# *Interactive comment on* "Irreversible ocean thermal expansion under negative $CO_2$ emissions" *by* Dana Ehlert and Kirsten Zickfeld

**Anonymous Referee #4**

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Overview:

This manuscript explores the forward and reverse pathways of oceanic heat uptake and sea level rise and their sensitivity to sub-grid scale mixing parameterization choices in the UVic ESCM model. The experimental design is based on idealized simulations where atmospheric CO2 increases at a rate of 1%/year to quadrupling followed by a 1%/year decrease back to preindustrial values. A suite of sensitivity experiments are run based on varying a uniform constant background diffusivity, a vertically-dependent mixing scheme (Bryan & Lewis 1979), and tidal dissipation scheme (Schmittner et al. 2005). The manuscript demonstrates global sea level rise is irreversible on decadal to centennial time scales, which the authors demonstrate both in the UVic model and using a simple 2-layer diffusion model. The reversibility pathways for bottom-water formation processes are also dependent on the nature of sub-grid scale mixing and that an increases in NADW and AABW relative to preindustrial values leads to global sea level that is below the preindustrial starting value.

Response: We want to thank the reviewer for the helpful and positive review.

Major comment:

All ocean models have some element of temperature drift. This is not discussed in the manuscript. This drift can arise for variety of reasons, including spurious mixing in depth-based coordinate models. This drift can be on the order of several tenths of a degree per century for the global volume average temperature. Drifts of this magnitude are non-negligible on the millennial timescales discussed in this manuscript. Furthermore, the magnitude of this drift is directly linked to the strength of the sub-grid scale mixing parameterizations used in ocean models. After the 6,000 year spin up of the model, suddenly varying the mixing coefficients in the model will produce noticeable changes in global ocean temperature and sea level regardless of changes in atmospheric CO2. It would be preferable to run control simulations for each of the mixing perturbations considered in this study. The difference plots in each of the figures should be relative to their respective control simulations rather than year 0 of the simulation. This approach would more cleanly separate the response to forcing from the inherent model drift.

Response: Each model version with the changed mixing is spun up to account for the effect of the changes in mixing as described in the simulation section. Thus changes relative to year 0 are changes relative to the end of spin up state for each individual mixing parameter scheme/setting. Therefore, the changes in global mean temperature and sea level account only for changes induced by the forcing and not induced by changes in mixing. The effect of mixing can then be inferred by comparing the different lines in 1d plots or subplots in Figure 3. The 6000 year spin up also nearly eliminates any drift in the model. We included a mentioning of the absence of drift in the simulation section.

Minor Comments:

Page 1, Line 22: Recovery on what timescale?
Response: On multi-millennial time scales. We included this here.

Page 2, Line 2: How do the negative emissions in RCP2.6 compare with decreasing atmospheric CO2 at a rate of 1%/year?
Response: We included the highest rates for negative emissions (around 20 PgC/yr for 1% yearly atmospheric CO2 decline and 1.6PgC/yr for RCP2.6) in the discussion section, where the limitations of the 1% scenario are discussed.

Page 2, Line 8: Sea ice decline should be sea ice recovery
Response: We added recovery into the sentence.

Page 3, Line 6: This is an excellent place to discuss the known constraints that the modeling community does have in regards to sub-grid scale mixing? (i.e. how big is the uncertainty?)
Response: It is difficult to generalize uncertainties for the different diffusivities and going into detail about the different diffusivities at this point in the manuscript does not seem adequate as they have not been introduced specifically. Furthermore, the uncertainties for the parameters are also model specific and mixing parameter values for varying ESM are very difficult to access. As discussed in the simulation section, the range for the background diffusivity in the tidal mixing scheme is based on uncertainty studies. There are no uncertainty studies for Uvic for the other vertical mixing schemes to our knowledge.

Page 5, Line 17: On what timescale?
Response: GMTSL change is proportional to GMSAT changes on multi-centennial time scales. Thank you for pointing to this missing information. We included it now at this point.

Page 6, Line 1: Does Delta-T imply the near-surface air temperature?
Response: In the equation it simply reflect the temperature change in the 0-D EBM. When this approach is being applied to the model out put as in Figure 4, yes change in GMSAT is used as Delta T. This is being described in the caption of Figure 3.

Page 12, Line 1: What are precise definitions used to assess AMOC and AABW rates? e.g. Is it the annual time series of the meridional overturning at the latitude of the RAPID array (26.5N)?
Response: Both AMOC and AABW formation are now computed from maximum respectively minimum of the zonally averaged stream function below a depth of 400 m. The stream function is calculated from decadal averages of the velocity. The maximum of the zonally averaged stream function occurs between 30N and 40N and the minimum occurs between 0S and 70S. For consistency we now use decadal averages for the AMOC calculations as well. We expand the information given on the calculations in captions of Figures 6 and 7.

Figure Comments:

Figure 1, panels b & d: A line denoting zero would be helpful.
Response: We included those lines now.
Figure 2, panels c & d: What are the surface values? They could potentially be very unrealistic.
Response: The surface values are cropped out here as otherwise the differences in temperature change in deeper layers between the model version would not be visible. The surface values are very similar to the global mean surface air temperatures for those points in time, which can be inferred from the time evolution plots of the global mean surface air temperatures.

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