibration.

Concerning changes between “dry and wet climates (small ice sheet and large riverine runoff)”, we conducted additional test with model simulations to investigate if the calibration is likely to provide density estimates with a larger uncertainty. We agree that it is interesting to put into context our results regarding other climate periods. As asked by the reviewer 1 in point 9, we conducted some preliminary tests using isotope-enabled model runs of the mid-Holocene (e.g., Shi et al. 2023). According to reviewer 1, the strongest precipitation changes (and hence changes in surface $\delta^{18}\text{O}$ and salinity) occur in the early to mid-Holocene with the strengthening of the Monsoon. Our results clearly indicate a strong stability of foraminifera $\delta^{18}\text{O}_{\text{c}}$ -density relation between the mid-Holocene (MH) and pre-industrial (PI) and thus a very weak influence of $\delta^{18}\text{O}$ /Salinity relation instability on final density predictions. Therefore uncertainties remain within the 95% confidence interval of our calibration (see our response to point 9 of the reviewer 1). We also conducted additional tests for the last interglacial period (LIG) as requested by reviewer 2 and found a similar conclusion (see our response to reviewer 2 point “I would like the authors to put into context their results regarding other climate periods” for results). We already tested in the initial version of our paper the extreme cold and arid climate of the LGM and found that additional uncertainties are small and that our approach is valid (except for the Nordic Seas region), within propagated uncertainties from calibration into predictions of past climate conditions.

So, even if the salinity role in shaping the predicted density could be slightly underestimated (indirectly because of foraminifera ecology) for the present day calibration, applying our calibration to past extreme climates (and taking into account ecological changes) provide density predictions within the uncertainties of the calibration as demonstrated for the LGM, and now also for the MH and LIG time periods. Note that these time periods correspond to extreme climate configurations over the quaternary period as visible on Figure c, so it is reasonable to state that the new calibration has great potential to be applied to other past periods and to reconstruct the past temporal evolution of ocean surface density over the Quaternary (last 2.6 Ma).

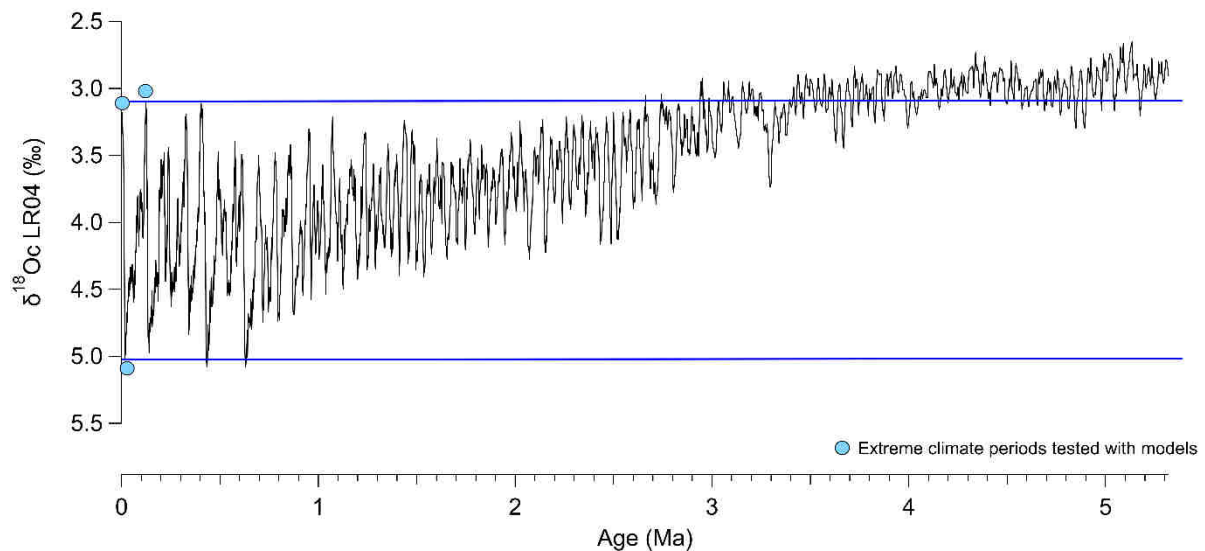


Figure c: $\delta^{18}\text{O}$ benthic foraminifera curve (LR04, Lisiecki and Raymo, 2005). Benthic $\delta^{18}\text{O}$ reflects ice volume and deep ocean temperature changes and is used here to highlight extreme climatic periods (colder and more arid glacial periods versus warmer and more humid interglacial periods). Extreme climate periods tested with isotope-enabled model runs representing the mid-Holocene, LIG and LGM are represented by blue dots. Blue lines indicate the range of extreme climate conditions investigated with our climate simulations tests.

Nonetheless, we agree with reviewer 3 that under very extreme climates outside the quaternary (see Figure c) and in ocean basin characterized by anti-estuary circulation, like the current Mediterranean Sea and Red Sea, our calibration could provide density estimates with larger uncertainty, a point that requires further investigations.

We will therefore mention this in the revised version and moderate the concluding statement made in lines 465-475.

References

- Lisiecki, L. E., & Raymo, M. E. (2005). A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records. *Paleoceanography*, 20(1).
- Mulitza, S., Boltovskoy, D., Donner, B., Meggers, H., Paul, A., & Wefer, G. (2003). Temperature: $\delta^{18}\text{O}$ relationships of planktonic foraminifera collected from surface waters. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 202(1-2), 143-152.