Author responses to reviewer comments for the manuscript

Complementing thermosteric sea level rise estimates

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We sincerely thank the two reviewers for many helpful comments, criticisms and suggestions, their overall positive and encouraging remarks. Aiming for depth and clarity in reporting our results, our response to the reviewer remarks have, in our opinion, resulted in an improved manuscript. Please find the point-by-point addressing of all comments below, whereby changes in the main text are indicated in blue.

1 Responses to Reviewer #1

This section details our responses to Reviewer #1

1.1 Specific remarks

1.1.1 Reviewer #1: *p.1209 and Fig.3 To me it is absolutely not clear why the contribution of the deep ocean (>2000m depth) to the global mean thSLR is decreasing with time in the RCP scenarios, but not in the 4xCO2 scenario. The authors try to explain this with the increasing vertical temperature gradient in the 4xCO2 runs, but why doesn't the same explanation hold in the RCP8.5 case? Indeed, if the different RCP scenarios are compared in Fig.3, it appears that the stronger the forcing, the /faster/ the decline of the contribution of the deep ocean. The authors say that the 20th century history (which the RCP runs have, as opposed to the 4xCO2 runs) plays a role here. It certainly will, but if anything, I would have expected the opposite effect: the OHU in the 20th century would already have increased the vertical temperature gradient, so over the course of the 21st century the deep ocean should start to warm up too. Consider also Purkey & Johnson (2010) and further studies that report on the accelerate warming of AABW in observations in the early 21st century. Fig. 3 shows a very interesting result in this respect, but more explanation is needed.*

***1.1.1* Author Response:** We are sorry that our description of the thermal expansion contribution from different depth to the total thermosteric sea level rise (thSLR) and vertically-intergated thermal expansion, respectively, for different CMIP5 scenarios, apparently lacks clarity. Vertical temperature gradients and the stratification of the water column are keys to the corresponding vertically-integrated thermal expansion and the thSLR, respectively. The evolution of these vertical profiles depends on the radiative forcing at the sea surface and the redistribution of temperature changes in the interior ocean. In general, our simulated globally and hemispherically averaged thSLR evolutions show an exponential (higher-order) warming in the upper 2000 m whilst below this depth the warming is linear. This is consistent with observational results (e.g. Purkey and Johnson, 2010). We tried to clarify what happens with the heat uptake at the sea surface and its redistribution in the interior ocean, in particular in case of the historical and abruptCO2 CMIP5 scenarios as function of depth with an updated paragraph and two additional depth profiles in Fig. 2. The paragraph now reads: *"Observed thSLR estimates with a vertical integration limit that is not the entire ocean depth due to data sparsity will need to be complemented by an approximation for the thSLR contributions originating by changes in deeper layers. Our CMIP5 analysis derives those deeper layer contributions as percentage shares of total thSLR across our range of scenarios (see multi-model median in Fig. 3). The contributions relevant to a global sea level budget clearly depend on the scenario and hence the atmospheric forcing. The higher the radiative forcing gradient of the scenario, the lower is the contribution from depths below 2000 m. The stronger the warming signal in the ocean's upper layers the more enhanced is the stratification in the upper layers. Noticeable area the tendencies in the abrupt4xCO2 scenario where 90% of the thermal expansion is confined to the upper 700m in the first 20 years and thSLR contributions from depth below 2000 m (as* *share of total thSLR) shows an opposing trend compared to the 21st century evolution of the multi-gas scenarios. Firstly, the idealized experiments are started from pre-industrial control equilibrium conditions and hence miss the initial stratification and upper layer expansion between historical's start year (usually 1850) and the start year of our analysis (1900 for the historical and 2006 for the RCP scenarios) (Russell et al. 2000). Secondly, the initial warming pulse in abrupt4xCO2 is extreme: Already within the first year of the model scenario, thermal expansion in the upper 300 m shows a clear increase in the global mean, for all CMIP5 models, and amounts to a magnitude of thermal expansion corresponding to the last twenty years (1986-2005) of the historical scenario (Fig 2d, h and Fig. S3a). After twenty years, the thermal expansion for the abrupt4xCO2 scenario in this upper layer equals almost the thermal expansion of the rcp2.6 scenario at the end of the 21st century (not shown). Both characteristics of abrupt4xCO2 define a large vertical temperature gradient between surface and deeper water almost instantaneously. Mixing and advection erodes this large vertical temperature gradient, so that after 90 years the contribution below 700 m increased to 33% and below 2000 m to 7%. At the beginning of the 21st century, the initial thSLR contribution for the four RCP scenarios shows high levels around 40% (20%) for depth below 700 m (2000 m) and then decreases in layers below 2000 m. For the lower and intermediate forcing scenarios, rcp2.6 and rcp4.5, the 700m upper layer's proportion decreases, too. In all multi-gas scenarios, the middle layer's share of total thSLR, i.e between 700 m-2000 m (light grey band in Fig 3), tends to increase over the 21st century. The explanation for this tendency of middle and deeper layer thSLR contributions to the total thSLR is likely related to multiple effects. The warming induced intensified stratification in the upper 700 m seems the obvious effect. Additionally, we propose the effect of the cessation of sporadic volcanic forcing in the RCP scenarios compared to the historical simulations. Towards the end of the historical scenario, i.e the start of the RCP scenarios, the volcanic forcing in historical might suppress the thermal expansion of middle layers (700 m-2000 m) and might therefore lead to a certain rebound effect of the middle layer thSLR contributions in the mid-21st century (cf Fig S3). However, for the multi-gas scenarios, the overall 21st century multi-model median thSLR contribution of the deep ocean is 39% from depth below 700 m with 24 to 58% as 90% uncertainty and 17% from depth below 2000 m with 5 to 31% as 90% uncertainty (see Fig 3a-d). The contributions for the RCP reference period (1986-2005, Church et al., 2013a) taken from the historical simulations are 46% [21 to 73%] (and 21% [4 to 44%]) (Fig 3e)."*

1.1.2 Reviewer #1: *Fig. 4 Is there anything essential in Fig. 4 that we haven't seen in Fig.3 already? Perhaps it can be cut out altogether? If anything, what I see here is again the deeply puzzling role of the deep ocean (>2000m) in the historical runs. Why does 'historical' have the largest spread of all scenarios, and the largest contribution to the overall thermal expansion? I actually wonder whether this is a feature (or a weakness) of your 1.5D estimate of alpha? Perhaps the 6 parameters aren't well constrained in the historical runs for some reasons? Please elaborate.*

1.1.2 Author Response: In Fig. 4 we would like highlight the robustness of the equation of state expressed in the simplified version of the thermal expansion coefficient (Eq. 3) and how the results might differ among the scenarios, also considering different depth intervals for the vertical integration. Fig. 4 shows clearly that our results do not depend crucially on our calibration parameters but on individual model characteristics like the 3D-pattern where the heat was taken up and redistributed in the interior ocean. Induced by subduction of a sea surface warming signal, historical scenarios for all models show the weakest changes in stratification, the smallest changes in the vertical gradient of temperature and of thermal expansion, respectively, as if compared to the corresponding vertical profiles in the forcing scenarios. Please see Fig.2, as well as our comments to your first point and to point 2.2.2.f by Reviewer #2. In the discussion we adjusted the corresponding sentence accordingly: *"... the amount of thSLR due to the externally-forced warming during the period 1986-2005 is small compared to the underlying interannual variability that is generated by the internal variability of ocean dynamics (Palmer et al., 2009; Palter et al., 2014)."*

1.1.3 Reviewer #1: *p.1211 l.12 How has the result on the "augmentation" of the thSLR estimates been obtained? I'm completely at a loss to see this from your ms. Is there a whole section missing? You're even mentioning this result in the abstract. If you do not show it, then just cut these two sentences (here and in the abstract) out.*

1.1.3 Author Response: We apologize if our presentation appears to be not clear enough on how we arrive at the augmentation of thSLR estimates. We quantify *augmentation* as the percentage contribution/share of thermal expansion to/of total thSLR estimates as function of depth for each individual model and forcing scenario. Based on values in Fig. 3 we provide multi-model median values. Please see our revised text included in our comment to your first point. The corresponding sentence in the abstract reads now: *"We find that 21st century thSLR estimates derived solely based on observational estimates from the upper 700 m (2000 m) would have to be multiplied by a factor of 1.39 (1.17) with 1.24 to 1.58 (1.05 to 1.31) as 90% uncertainty in order to account for thSLR contributions from deeper levels."* And in the discussion: *"Our results suggest that 21st century thSLR estimates derived solely based on observational estimates from the upper 700 m would have to be multiplied by a factor of 1.39 (with a 90% uncertainty range of 1.24 to 1.58) in order to be used as approximation for total thSLR originating from the entire water column. Correspondingly, our CMIP5 model analysis suggests that partial thSLR contribution based on hydrographic measurements from the upper 2000 m can be expected to account already for around 85% of the total thSLR and consequently have to be multiplied only by 1.17 (with a 90% uncertainty range of 1.05 to 1.31)."*

1.1.4 Reviewer #1: *p.1212 l.15 "... meridional gradients..." Another result that is mentioned in the Discussion, but is not derived at all. I would just cut this.*

1.1.4 Author Response: We refer to details for horizontal and vertical behaviour of alpha with studies by Griffies et al. (2014) and Palter et al. (2014) on p. 2012 l.7-8. However, we mention now the mean meridional gradient of alpha explicitly, given that spatial variations (both horizontal and vertical) are decisive for the integral values of heat uptake and redistribution in the interior ocean, thus for the sea level estimates. The sentence around p1208 l.27 reads now *"Independent of the model and scenario, the thermal expansion coefficient alpha at the sea surface decreases from 4x10^{-4}degC-1 in tropical, to near zero in polar regions and, globally-averaged, shows the familiar concave vertical profile (Griffies et al., 2014) with a minimum around 1500 m (Fig. 1 in Griffies et al. (2014) and Fig. 2)."*

1.1.5 Reviewer #1: *p.1212 l.18 "errors of +/-5 and =/-9%": again, where do these numbers come from? It almost appears as if the Discussion section belongs to another paper - there are so many references to results that have not been described in the body of the paper. I would suggest to start from scratch writing the Discussion, based on what you actually write about in the previous sections. The abstract should be amended accordingly.*

Author Response: These numbers quantify the goodness-of-fit between thSLR estimates that are currently published within CMIP5 and based on Eq. (2) and Eq. (3). We calculate three "goodness-of-fits" (in an root-mean-square statistics) to quantify *"that our 3D-equation of state implementation is consistent with those of CMIP5 modelling groups"* (1%), and *"that simplified approaches estimating thSLR that collapse either the meridional component (our 1.5-D simplification) or both dimensions (the 0-D approach are sufficiently reliable"* (5% and 9%). The first two quantities are still defined in Section 3 and 5. At the end of section 6 we added the sentence *"Our 0-D approach results in a normalized difference between thSLR estimates based on a 3-D (in Eq. 2) and spatially constant (0-D) thermal expansion coefficients of 9%".* Please see also our comments to point 2.1.3 by Reviewer #2.

1.2 Technical remarks:

1.2.1 R #1: ***p**.1201 l.8: "we complete diagnostics" doesn't sound right. Perhaps say "extend"*

1.2.1 AR: We agree that "complete" and "augmented" might not have been the most appropriate verbs and we replaced them by "extend" or "add".

1.2.2 R #1: ***p.1201 l.9:** "We obtain 30% more thermal expansion ..." It is absolutely not clear how you obtain this result. See my remark on your Discussion above.*

1.2.2 AR: We agree and we re-wrote the sentence as follows: *"Specifically, based on CMIP5 temperature and salinity data, we provide a compilation of thermal expansion time series that comprise 30% more simulations than currently published within CMIP5"*; (see also point 2.1.2 Reviewer #2).

1.2.3 R #1: *p.1203 l.1: "due to (nonlinearities of)" sounds awkward. Perhaps say "due to the nonlinear way in which the equation of state depends on the ..."*
1.2.3 AR: The study by Sarah Gille (2004) is titled: "*How non-linearities in the equation of state of sea water can confound estimates of steric sea level change*". We prefer the original text but removed the brackets. (Gille, S. T., 2004, J. Geophys. Res., 109, C03005, doi:10.1029/2003JC002012.)

1.2.4 R #1: *p.1203 l.4: "ocean's" should be "the ocean's" (there are several more instances of this mistake)*
1.2.4 AR: Thanks for pointing out the missing article.

1.2.5 R #1: *p.1203 l.27: "up to date": I think you mean "currently"*
1.2.5 AR: We want to refer to the history and status of observed contributions to SLR from thermal expansion and not just to its present state. We changed the wording to *"down to the present day"*.

1.2.6 R #1: *p.1205 l.15: for human readability it should be ".10^{-6"*
1.2.6 AR: We agree and changed the expression of the multiplier accordingly.

1.2.7 R #1: p.1207 l.9: missing URL
1.2.7 AR: You find our extended data set here: http://climate-energy-college.net/complementing-thermosteric-sea-level-rise-estimates and as supplementary material.

1.2.8 R #1: *p.1212 l.14: "density gradients": This sentence strikes me as odd: as you say very clearly in sec.2, it is the vertical gradients of temperature and pressure that mainly determine alpha - not the density. That there is a strong vertical gradient of alpha is first year textbook knowledge and doesn't need mentioning here at all.*
1.2.8 AR: Thank you for this comment. The sentence reads now: "*Our diagnosis of CMIP5 profiles confirms the large variations in alpha due to strong meridional (not shown) and vertical density gradients originating from strong temperature gradients (see Eq. (2) and Fig. 2).*"

1.2.9 R #1: *Fig. 2d,e: Is it useful to show the Roemmich & Gilson values all being zero in these two panels? I would simply leave that out.*
1.2.9 AR: We prefer to include Roemmich and Gilson's values for consistency and to visualise that the observed warming over the last ten years is not noticeable against the amount of warming projected until the end of 21st century. However, we don't show the data in the final version but added two figures of simulated vertical thermal expansion profiles.

1.2.10 R #1: *All figures, as rendered in the ms., are much too small and thus illegible. The authors will have to use much larger fonts for labeling, or rather break down the existing panels into more figures.*
1.2.10 AR: All figures are revised regarding fonts, size etc. We incorporated some of Reviewer #2 suggestions as well (see point 2.2.2).