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 for the decreasing contributions from layers below 2000 m. 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.*

1.1.1 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).

2 Responses to Reviewer 2:

This section details our responses to Reviewer #2:

2.1 Special remarks

2.1.1 Reviewer #2: *Page 1202, line 4: ". . .mostly limited to the upper ocean layers..." As noted in subsequent text, significant (and potentially accelerating) warming has been documented by Purkey and Johnson (2010) – I believe this should be better reflected.*

2.1.1 Author Response: In the abstract we start the second sentence now with *"Yet, observational estimates of this volumetric response of the world ocean to temperature changes are sparse, mostly limited to the ocean's upper 700 m ..."* to point to limits of available data not to the "limits" of warming (as function of depth). We reflect on the latter in more detail throughout the paper.

2.1.2 Reviewer #2: *Page 1202, lines 9-10: "We obtain 30% more thermal expansion time series than currently published" I am a little uncertain about this sentence and what the authors mean. A rewrite would be useful.*

2.1.2 Author Response: 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."*

2.1.3 Reviewer #2: *Page 1202, lines 18-19: "(goodness of fit.." I was interested to understand this better, however the last sentence of the discussion didn't provide much information.*

2.1.3 Author Response: Generally, the goodness-of-fit captures the root of mean squared (RMS) differences between test and reference data. For our calibration purpose, it is the minimum of root-mean-squared differences between our thermal expansion estimates based on Eq. 3 and Eq. 2 over all individual model-scenarios; we estimate the goodness-of-fit for each model and list it together with the corresponding calibration parameters in the supplementary Table 1. For testing the reliability of our simplified approach estimating thSLR, we calculate the RMS difference between our global mean thSLR time series based on Eq. 2 and the published ones within CMIP5 (1%), the difference between our global mean thSLR time series based on Eq.2 and our thSLR time series based on Eq. 3 taking into account the entire depth as vertical integration limit (5%) as well as the difference between our global mean thSLR time series based on Eq. 2 and our thSLR time series based on Eq. 3 but for vertically integrated values (9%). We tried to extend the text accordingly. See as well our comment to point 1.1.5 by Reviewer #1.

2.1.4 Reviewer #2: *Page 1202, line 23: "30% of the net heating" Is this Earth total or global ocean total, it wasn't clear to me.*

2.1.4 Author Response: Thanks for pointing out the missing reference quantity, the world ocean. The sentence reads now: *"The climate system is warming and during the relatively well-sampled recent 40 year period (1971—2010) the world ocean stored 70% of the net oceanic heat gain in depths above and 30% below 700 m (Rhein et al., 2013)."*

2.1.5 Reviewer #2: *Page 1202, lines 24-25: ". . .the thermal expansion of seawater is a major driver behind SLR." It would be useful to quantify this statement – Church et al., (2013a) note 40% (0.8 of 2.0 mm yr-1) can be attributed to thermal expansion over 1971-2010.*

2.1.5 Author Response: For the observational record with satellite altimeter data since 1993, we quantify the contribution to global mean SLR from thermal expansion at p.1203, l.26 and now also, like you suggested, the one over the 40 year period: *"Church et al. (2013a) note that 40 % of the observed SLR over 1971-2010 can be attributed to thermal expansion."*

2.1.6 Reviewer #2: *Page 1203: lines 3-10: I believe the recent publication Rose et al. (2014) provides useful background here.*

2.1.6 Author Response: Thank you for pointing out this reference. We added the following sentence: "*In turn, processes in the interior ocean cause spatial patterns of ocean heat uptake at the sea surface which define regional and global warming rates (Rose et al. 2014).*"

2.1.7 Reviewer #2: *Page 1203: lines 13-14: ". . .mass changes together with ocean's thermal expansion. . ." Again quantifying this statement would be useful (e.g. Church et al., 2013a).*

2.1.7 Author Response: We extended the previous section as follows: *"... ice-sheet and glacier mass and land water storage that combined amount to 60% of the observed global mean SLR over 1971-2010 (Church et al., 2013a)."*

2.1.8 Reviewer #2: *Page 1203, lines 15-17: ". . .such as salinity variations associated with freshwater tendencies have a negligible effect on seawater density and thus global mean sea level changes. . ." This statement is true for global integrals, but certainly is not true for regional (e.g. Durack et al., 2014).*

2.1.8 Author response: Thank you for pointing out the regional role of salinity in understanding sea level changes. We adjusted the sentence accordingly and added *"; on regional to basin-scales, however, the role of salinity should not be neglected in sea level studies (e.g. Durack et al., 2014a).*"

2.1.9 Reviewer #2: *Page 1203, lines 20-23: ". . .simulating the land ice-sheet. . . . . .still translates into large uncertainties in climate models." A more correct statement would be that CMIP5 generation climate models do not include land-ice contributions to the SLR budget – which was the motivation for the cited publication Church et al. (2013b).*

2.1.9 Author Response: The sentence reads now "*However, the current climate models of the Coupled Model Intercomparison Project phase 5 (CMIP5) do not include land ice-sheet discharge dynamics and their contributions to the global mean SLR budget (Church et al., 2013b). Furthermore, simulating land ice-sheet discharge dynamics from the Antarctic Ice Sheets, might translate into large uncertainties in climate models ...*"

2.1.10 Reviewer #2: *Page 1204, lines 1-3: ". . .to cover the upper 2000 m at maximum." The publications Palmer et al., (2007, 2009) and Smith and Murphy (2007) are relevant here – I also note that the Smith and Murphy (2007) analysis extends to 5000 m, and the* Levitus *et al. (2005) analysis extends to 3000 m. It would also be useful to mention the platform bias issues – Abraham et al. (2013) provide a nice summary.*

2.1.10 Author response: Thank you very much for pointing to these references. The studies by Palmer et al. (2007, 2009) and the one by Smith and Murphy (2007) are mainly concerned with the masking of the warming trend of the subsurface ocean due to natural variability in the temperature time-series, whereby subsurface covers a maximum depth of 500 m. We are mainly concerned with the spatial and temporal oceanic temperature data coverage to arrive at observed long-term time-series of thSLR with contributions to this integral value from the entire water column. And the current time-series by Levitus et al. (2012) do not exceed depths of 2000 m. The authors quote "A lack of high-quality CTD and reversing thermometer data at depths exceeding 2000 m in recent years precludes us from producing recent analyses for deeper depths." However, we added as last sentence of this paragraph "*For details on the spatial and temporal coverage and quality of oceanic temperature measurements that underlie thSLR estimates we refer to Abraham et al. (2013) and references therein.*"

2.1.11 Reviewer #2: *Page 1204, lines 3-5: ". . .assumed to increase.." due to data sparsity.*

2.1.11 Author Response: We start the sentence now with "*Due to data sparsity observed ....*"

2.1.12 Reviewer #2: *Page 1204, lines 8-11: "We begin . . . to derive thSLR." I suggest a rewrite.*

2.1.12 Author Response: We re-wrote this to: *"We begin by introducing the observed and simulated datasets as well as the method to arrive at thSLR estimates. Subsequently, we calculate the simulated* *thermal expansion over the entire ocean grid for a number of CMIP5 models that have not published those time series yet."*

2.1.13 Reviewer #2*: Page 1205, lines 10-20: This text was difficult to follow, even after a re-read. From where did the 6000 and 3500 denominators come from, are these assuming some depth of integration? A rewrite of this section would be useful.*

2.1.13 Author Response: Like we state in the manuscript, the simplified parameterisation of the thermal equation coefficient is based on a simplification of the equation of state of seawater given in appendix 3 in Gill (1982) assuming a constant salinity of 35 PSS-78. It is, for example, included in the reduced-complexity Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) (e.g. Raper et al., 1996; Wigley et al., 2009, Meinshausen et al., 2011) but not published yet. "3500" presents the global mean ocean depth of 3500 m. We polished the paragraph for clarity.

2.1.14 Reviewer #2: *Page 1205, line 19: psu -> PSS-78.*

2.1.14 Author Response: We changed the unit of the practical salinity accordingly.

2.1.15 Reviewer #2: *Page 1205, lines 22-25: "As a first step, we use for each hemisphere. . ." Can the authors elaborate further on why this simplification is useful?*

2.1.15 Author Response: Now we start this paragraph on our simplified approach of thSLR with: *"In order to derive thermal expansion estimates, and zostoga, from hemispherically or globally averaged vertical temperature profiles, rather than* from sparsely *observed and computationally expensive spatial 3-D fields of temperature, salinity and pressure ... "* and further down we added: *"As a first step, we use time-dependent vertical global and hemispheric profiles of Theta from the CMIP5 models to test the reliability of thermal expansion estimates based on this simplified approach (Eq. 3)."*

2.1.16 Reviewer #2: *Page 1206, lines 15-19: Some new insights regarding the "adjusted forcing" by Forster et al. (2013) for simulations contributing to CMIP5 would be useful background to the reader here.*

2.1.16 Author Response: We incorporated the study by Forster et al. (2013) as follows: *"However, recent literature suggests that the rapid adjustment primarily due to clouds generates forcing variations that cause differences in the projected surface warming among the CMIP5 models even if radiative forcing is equally prescribed for each individual CMIP5 model (Forster et al., 2013)."*

2.1.17 Reviewer #2: *Page 1206, lines 19-22: model drift – some discussion of this drift correction methodology with reference to Sen Gupta et al. (2013) would be useful.*

2.1.17 Author Response: Our model climate drift discussion reads now as follows: *"... a ``full linear drift" is removed by subtracting a linear trend based on the entire corresponding piControl scenario for comparison with observational time series. For our globally and hemispherically averaged thSLR time series the sensitivity to the method of drift correction is less than 1% due to a small low-frequency (inter-annual and inter-decadal) variability in the evolution of this integral oceanic property. This contrasts the large low-frequency variability, e.g., in the sea surface temperature evolution (e.g. Palmer et al., 2009). For details about methods of climate drift correction in CMIP5 models see Taylor et al. (2012), Sen Gupta et al. (2013) and the supplementary by Church et al. (2013a)."*

2.1.18 Reviewer #2: *Page 1206, lines 22-26: This Gregory et al. (2013) correction is certainly justifiable, however as thermal expansion has been estimated as contributing just 40% of the 1971-2010 SLR (Church et al., 2013a) I think some discussion would be useful. The Lorbacher et al. (2012) publication would provide some insights here.*

2.1.18 Author Response: We note now **"***The adjustment of global mean SLR to changes in ocean mass is fast and linear (Lorbacher et al., 2012); thus in the long term, impacts of changing ocean mass on SLR may well become in the primary contribution to the trend in SLR."*

2.1.19 Reviewer #2: *Page 1207, line 8: ". . .30% more time series of zostoga than previously published." A reference would be useful to a reader here.*

2.1.19 Author Response: We extended the text in brackets *"compare Table S1 and Fig. 1,e.g., to Fig. 13.8 in Church et al. (2013a).*"

2.1.20 Reviewer #2: *Page 1207, line 9: The PCMDI ESGF portal link http://pcmdi9.llnl.gov/esgf-web-fe (or an alternative ESGF master node) would be a suitable URL.*

2.1.20 Author Response: We intended the URL for our complementary time series, but after your suggestion we now also provide the possible link for the currently published data.

2.1.21 Reviewer #2: *Page 1207, lines 12-13: ". . .previous CMIP5 multi-model ensemble estimates by Church et al. (2013a) have been robust. . ." It would be useful to elaborate and quantify this agreement. It would also be useful to elaborate and highlight this result as "observational augmentation of 36%" is noted in the abstract.*

2.1.21 Author Response: We extended the sentence to *"For rcp4.5 in year 2100, the projected model median thSLR and its 90% confidence interval, for example, by the end of the 21st century amounts to 0.28±0.06 m (see Table 1 for more scenario results). The corresponding thSLR published by Church et al. (2013a) is 0.27±0.06 m. For all four RCP-scenarios our results indicate that previous CMIP5 multi-model ensemble estimates by Church et al. (2013a) have been robust, despite being based on 30% less models than used here (Table 1, S1 and Table 13.5 in Church et al. (2013a)).*" Please note that our augmentation of observed thSLR estimates is not based on the number of CMIP5 models used but on the multi-model median percentage contribution from different depth intervals to thSLR.

2.1.22 Reviewer #2: *Page 1207, line 19: "1993-2010" as the historical simulations nominally end in 2005 and RCP simulations begin in 2006 it would be useful to highlight in methods how temporal splicing was undertaken.*

2.1.22 Author Response: Please find the following sentence in the introduction of the CMIP5 scenarios *"For projected time series beyond the historical simulations, we use the rcp4.5 simulations consistent with Church et al. (2013a)."*

2.1.23 Reviewer #2: *Page 1207, lines 21-25: A rewrite of this sentence would be useful – it was not clear what was being discussed here. If the "hiatus" is a focus, it would be worthwhile noting some relevant citations.*

2.1.23 Author Response: We would like to highlight the robustness of simulated thSLR estimates here and have no intention to speculate about reasons that explain differences in model output compared to observations. We checked our results, re-arranged and revised the first part of this paragraph that starts now as follows: "*For the upper 700 m, our extended CMIP5 multi-model median rate of thSLR and its standard deviation globally amounts to 0.57±0.03 mm yr^{-1} from 1971 onward to2010 (Fig. 1b) and is similar to the observed arithmetic mean ...*"; near the end it reads: *"For the altimetry period (1993-2010), our multi-model median is 1.45 mm yr^{-1}, with 1.02 to 1.97 mm yr^{-1} as 90% uncertainty, taking into account the contribution of thermal expansion to the global mean SLR from the entire ocean depth. This rate of thSLR equals the corresponding rate of 1.49 mm yr^{-1} within the uncertainty 0.97 to 2.02 mm yr^{-1} listed in Table 13.1 by Church et al. (2013a) and confirms again the robustness of simulated thSLR estimated presented by Church et al. (2013a) with 30% less models for a multi-model estimate than used here."*

2.1.24 Reviewer #2: *Pages 1207, lines 18-26, 1208, lines 1-11: I really had a hard time determining what the authors are describing here. In a previous paragraph the new results are noted as "robust" to Church et al. (2013a) [page 1207, lines 11-14], whereas this paragraph tends to suggest this is no longer true – and is the discussion on observations, models, the contrast between these? – A re-write would be useful here.*

2.1.24 Author Response: Please see our comments on your points 2.1.21 and 2.1.23.

2.1.25 Reviewer #2: *Page 1208, line 16-19: "Based on observed and, additionally by assimilating. . ." I assume that the Kouketsu et al. (2011) results described where from two independent analyses?*

2.1.25 Author Response: Yes, your assumption is correct. We re-wrote the sentence for clarification: *"For an ocean warming occurring at depth below 3000 Kouketsu et al. (2011) estimate a similar thSLR over a 40-year period; based on observed and assimilated data it amounts to 0.10 mm yr^{-1} and 0.13 mm yr^{-1}, respectively."*

2.1.26 Reviewer #2: *Page 1208, line 20-23: "... aligned with the Argo observational climatological profiles of potential temperature and salinity for the modern day (2005-2013) ocean (Roemmich and Gilson, 2009). . ." It would be useful to provide some additional information here for the reader.*

2.1.26 Author Response: The sentence reads now: *"For the upper 2000 m, the depth profiles of thermodynamic properties across CMIP5 models are largely aligned with observational depths profiles for Theta and S of the modern day (2005-2013) ocean provided by the Argo program (Roemmich and Gilson, 2009)."*

2.1.27 Reviewer #2: *Page 1209, lines 8-28: I really had a hard time following the thread here – I suggest a re-write.*

2.1.27 Author Response: Please see our comments on point 1.1.1 by Reviewer #1.

2.1.28 Reviewer #2: *Page 1210, lines 1-5: ". . .[observations] upper 200 m by 4%... . . .[models] upper 700 m by 8%." I wonder why the depth of comparison is not the same; a direct obs vs model contrast would have more utility I believe.*

2.1.28 Author Response: We provide now some direct quantitative comparison between observations and simulations *"Independent of the concatenated radiative forcing scenario we estimate an increase in the multi-model median contribution to thSLR in the upper 200 m during 1971 to 2010 by 11% (not shown)."*

2.1.29 Reviewer #2: *Page 1210, lines 14-16: Model dependent AABW formation rates – a relevant citation would be helpful.*

2.1.29 Author Response: We altered the sentence to: *"The thermal expansion related contribution to SLR from depths below 2000 m is larger in the southern hemisphere than in the northern hemisphere. This might be due to model dependent mixing rates forming Antarctic bottom water, that Wang et al. (2014) assigned to CMIP5 model biases in the Southern Ocean's sea surface temperature."*

2.1.30 Reviewer #2: *Page 1211, line 11: ". . .our results show that observed estimates of thSLR for the upper 700 m. . ."*

2.1.30 Author Response: This sentence in the discussion reads now: *"Secondly, we quantify the thSLR contribution from the entire ocean depth in order to complement observational estimates that are primarily available for the upper ocean layers down to 700 m (cf. Domingues et al., 2008). Sparse observational evidence points to non-significant contributions to global mean thSLR from depths below 2000 m during 2005 to 2013 (Llovel et al., 2014). 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).*

2.1.31 Reviewer #2: *Page 1211, lines 12-16: ". . .augmented on average by 36%.." This number and subsequent numbers appears out of the blue to me, I'm a little uncertain how these numbers are supported by the analysis.*

2.1.31 Author Response: We introduce the percentage augmentation of the total thSLR as contribution/share from different depth intervals when we describe Fig. 3 and pick up the numbers in the discussion (please see our response to your comments 2.1.27 and 2.1.30).

2.2 Technical remarks:

2.2.1 Text

2.2.1.a R #2: *Page 1207, line 21: Additionaly -> Additionally*
2.2.1.a AR: .corrected.

2.2.1.b R #2: *Page 1212, lines 1-2: ". . .underlying interannual variability because of the internal variability of ocean dynamics."*
2.2.1.b AR: .corrected.

2.2.1.c R #2: *Page 1212, line 9: perists -> persists*
2.2.1.c AR: .corrected.

2.2.1.d R #2: *Page 1212, line 16: merdional -> meridional*
2.2.1.c AR: .corrected.

2.2.2 Figures

2.2.2.a R #2: *I found many of the graphics difficult to view as they are small and contain a lot of material – some further work to optimise these results would be useful.*
2.2.2.a AR: All figures are revised regarding fonts, size etc. (see point 1.2.10 by Reviewer #1).

2.2.2.b R #2: *Figure 1: The standard units of SLR in the literature are mm yr-1 to maintain continuity with a large number of publications cited in this manuscript I would suggest altering axes to reflect this. I assume the thin coloured lines indicate a linear fit to the Roemmich and Gilson (2009) and Levitus et al. (2012) plotted timeseries, if yes what is the origin? Additionally I'd check these, they don't appear to faithfully intersect the timeseries they are calculated from. Figure 1 caption: what are the numbers following each of the experiments: e.g. historical (31/47)?*
2.2.2b AR: 1/ Thanks for pointing to the importance of maintaining consistency with literature regarding the units of SLR. Our focus in Fig. 1 is on the temporal evolution of thSLR depending on the vertical integration limit. In our opinion these show more clearly the model spread and the decline of low-frequency (inter-annual to inter-decadal) variability of the time series as function of depth, thus make possible a direct comparison with IPCC-AR5 results (Table 13.5 in Church et al., 2013a). However, we are showing the evolution of the rate of thSLR in the supplementary material (Fig. S3). 2/ We checked the linear fit to the data by Roemmich and Gilson (2009) and Levitus et al. (2012), with the linear fit originating in year 1993, the beginning of the altimeter measurements. 3/ We still explain the numbers in the caption of Fig. 1a: "*the ratio in brackets indicates the number of models of published (solid lines) zostoga and recalculated (dashed lines) zostoga in this study based on simulated temperature and salinity fields.*"

2.2.2.c R #2: *Figure 2: As noted by reviewer 2, there is little use in plotting a 0 value for Roemmich and Gilson (2009) on panels d and e. There is a note here about model outliers, but I do not recall any discussion of this in the text – if there is some use in highlighting outliers they should be described in text.*
2.2.2c AR: 1/ Please see our comment to point 1.2.9 by Reviewer #1. 2/ Thanks, we now mention the model outliers in section 4 of the main text.

2.2.2.d R #2: *Figure 3: Using the same vertical scale for each experiment would be much more useful to a reader.*

2.2.2d AR: The vertical scale should now be consistent for the radiative forcing experiments though still different to the historical one for better readability of the numbers.

2.2.2.e R #2: *Figure 4: As noted by reviewer 1 I'm uncertain if this figure shows any new information that was not presented in Figure 3. If the 700-2000 m results are indeed important, I suggest incorporating them into Fig 3 and cleaning a single figure up.*

2.2.2.e AR: In Fig. 4 we would like to point out 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 as well as by using different depth intervals for the vertical integration. Please see our comment to point 1.1.2 by Reviewer #1.

2.2.2.f R #2: *Figure 5: Including observed estimates on this plot would be useful. Ditto to comment (1) from reviewer 1 (deep ocean contribution RCPs vs abrupt4xCO2). Also the spread n the mean and median is quite large, is there a specific reason why median (rather than mean with errors) was selected for use within text?*

2.2.2.f AR: 1/ We included the estimates from the World Ocean Database (Boyer et al., 2013) due to their global horizontal resolution and coverage of the entire ocean depth in the discussion: "For climatological temperature and salinity profiles (Boyer et al., 2013), the difference between the mean (1200 m) and median (700 m) depth in is even greater compared to our model diagnostic results of the historical scenario. This can be explained by a reduced vertical temperature gradient within the main thermocline and a weaker stratification above the main thermocline induced by the absent end of 20th century warming in the climatological profiles." 2/ Please see our comment on point 1.1.1 by Reviewer #1 covering scenario dependent contributions of thermal expansion from different depth layers to thSLR. 3/ We would like to quantify here, that the vertical distribution of thermal expansion is skewed towards greater depths (Fig. 2e) and the mean depth is always deeper than the median depth. In general, for skewed distributions it is not at all obvious whether the mean or median is the more meaningful measure. In our case, in particular with the difference between mean and median depth of thermal expansion you can make an assumption how deep a warming signal might have penetrated and how large the vertical temperature gradient that defines the main thermocline might have become; so we show both measures as multi-model mean. We make the following statement in the discussion: *"The mean depths are 100 (300) m lower than the medians for the idealized (RCP) scenarios and 400 m for the historical scenario (Table S5). This indicates a positive skewness of the vertical distribution of thermal expansion because of its long tail towards depths below 700 m."* And adjusted the figure caption slightly for increased clarity *"The multi-model mean depth and standard deviation (in m) from where the individual model mean and median depth of thSLR originates ..."*.

(Boyer, T.P., J. I. Antonov, O. K. Baranova, C. Coleman, H. E. Garcia, A. Grodsky, D. R. Johnson, R. A. Locarnini, A. V. Mishonov, T.D. O'Brien, C.R. Paver, J.R. Reagan, D. Seidov, I. V. Smolyar, and M. M. Zweng, 2013: World Ocean Database 2013, NOAA Atlas NESDIS 72, S. Levitus, Ed., A. Mishonov, Technical Ed.; Silver Spring, MD, 209 pp., doi.org/10.7289/V5NZ85MT)

2.2.3 References:

AR: We thank you very much for the comprehensive additional literature suggestions!

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Complementing thermosteric sea level rise estimates

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Abstract. Thermal expansion of seawater is one of the most important contributors to global sea level rise ~~in~~ (SLR) over the past 100 years. Yet, observational estimates of ~~thermal expansion are sparse ,~~ this volumetric response of the world ocean to temperature changes are sparse and mostly limited to the ~~upper oceanlayers, and~~ ocean's upper 700 m. Furthermore, only a part of the available climate model data is sufficiently diagnosed to complete our quantitative understanding of thermosteric ~~sea level rise~~ SLR (thSLR). ~~In order to support usage of results of~~ Here, we extend the available set of thSLR diagnostics from the Coupled Model Intercomparison Project Phase 5 (CMIP5), ~~complement~~ analyse those model results in order to complement upper-ocean observations and enable the development of surrogate techniques to project thSLR ~~, we complete diagnostics of~~ using vertical temperature profile and ocean heat uptake time series. Specifically, based on CMIP5 ~~models. We obtain 30% more~~ temperature and salinity data, we provide a compilation of thermal expansion time series that comprise 30% more simulations than currently published ~~.~~ within CMIP5. We find that 21^{st} century thSLR estimates derived solely based on observational estimates from the upper 700 m (2000 m) ~~observational estimates need to be augmented by 36±9% (15±6%) on average to be considered for a global sea level budget. Half of the~~ would have to be multiplied by a factor of 1.39 (1.17) with 90% uncertainty ranges of 1.24 to 1.58 (1.05 to 1.31) in order to account for thSLR contributions from deeper levels. Half (50%) of the multi-model total expansion originates from depths below ~~480~~490±~~250 m~~ 90 m, with the range indicating scenario-to-scenario variations. ~~Lastly, to~~ To support the development of surrogate methods to project thermal expansion, we calibrate two simplified parameterisations against CMIP5 estimates of thSLR: One parameterisation is suitable for scenarios where ~~only~~ hemispheric ocean temperature profiles are available, the other, where only the total ocean heat uptake is known (goodness-of-fit: ±5% and ±9%, respectively).

1 Introduction

Sea level rise due to anthropogenic climate change constitutes a major impact to the world's coastlines, low-lying deltas and small island states. The climate system is warming and during the relatively well-sampled recent 40-year period (1970-2010) the world ocean stored ~~30~~70% of the net ~~heating in depths~~ oceanic heat gain in depths above and 30% below 700 m (*Rhein et al.*, 2013). As the ocean takes up heat, the thermal expansion of seawater is a major driver behind sea level rise (SLR). *Church et al.* (2013a) note that 40% of the observed global mean SLR over 1971-2010 can be attributed to thermal expansion. This volumetric response of the ocean to temperature changes ~~, to the uptake and redistribution of heat,~~ is expressed by its thermal expansion coefficient α (e.g., *Griffies et al.*, 2014) and is due to ~~(nonlinearities of)~~ nonlinearities of the thermodynamic properties (potential temperature, Θ, salinity, S, and pressure, p) in the equation of state of seawater density, ρ (e.g., *Jackett et al.*, 2006). Thus, changes in heat fluxes at the sea surface and heat redistribution in the ocean's interior by advection, eddies and diffusion, lead to non-zero temperature differences altering the sea level even if the global mean potential temperature changes equal zero (*Lowe and Gregory*, 2006; *Piecuch and Ponte*, 2014). In turn, processes in the interior ocean cause spatial patterns of ocean heat uptake at the sea surface which define regional and global warming rates (*Rose et al.*, 2014). Sea level is often defined as the height of the sea surface relative to the geoid – the surface of equal gravitational potential of a hypothetical ocean at rest – also called the geocentric sea level according to *Church et al.* (2013a). ~~Thus~~ Therefore sea level changes integrate all volume changes of the world ocean.

Aside from thermal expansion, SLR is also induced by changes in ~~ice-sheets~~ ice-sheet as well as ~~glaciers~~ glacier mass and land water storage that combined amount to 60% of the observed global mean SLR over 1971-2010 (*Church et al.*, 2013a). Over the last century, these mass changes in the ocean (termed "barystatic" sea level changes by *Gregory et al.*, 2013a) together with ocean's thermal expansion are the main contributors to global mean SLR~~; some~~. Some other influences, such as salinity variations associated with freshwater tendencies at the sea surface and redistributed in the ocean's interior have a negligible effect on seawater density and thus ~~global mean~~ sea level changes ~~(e.g., *Lowe and Gregory*, 2006)~~on the global scale (e.g., *Lowe and Gregory*, 2006); on regional to basin-scales, however, the role of salinity should not be neglected in sea level studies (e.g., *Durack et al.*, 2014a). In the long term, the mass contribution might become substantially larger than thermal expansion contribution to SLR because of the larger efficiency of land-ice melting for a given amount of heat (*Trenberth and Fasullo*, 2010). However, ~~simulating the~~ the current climate models of the Coupled Model Intercomparison Project phase 5 (CMIP5) do not include land ice-sheet discharge dynamics ~~, for example~~ and their contributions to the global mean SLR budget (*Church et al.*, 2013b). Furthermore, simulating land ice-sheet discharge dynamics from the Antarctic Ice Sheets ~~, still translates~~ might translate into large uncertainties in climate models, since ~~irreversible~~ non-linear processes may be triggered that could alter the sea level rise contribution dramatically (e.g., *Joughin* *et al.*, 2014; *Rignot et al.*, 2014; *Mengel and Levermann*, 2014). For the observational record with satellite altimeter data since 1993, the observed and simulated contribution of thermosteric expansion to global mean SLR amounts to 34% and 47%, respectively (see Table 13.1 in *Church et al.*, 2013a). ~~Up to date~~Down to the present day, the observed ~~contribution to SLR~~ thSLR contribution from thermal expansion is limited in the space and time ~~dimensions~~dimension: Available observed long-term (decadal) time series of thermosteric sea level rise (thSLR) are mainly globally-averaged values using different spatio-temporal interpolation/reconstruction methods and cover the upper 2000 m at maximum (*Domingues et al.*, 2008; *Ishii and Kimoto*, 2009; *Levitus et al.*, 2012). Observed contributions to thSLR from depths below 2000 m are assumed to increase monotonically and linearly in time (*Purkey and Johnson*, 2010; *Kouketsu et al.*, 2011). For details on the spatial as well as temporal coverage and quality of oceanic temperature measurements that underlie thSLR estimates we refer to *Abraham et al.* (2013) and references therein.

The objective of the present study is both to complement observed and existing simulated thSLR estimates in a number of ways and to enable the development of surrogate techniques for long-term thSLR projections. We begin by ~~calculating the simulated~~ introducing the observed and simulated datasets as well as the method to arrive at thSLR estimates. Subsequently, we calculate the simulated thermal expansion over the entire ocean ~~depth~~ grid for a number of CMIP5 models that ~~did not publish~~ have not published those time series yet~~, after introducing the simulated and observed datasets as well as the method to derive thSLR~~. Section 3 and Section 4 present both the extended CMIP5 thSLR (*zostoga*) dataset and depth-dependent results that can complement upper ocean layer observations. Section 5 and Section 6 investigate hemispheric and global averages of calibrated thSLR mimicking CMIP5 estimates. In Section 7 we discuss and summarize our results focussing on the extent to which the observations might underestimate the contribution to thSLR from depths below the main thermocline.

2 Methods and Models

The volumetric response to changes in the ocean's heat budget, the thermosteric sea level, η_Θ, at any horizontal grid point and any arbitrary time step is defined by the vertically integrated product of the thermal expansion coefficient, α, and the potential temperature deviation from a reference state, $\Theta_{exp} - \Theta_{ref}$,

$$\eta_\Theta(x,y,t) = \int_{-H}^{0} \alpha(\Theta_{exp} - \Theta_{ref})\,\mathrm{d}z \qquad (1)$$

where the spatial 3-D thermal expansion coefficient, α is defined by:

$$\alpha = \frac{-1}{\rho(S_{ref},\Theta_{ref},p)} \frac{\rho(S_{ref},\Theta_{exp},p) - \rho(S_{ref},\Theta_{ref},p)}{(\Theta_{exp} - \Theta_{ref})} \qquad (2)$$

CMIP5 publishes time series of global mean (0-D) η_Θ, called *zostoga* and represents the integral value of ocean's *thermal expansion*, $\alpha\,(\Theta_{exp} - \Theta_{ref})$, at each grid point, over the entire ocean volume. For the majority of the fully coupled climate models, sea level changes due to net gain of heat need to be diagnosed offline as a result of using the Boussinesq approximation, conserving ocean's volume and not mass (*Greatbatch*, 1994). Here, we derive global mean yearly depth profiles of thermal expansion by using independent Θ and S prognostics of CMIP5 model simulations in Equation 2.

In order to derive thermal expansion estimates, thus and *zostoga*, from hemispherically or globally averaged vertical temperature profiles, rather than from sparsely observed and computationally expensive spatial 3-D fields of temperature, salinity and pressure, we use a simplified parameterisation of a thermal expansion coefficient, $\alpha_{1.5}$, as a polynomial of Θ and p:

$$\begin{aligned}\alpha_{1.5} \;=\;& \left(c_0 + c_1\,\Theta_0\,(12.9635 - 1.0833\,p) - c_2\,\Theta_1\,(0.1713 - 0.019263\,p)\right. \\ +\;& \left. c_3\,\Theta_2\,(10.41 - 1.1338\,p)\,c_4\,p, - c_5\,p^2\right) \times 10^{-6}\end{aligned} \tag{3}$$

with $\Theta_0 = \Theta_{exp}$, $\Theta_1 = \Theta_0^2$ and $\Theta_2 = \Theta_0^3/6000$ and calibration parameters $c_{n=0-5}$. This polynomial algorithm simplifies is based on a simplification of the equation of state of seawater given in *Gill* (1982), assuming a constant salinity of 35 psu. It has for examplebeen part of PSS-78. It is, for example, included in the reduced-complexity Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) (*Raper et al.*, 1996; *Wigley et al.*, 2009; *Meinshausen et al.*, 2011). The depth profile, z, is expressed by the pressure profile $p = 0.0098\,(0.1005\,z + 10.5\exp((-1.)\,z/3500) - 1.0\,)$, assuming a mean ocean depth of 3500 m. As a first step, we use for each hemisphere, the time-dependent vertical global and hemispheric profiles of Θ from the CMIP5 models to test the reliability of thermal expansion estimates based on this simplified approach (Eq. 3). With these time-series of vertical temperature profiles we calibrate $\alpha_{1.5}$ by the in Eq. (3) with calibration parameters c_n against hemispherically-averaged globally and hemispherically averaged vertical profiles of α in Equation Eq. (2) (using squared differences as goodness-of-fit statistic).

We name this parameterisation the 1.5-D simplification, as it uses two hemispherically-averaged hemispherically averaged depth profiles. In addition, we use the CMIP5 data to estimate the zero-dimensional (0-D) thermal expansion coefficient α_0. Divided by ocean's specific heat capacity, reference density and area, it gives the "expansion efficiency of heat"" (in m YJ^{-1}, 1 YJ $\equiv 10^{24}$ J) and allows the comparison of thermal expansion from models with different spatial dimensions (*Russell et al.*, 2000). This constant quantifies the proportionality between global mean thSLR and ocean heat uptake (OHU) (cf. *Kuhlbrodt and Gregory*, 2012).

We examine a broad range of CMIP5 scenarios, namely the post-industrial climate simulations (*historical*)(post-1850) climate simulations, the idealized 1% CO_2 per year increase (*1pctCO2*) and the response to abrupt 4× pre-industrial CO_2 increase (*abrupt4xCO2*). But as we aim to provide tools to complement thermal expansion scenarios not directly considered in CMIP5 and to enable the design of complement observed and existing simulated thSLR estimates and to design surrogate techniques to project ~~thSLR, the focus is~~ long-term thSLR, we focus on the four scenarios ~~of~~ defining future change in radiative forcing, namely *rcp2.6*, *rcp4.5*, *rcp6.0* and *rcp8.5*. These scenarios specify four greenhouse gas concentration ~~trajectoriers and representative concentration pathways (rcp), respectively~~trajectories and their Representative Concentration Pathways (RCP). They are named after ~~a possible range~~ the amount of radiative forcing (in W m^{-2}) ~~in~~ realised in the year 2100 relative to values of the pre-industrial (pre-1850) control scenario (*piControl*) (for details see *Taylor et al.*, 2012; *Moss et al.*, 2010, and Table S1). However, recent literature suggests that the rapid adjustment primarily due to clouds generates forcing variations that cause differences in the projected surface warming among the CMIP5 models even if radiative forcing is equally prescribed for each individual CMIP5 model (*Forster et al.*, 2013).

Independent of the model and estimation method, a "full linear drift" is removed from all simulated thermosteric sea level time series, *zostoga* and temperature time series ~~, are de-drifted~~ by subtracting a ~~long-term linear trend of the~~ linear trend based on the entire corresponding (*piControl*) scenario in order to allow for comparison with observational time series~~(*Yin*, 2012; *Church et al.*, 2013b).~~ . For our globally and hemispherically averaged thSLR time series the sensitivity to the method of drift correction is less than 1% due to small low-frequency (inter-annual to inter-decadal) variability present in the evolution of this integral oceanic property. This contrasts the large low-frequency variability, e.g. in the sea surface temperature evolution (*Palmer et al.*, 2009). For details about methods of climate drift correction in CMIP5 models see *Taylor et al.* (2012), *Sen Gupta et al.* (2013) and the supplementary by *Church et al.* (2013a). Additionally, we correct the *historical* time series by adding the suggested ~~trend in thSLR~~ thSLR trend of 0.1$\pm$0.05 mm yr^{-1} by *Church et al.* (2013b) to take into account that the CMIP5 *piControl* scenario might be conducted without volcanic forcing and thus ~~might~~ underestimate the oceanic thermal expansion in the *historical* scenario (*Gregory et al.*, 2013b). The adjustment of global mean SLR to changes in ocean mass is fast and linear (*Lorbacher et al.*, 2012); thus in the longer term, impacts of changing ocean mass on SLR may well become the primary contribution to the trend in SLR. For projected time series beyond the historical simulations, we use the *rcp4.5* simulations consistent with *Church et al.* (2013a).

3 Extended CMIP5 zostoga dataset

For CMIP5 models that report *zostoga*, we calculate the RMS-error between published *zostoga* values and our recalculated values based on the provided Θ and initial S depth profiles. Averaged over all CMIP5 models and scenarios and normalised by the mean *zostoga* value, the RMS-error amounts to $\pm$1%, providing confidence that our 3-D equation of state implementation ~~coincides~~ is consistent with those of CMIP5 modelling groups. As not all CMIP5 models that provide Θ and S also provide *zostoga*, our recalculated dataset comprises 30% more ~~time series of *zostoga*~~ modelled *zostoga* time series than previously published ~~, available at URL(TBA) (see~~ within CMIP5 (compare Table

S1 and ~~Figure~~ Fig. 1a~~)~~, e.g., to Fig. 13.8 in *Church et al.* (2013a)). These complementing *zostoga* time-series are available at http://climate-energy-college.net/complementing-thermosteric-sea-level-rise-estimates and as supplemetary material; time-series of *zostoga* published by the individual model groups are available e.g. here http://pcmdi9.llnl.gov/esgf-web-fe.

~~Our~~ For the RCPs, our extended dataset implies a maximum thSLR of 40 cm ~~thSLR for the 21st centuryfor the RCPs. The model median~~ for the 21^{st} century. For *rcp4.5* in year 2100, the projected model median thSLR and its 90% confidence interval ~~by the mid- and end of the 21st century~~ amounts to 0.28±.06 m (see Table 1 for more scenario results). The corresponding thSLR published by *Church et al.* (2013a) is 0.27±06 m. For all four RCP-scenarios, our results indicate that previous CMIP5 multi-model ensemble estimates by *Church et al.* (2013a) have been robust, despite being based on 30% less models than used here (Table 1~~and~~ , S1 and Table 13.5 in *Church et al.* (2013a)). The ~~idealised scenarios due to increasing CO_2~~ idealized scenarios reveal a concave thSLR up to 40 cm in *1pctCO2* and a convex sea level rise up to 80 cm in *abrupt4xCO2* over the first 100 years.

4 Complementing Observations

~~Our multi-model ensemble median contribution of thermal expansion to the global mean SLR for the period 1993-2010 is 1.1 mm yr^{-1}, with 0.8 to 1.4as 90% confidence interval. It reproduces the observational estimates listed in Table 13.1 by *Church et al.* (2013a). Additionaly, this table shows that over this time period the number of available models seems to have an influence on the thSLR: based on 70% of the dataset used here the simulated trend for 1993-2010 is 1.49 mm yr^{-1} 0.97 to 2.02(cf. Table 13.1 by *Church et al.*, 2013a), thus 13% higher than both the observational and our estimates.~~ For the upper 700 m, ~~the amplitude of~~ our extended CMIP5 ~~model mean thSLR from 1970s onward~~ multi-model median rate of thSLR and its standard deviation globally amounts to 0.57±0.03 mm yr^{-1} from 1971 onward to 2010 (Fig. 1b and Fig. S3b) and is similar to the observed arithmetic mean 0.53±0.02 mm yr^{-1} of the three individual trends 0.63±0.02 mm yr^{-1} (*Domingues et al.*, 2008), 0.45±0.02 mm yr^{-1} (*Ishii and Kimoto*, 2009) and ~~0.53~~0.50±0.03 mm yr^{-1} (*Levitus et al.*, 2012) (cf. Figure 13.4 in *Church et al.*, 2013a). ~~Around~~ For the same period, around half of the models underestimate the ocean's thermal expansion in simulations~~since the warming period of the upper ocean (above 700 m) commenced in year 1971 (*Rhein et al.*, 2013)~~, even after the correction for missing volcanic forcing in the *piControl* scenario (*Gregory et al.*, 2013b). Nevertheless, the majority of the *historical* scenarios capture the main volcanic eruptions in the years 1963 (Agung), 1982 (El Chichon) and 1991 (Pinatubo) with a sea level drop 1-2 years later. Generally, differences in the observed and interannual variability suggest that the underlying spatial patterns of interannual thermosteric sea level variability are different (*Fyfe et al.*, 2010). For the altimetry period (1993−2010), our multi-model median is 1.45 mm yr^{-1}, with 1.02 to 1.97 mm yr^{-1} as 90 % uncertainty, taking into account the contribution of thermal expansion to the global mean SLR from the entire ocean depth. This rate of thSLR equals the corresponding rate of 1.49 mm yr^{-1} and its uncertainty range of 0.97 to 2.02 mm yr^{-1} listed in Table 13.1 by *Church et al.* (2013a) and confirms again the robustness of simulated thSLR estimated presented by *Church et al.* (2013a) with 30% less models for a multi-model estimate than used here.

The model median contribution to thSLR from the layer between 700-to-2000 m suggests a slight underestimation in the observational data (Fig~~.~~. 1c and Fig. S3c). For ocean depths below 2000 m, the model median trend for the years 1990-2000 of 0.11 mm yr^{-1} in the *historical* scenario seems to reliably represent the ~~contribution to thSLR ,~~ thSLR contribution which *Purkey and Johnson* (2010) estimated (Fig. 1d ~~). Based on observed and, by assimilating data, reproduced~~ and Fig. S3c). For an ocean warming occurring at depth below 3000 m *Kouketsu et al.* (2011) estimate a similar thSLR over a 40-year period; based on observed and assimilated data it amounts to 0.10 mm yr^{-1} and 0.13 mm yr^{-1}, respectively.

~~The~~ For the upper 2000 m, the depth profiles of thermodynamic properties across CMIP5 models are largely aligned with observational ~~profiles of potential temperature, salinity by *Roemmich and Gilson* (2009) and~~ depths profiles for Θ and S of the modern day (2005$-$2013) ocean provided by the Argo program (*Roemmich and Gilson*, 2009). The same is true for the derived thermal expansion coefficient ~~(Figure 2 and cf. depth profiles of poter~~ The simulated salinity profile shows the observed maximum at around 200 m that reflects evaporation zones and a minimum at around 500 m that reflects mode water regions. For depths below 500 m, the model spread of Θ and S amounts to 2 degC and 0.4 ~~psu, respectively~~PSS-78, with only a few model outliers. Independent of the model and scenario~~the global mean~~ , the thermal expansion coefficient α at the sea surface decreases from 4$\times$10^{-4} degC^{-1} in tropical, to near zero in polar regions and, globally-averaged, shows the familiar concave vertical profile (e.g., *Griffies et al.*, 2014) with a minimum around 1500 m (Fig. 2). The minimum global mean climatological value of α amounts to 1.3$\times$10^{-4} degC^{-1} for the *historical* scenario and agrees well with the observed one. Averaged over the entire water column, α (1.56$\times$10^{-4} degC^{-1}) compares well with the corresponding value from ocean-only simulations (1.54$\times$10^{-4} degC^{-1}, *Griffies et al.*, 2014). In the northern hemisphere, α is 1% higher than in the southern hemisphere because average temperatures tend to be higher above 2000 m in the northern hemisphere (not shown). For details ~~in~~ on the horizontal and vertical behaviour of α see e.g. *Griffies et al.* (2014) and *Palter et al.* (2014).

~~The median percentage contribution to thSLR from depths below 700 m and below 2000 m both clearly depends~~ 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~~(Fig. 3).~~ . The higher the radiative forcing ~~the~~ gradient of the scenario, the lower is the contribution from depths below 2000 m~~and the~~ . The stronger the warming signal in the ocean's upper layers the more enhanced is the stratification in the upper layers~~, respectively. The exception~~ . Noticeable is the *abrupt4xCO2* scenario where 90% of the thermal expansion is confined to ~~90% in the upper 700 m in the first 20 years. The~~ and that the evolution of 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 ~~equilibrium~~ 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 ~~underestimate the thermal expansion that should have taken place in the real world's post-industrial climate (cf. *Russell et al.*, 2000). Thus the initial extreme~~ 2006 for the RCP scenarios) (cf. *Russell et al.*, 2000). Secondly, the initial warming pulse in *abrupt4xCO2* ~~sets up a~~ 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%. ~~Because the multi-gas scenarios are not started from equilibrium but from year 2006, the trend of the deeper layers contribution over the 21st century is the reverse:~~ At the beginning of the ~~21st century, it starts at~~ 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 ~~because of the~~ in layers below 2000 m. For the lower and intermediate forcing scenarios, *rcp2.6* and *rcp4.5*, the 700 m 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 21^{s}t 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 ~~. At the~~ seems the obvious effect for the decreasing contributions from layers below 2000 m. 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 ~~21st century the projected median and its 90% confidence interval of the percentage contribution to thSLR from depth below~~ *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 (and below 2000 m) amount to 33% 22 to 57%(and 9% 2 to~~ 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 21~~%) for the highest emission scenario (*rcp8.5*)and to for the lowest emission~~

~~scenario (*rcp2.6*~~st 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)~~44% 31 to 69% (and 15% 4 to 36%)~~. The ~~corresponding values for the historical scenario during the reference period for the emission scenarios (1986-2005,~~ contributions for the RCP reference period (1986−2005, *Church et al., 2013a)* taken from the *historical* simulations are 46% [21 to ~~77~~73%] (and ~~22~~21% [4 to ~~46~~44%]) ~~. *Rhein et al.* (2013) note that the observed warming signal of ocean's upper 700 m during 1971 to 2010 seemed to increase the stratification in the upper 200 m by 4%. During 1971 to 2005 we estimate an increase in the multi-model median contribution to thSLR in the upper 700 m by 8%~~ (Fig. 3e).

5 The 1.5-D parameterisation

~~Minimising RMS errors, we~~ We obtain 6 calibration parameters c_n for each CMIP5 model through our optimisation scheme that minimises the RMS errors from iteration to iteration. When comparing our extended set of CMIP5 thSLR (*zostoga*) time series with the thSLR time series obtained by using potential temperatures and standard pressure profiles with Equation 3, we then obtain an average error of ±5%, ranging in between 1% and 17% across the CMIP5 model suite (see Table S2). The hemispherically-averaged percentage contributions to thSLR based on the 1.5-D simplified thermal expansion coefficient (Eq. 3) for all seven scenarios compare well with our extended CMIP5 dataset (Fig. 4). The ~~thermal expansion related contribution to SLR~~ thSLR contribution from depths below 2000 m is larger in the southern hemisphere than in ~~northern hemisphere and~~ the northern hemisphere. This might be due to model dependent mixing rates forming Antarctic bottom water, that *Wang et al.* (2014) assigned to CMIP5 model biases in the Southern Ocean's sea surface temperature. Strong outliers (values far outside the whiskers and the 90% confidence interval~~, respectively~~) are found in the depth range below the main thermocline between ~~700-2000~~ 700−2000 m independent of the scenario and spatial averaging.

6 The 0-D parameterisation

Our findings complement *Kuhlbrodt and Gregory* (2012) who analysed the "expansion efficiency of heat" ~~, the~~ as constant of proportionality between thSLR and OHU ~~,~~ for the *1pctCO2* scenarios and concluded that model differences in the stratification below the main thermocline largely explain the differences between the individual models. Based on the ~~ensemble of~~ original CMIP5 ensemble with 30% ~~less~~ less CMIP5 models than used here, the constant for global mean (0-D) time series estimated by *Kuhlbrodt and Gregory* (2012) amounts to 0.11±0.01 m YJ^{-1}. Our median and its 90% confidence interval ~~amount~~ amounts to 0.12 m YJ^{-1} [0.10 to 0.14] as integral over the entire water depths, 0.14 m YJ^{-1} [0.12 to 0.15] for the upper 700 m and 0.10 m YJ^{-1} [0.08 to 0.11] below 700 m (Table ~~S3~~S4.1). The constant depends on the 3-D-pattern of heat redistribution with the main contribution arising from the upper 700 m. This pattern depends in equal measure on the individual model and on the scenario for a given model (see Tables ~~S3~~S4.1 and ~~S3~~S4.2). 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%.

7 Discussion and Summary

~~With observational estimates being~~ The present study aims to complement our quantitative understanding of thSLR using CMIP5 results. Firstly, based on CMIP5 temperature and salinity data for a range of scenarios, we calculate a compilation of thermal expansion time series that comprise 30% more simulations than currently published within CMIP5. Our results indicate that previous CMIP5 multi-model ensemble estimates by *Church et al.* (2013a) have been robust, despite being based on 30% less models than used here.

Secondly, we quantify the thSLR contribution from the entire ocean depth in order to complement observational estimates that are primarily available for the upper ocean layers ~~and~~ down to 700 m (cf. *Domingues et al.*, 2008). Sparse observational evidence points to non-significant contributions to global mean thSLR from depths below 2000 m during 2005 to 2013 (*Llovel et al.*, 2014)~~, our results show that estimates of thSLR for~~ . Our results suggest that 21^{st} century thSLR estimates derived solely based on observational estimates from the upper 700 m would have to be ~~augmented on average by 36±9% (cf. *Domingues et al.*, 2008) and for the~~ 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 ~~by 15±6%~~ 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 ~~be considered for a global sea level budget~~1.31). In fact, our results indicate that half (50%) of the thSLR contributions ~~comes~~ can come from depths below ~~480~~ 570 m in the *historical* ~~runs~~ simulations and from slightly shallower levels (490±90 m) in the future RCP scenarios~~—~~, when averaged across the last 20 years of the scenario period (Fig. 5 ~~).~~

~~Half of the OHU can be attributed to ~~~and Table S5). Here, we define "half-depth" as the median of the depths distribution of OHU and thSLR contributions. We find that those "half-depths" are located within the thermocline. The OHU half-depth is around 100 m deeper ~~layers than of thSLR~~ than the thSLR half-depth due to nonlinearities in the seawater equation of state (not shown). Furthermore, ~~our results show that those "~~ those half-depths ~~" are~~ seem to be deeper in the southern than in the northern hemisphere because the layers above 2000 m are warmer in the northern hemisphere and less stratified below the main thermocline~~than the water masses in the southern hemisphere~~. The recent study by ~~?~~ *Durack et al.* (2014b) corroborates the relevance for hemispheric partitioning of model results to adjust for the poor sampling of the Southern Hemisphere's upper ocean ~~temperature. The depths where the mean of thSLR originates are ~~~temperatures. The mean depths are 100 ~~–200 m below the median depths (Fig. 5)~~ (300) m lower than the medians for the idealized (RCP) scenarios and 400 m for the *historical* scenario (Table S5). This indicates a positive skewness of the vertical distribution of ~~thSLR~~ thermal expansion because of its long tail towards depths below 700 m~~with the exception~~. For climatological temperature and salinity profiles (*Boyer et al.*, 2013), the difference between the mean (1200 m) and median (700 m) depth in is even greater compared to our model diagnostic results of the *historical* scenario~~: For the period 1986-2005 the~~. This can be explained by a reduced vertical temperature gradient within the main thermocline and a weaker stratification above the main thermocline induced by the absent end of 20^{th}-century warming in the climatological profiles. In case of the *historical* scenario, the difference between mean and median depth of thermal expansion shows that the amount of thSLR due to the externally-forced warming during the period 1986−2005 is small compared to the underlying interannual variability ~~because of~~ that is generated by the internal variability of ocean dynamics (*Palmer et al.*, 2009; *Palter et al.*, 2014). However, ~~all~~ these findings highlight ~~that the contribution to the present~~ the importance of the thSLR contribution from deeper ocean layers (e.g. *Palmer et al.*, 2011). Present and projected thSLR is not predominantly (>50%) attributable to the layers above the depth of 700 m, the depth most observational based estimated are still limited to (*Domingues et al.*, 2008; *Ishii and Kimoto*, 2009; *Levitus et al.*, 2012).

Lastly, in order to support the development of surrogate methods to project thermal expansion, we calibrate two simplified parameterisations against CMIP5 estimates of thSLR: One parameterisation is suitable for scenarios where hemispheric ocean temperature profiles are available (1.5-D approach), the other, where only the total OHU (0-D approach) is known. Generally, expanding a mass of warm, salty subtropical water is more efficient for a given temperature increase than a mass of cold, fresh subpolar water for the same temperature increase. In upper tropical waters a warming signal ~~perists~~ persists longer than in upper high-latitude waters due to the weaker, temperature dominated stratification in higher latitudes, except in the Southern Ocean around Antarctica where salinity changes play a fundamental role in determining the strength of stratification (*Bindoff and Hobbs*, 2013; *Rye et al.*, 2014). Our diagnosis of CMIP5 profiles confirms the large variations in α, the 3-D thermal expansion coefficient, due to strong meridional (not shown) and vertical density gradients originating from strong temperature gradients (see Eq. (~~see Figure~~ 2) ~~,~~ and Fig. 2). These strong vertical as well as meridional gradients in the thermal expansion efficiency raise the question whether simplified approaches that collapse either the merdional component (our 1.5-D simplification) or both dimensions (the 0-D approach) are sufficiently reliable. The introduced errors of ±5% (1.5-D) and ±9% ~~, respectively,~~ (0-D) compared to the CMIP5 data based on the entire ocean grid, suggest that the simplifications are sufficiently accurate for long-term SLR projections, when other uncertainties (land ice-sheet response, climate sensitivity or radiative forcing (e.g., *Hallberg et al.*, 2013) ~~tend to~~ dominate the final result.

8 List of Figures and Tables

Table 1. Median and its 90% confidence interval for projections of global mean ~~(0-D)~~ thSLR (in m) in ~~2046-2065 and 2081-2100 relative to 1986-2005~~ 2046−2065 and 2081−2100 relative to 1986−2005 for the four RCP scenarios.

Figure 1. Time series of observed and simulated global mean yearly ~~sea level~~thSLR (in cm). (a/) Simulated ~~thermosteric sea level~~ thSLR (*zostoga*~~, in cm~~) relative to year ~~1990~~ 1900 for seven CMIP5 scenarios: *historical* (31/47), *1pctCO2* (19/32), *abrupt4xCO2* (17/30), *rcp2.6* (18/26), *rcp4.5* (27/40), *rcp6.0* (13/20), *rcp8.5* (27/40); the ratio in brackets indicates the number of models of published (solid lines) *zostoga* and recalculated (dashed lines) *zostoga* in this study based on simulated temperature and salinity fields. Bars indicate the thSLR of the four RCP-scenarios in year 2100 relative to ~~year 1900~~ 1986-2005 (see also Table 1). (b/) Observed contribution to yearly thermosteric sea level ~~(in cm)~~ of the upper 700 m by *Domingues et al.* (2008), *Ishii and Kimoto* (2009) and *Levitus et al.* (2012) relative to year 1961 and corresponding simulated time series of the *historical* and *rcp8.5* scenarios, whereby the solid light (dark) grey lines represent the model mean (median). Observed contribution to yearly thermosteric sea level (in cm) from layers (c/) between 700-2000 m by *Levitus et al.* (2012) and *Roemmich and Gilson* (2009) and (d/) below 2000 m by *Purkey and Johnson* (2010). Corresponding simulated time series are indicated as in (b/).

Figure 2. Global mean vertical profiles for all models of *historical* in year 1900 (upper panels, (a/)−(c/))~~and of~~ , *historical* in year 2005 relative to year 1986 (d/), *rcp8.5* in year 2100 relatitve to the *historical* mean over 1986 to 2005 (lower panels, (~~d~~e/)−(~~f~~g/)) and *abrupt4xCO2* within the furst year (h/): (a/) potential temperature (in degC, 0 to 20), (b/) salinity (in ~~psu~~PSS-78, 32 to 36) and (c/) thermal expansion coefficient α (in 10^{-4} degC^{-1}, 1.2 to 2.8); (d/) thermal expansion per layer (in mm/m, -0.1 to 0.2), (e/) temperature deviation (in degC, -1 to 5), (~~e~~f/) thermal expansion per layer (in mm/m, -0.2 to 1.2) and (~~f~~g/) thermal expansion coefficient α (in 10^{-4} degC^{-1}, 1.2 to 2.8), (h/) thermal expansion per layer (in mm/m, -0.2 to 1.2). Observed profiles (grey lines) are based on the Argo-data as an average over the period 2005 to 2013, except for the ~~temperature deviation in (d/) and corresponding~~ thermal expansion in (~~e~~d/). Model outliers are indicated in (a/).

Figure 3. Model median percentage contribution to global mean thSLR for the entire water column from depths below 700 m (light grey) and below 2000 m (dark grey) for the *historical* scenario, for projections for the four RCP scenarios and the two idealized CO_2 scenarios derived from Equation 2. Whisker plots quantify the temporal average distribution of the contribution to thSLR of the first 20 years, the entire time series and the last 20 years, respectively: 2006−2025 / 2006−2100 / 2081−2100 for RCPs (a/)−(d/); 1901−1920 / 1900−2005 / 1981−2005 for the *historical* scenario (e/); and 1−20 / 1−100 / 81−100 for the *1pctCO2* and *abrupt4xCO* scenarios (f/),(g/). Bars and whiskers represent the 25-75% and 5-95% uncertainties of the median, respectively; the central mark of the bar indicates the model median, the asterisk the model mean.

Figure 4. Whisker plots of percentage thermal expansion from the layers between 700-2000 m, below 700 m and below 2000 m, respectively, relative to the total thermal expansion integrated over the entire water column, for seven scenarios. Thermal expansion estimates are derived from Equation 2 (left bar) and Equation 3 (right bar) used in simpler climate models (here with the optimized calibration parameters in Table S2) and based on (a/) globally, (b/) northern and (c/) southern hemispherically-averaged vertical potential temperature profiles, followed by a temporal averaging over the entire time series (see Fig. 3). Bars and whiskers represent the ~~25-75% and 5-95~~25−75% and 5−95% uncertainties of the median, respectively; the central mark of the bar indicates the model median, the asterisk the model mean. The number of models available for these statistical estimates are crosses on the left of the box, at which crosses above and below the whiskers indicate model outliers.

Figure 5. ~~Depth~~ CMIP5 multi-model mean depth and standard deviation (in m) where the ~~multi-model ensemble~~ individual model mean (left bar) and median (right bar) depth of thSLR originates for the four RCP scenarios, as well as the historical scenario and the two idealized CO_2-forcing scenarios. Thermal expansion estimates are derived from Equation 2 based on (a/) globally, (b/) northern and (c/) southern hemispherically-averaged vertical potential temperature profiles, followed by a temporal averaging over the last twenty years (see Fig. 3 and 4). Table ~~S4~~ S5 summarizes the estimates.

Table 1. Median and its 90% confidence interval for projections of global mean ~~(0-D)~~ thSLR (in m) in ~~2046-2065~~ 2046−2065 and ~~2081-2100~~ 2081−2100 relative to ~~1986-2005~~ 1986−2005 for the four RCP scenarios.

period scenario	1986-2005	2046-2065	2081-2100	2100	2081-2100 IPCC-AR5
historical	0.04 [0.01 to 0.07]				
rcp2.6		0.10 [0.06 to 0.13]	0.15 [0.10 to 0.20]	0.20 [0.15 to 0.20]	0.14 [0.10 to 0.18]
rcp4.5		0.11 [0.08 to 0.14]	0.19 [0.14 to 0.24]	0.23 [0.19 to 0.26]	0.19 [0.14 to 0.23]
rcp6.0		0.10 [0.08 to 0.14]	0.20 [0.15 to 0.25]	0.26 [0.20 to 0.29]	0.19 [0.15 to 0.24]
rcp8.5		0.13 [0.10 to 0.16]	0.28 [0.22 to 0.34]	0.32 [0.25 to 0.40]	0.27 [0.21 to 0.33]

9 Authors Contribution

All authors contributed designing and writing the text. KL conducted the analysis and drafted the manuscript.

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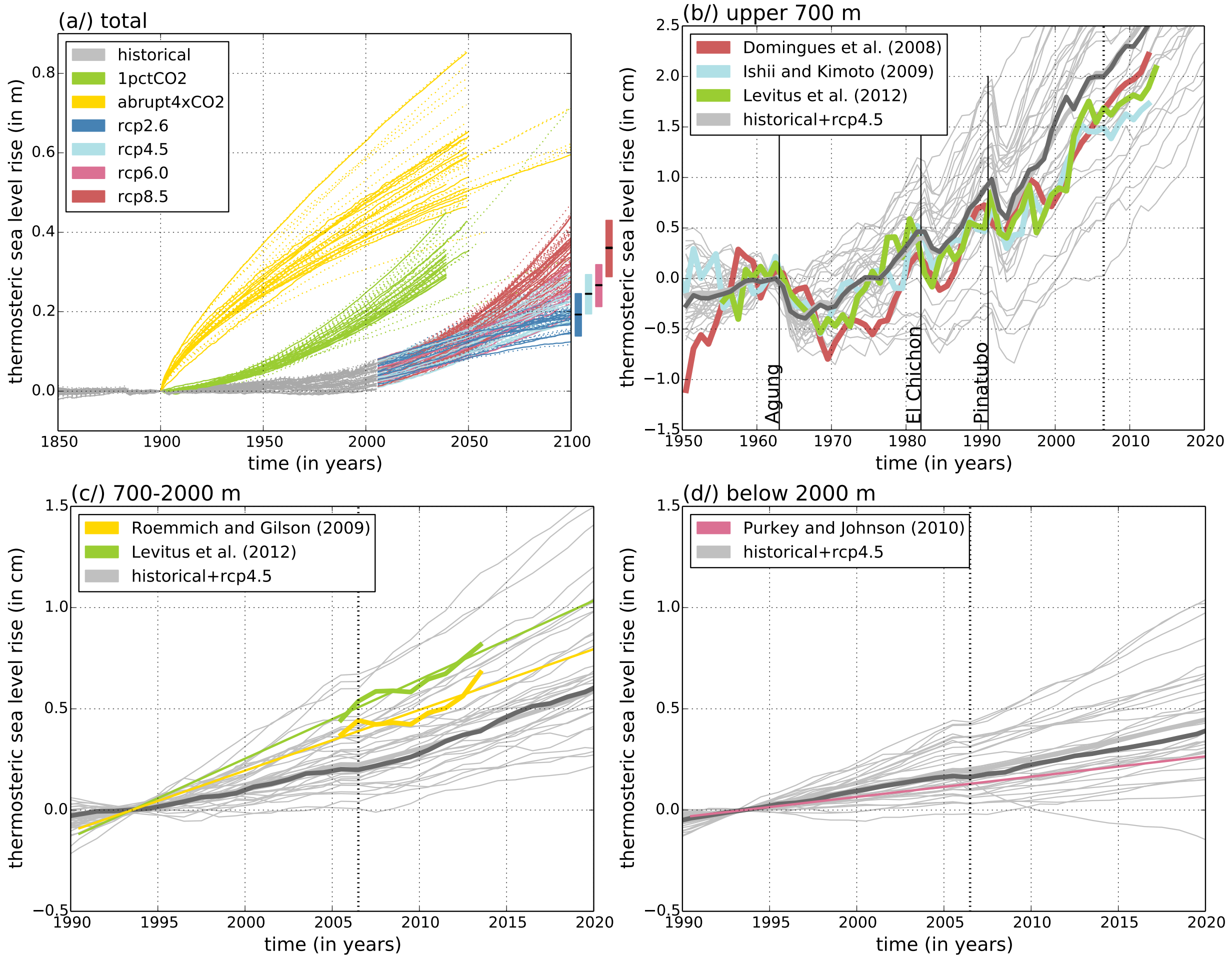

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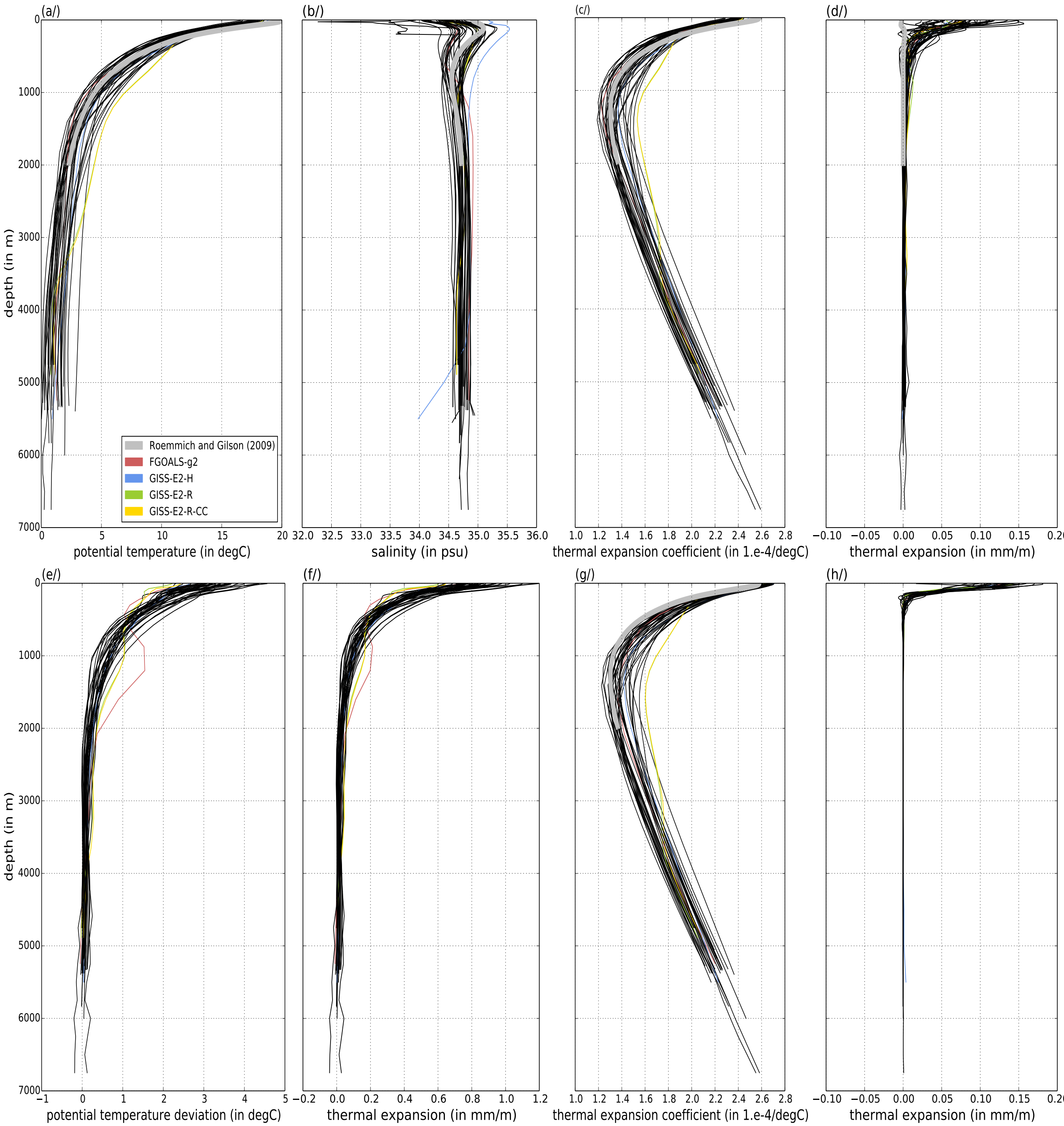

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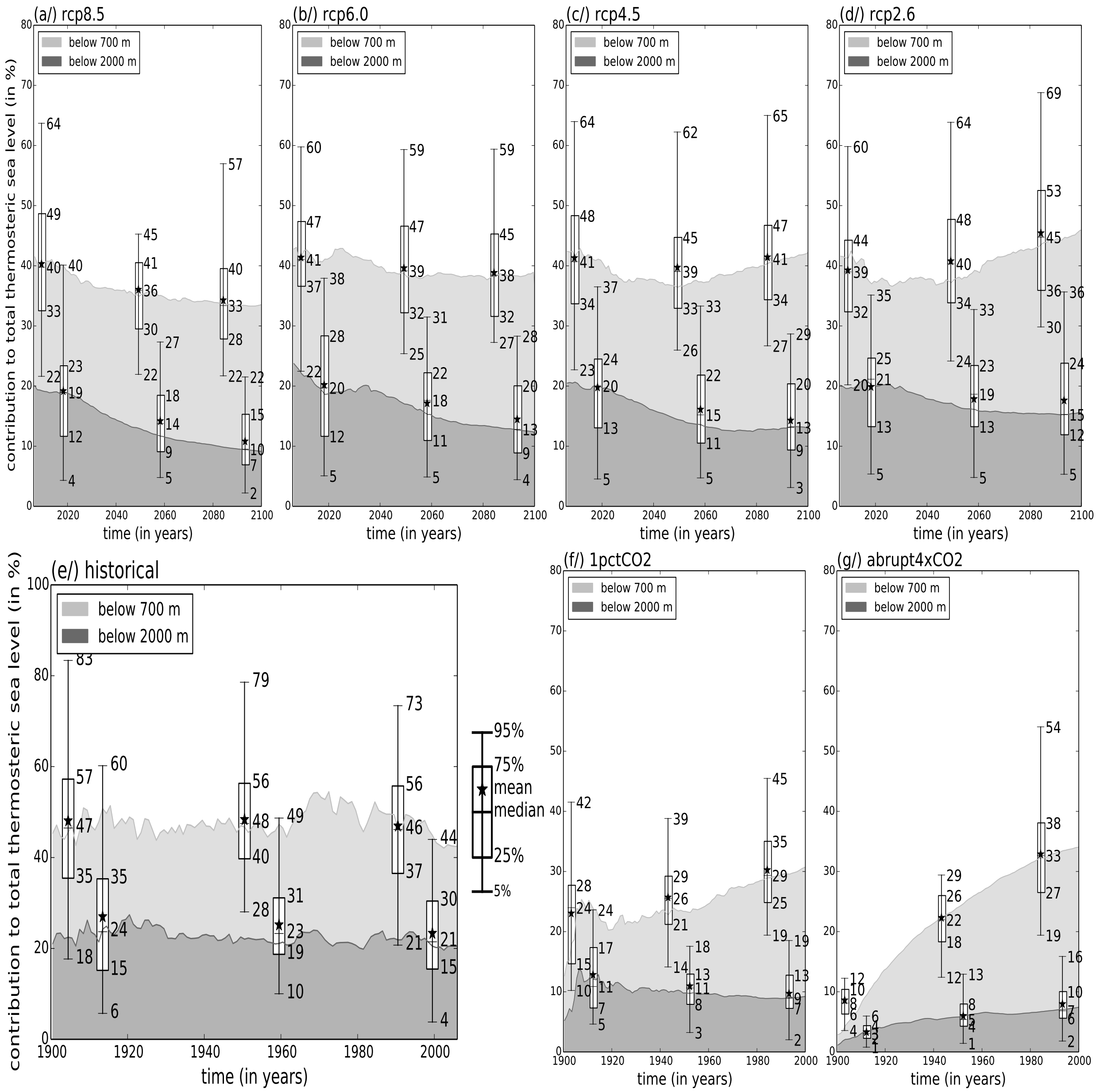

Figure 3. Model median percentage contribution to global mean thSLR for the entire water column from depths below 700 m (light grey) and below 2000 m (dark grey) for the *historical* scenario, for projections for the four RCP scenarios and the two idealized CO_2 scenarios derived from Equation 2. Whisker plots quantify the temporal average distribution of the contribution to thSLR of the first 20 years, the entire time series and the last 20 years, respectively: 2006−2025 / 2006−2100 / 2081−2100 for RCPs (a/)−(d/); 1901−1920 / 1900−2005 / 1981−2005 for the *historical* scenario (e/); and 1−20 / 1−100 / 81−100 for the *1pctCO2* and *abrupt4xCO* scenarios (f/),(g/). Bars and whiskers represent the 25-75 % and 5-95 % uncertainties of the median, respectively; the central mark of the bar indicates the model median, the asterisk the model mean.

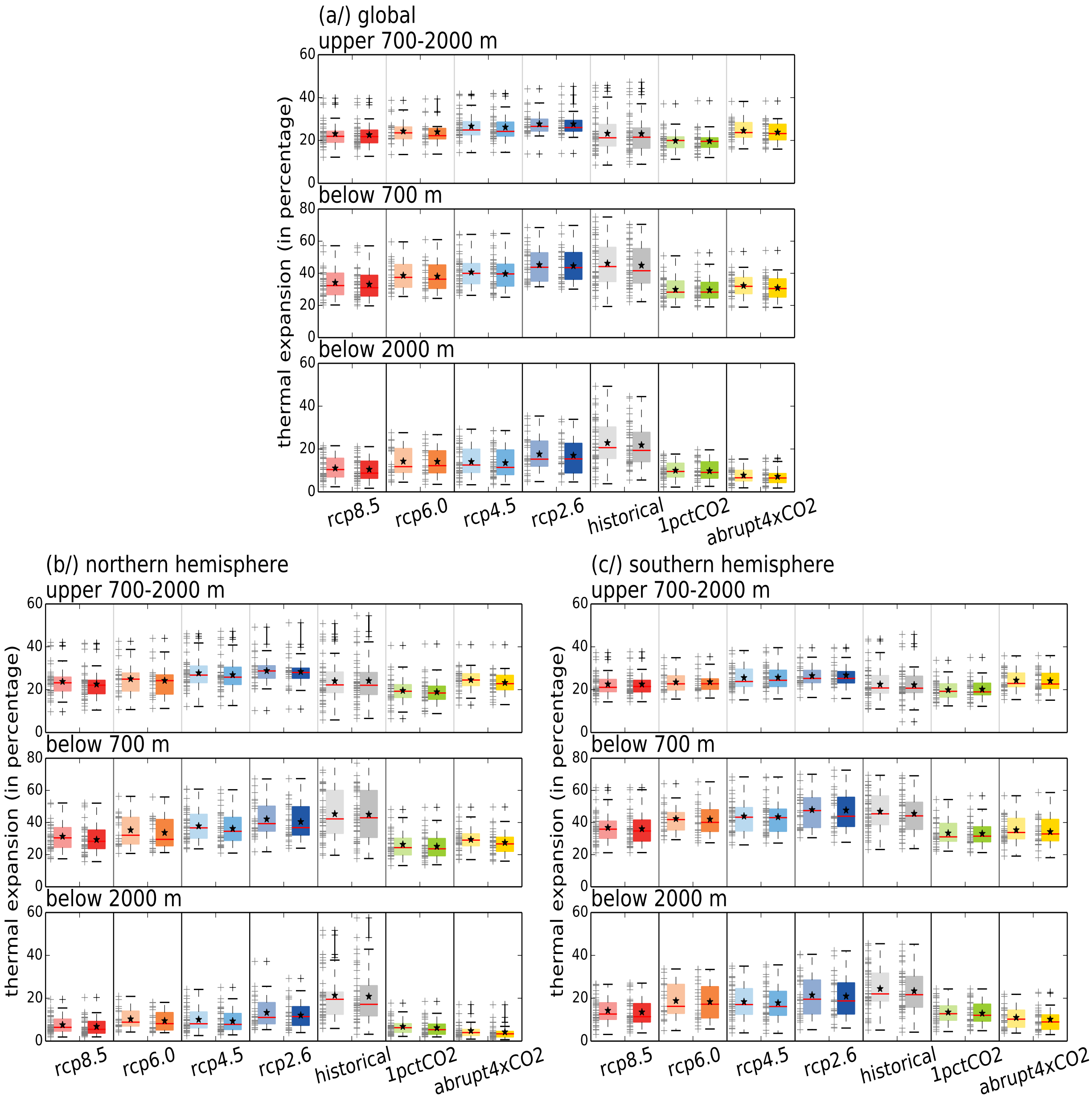

Figure 4. Whisker plots of percentage thermal expansion from the layers between 700-2000 m, below 700 m and below 2000 m, respectively, relative to the total thermal expansion integrated over the entire water column, for seven scenarios. Thermal expansion estimates are derived from Equation 2 (left bar) and Equation 3 (right bar) used in simpler climate models (here with the optimized calibration parameters in Table S2) and based on (a/) globally, (b/) northern and (c/) southern hemispherically-averaged vertical potential temperature profiles, followed by a temporal averaging over the entire time series (see Figure Fig. 3). Bars and whiskers represent the 25-75 % and 5-95% uncertainties of the median, respectively; the central mark of the bar indicates the model median, the asterisk the model mean. The number of models available for these statistical estimates are crosses on the left of the box, at which crosses above and below the whiskers indicate model outliers.

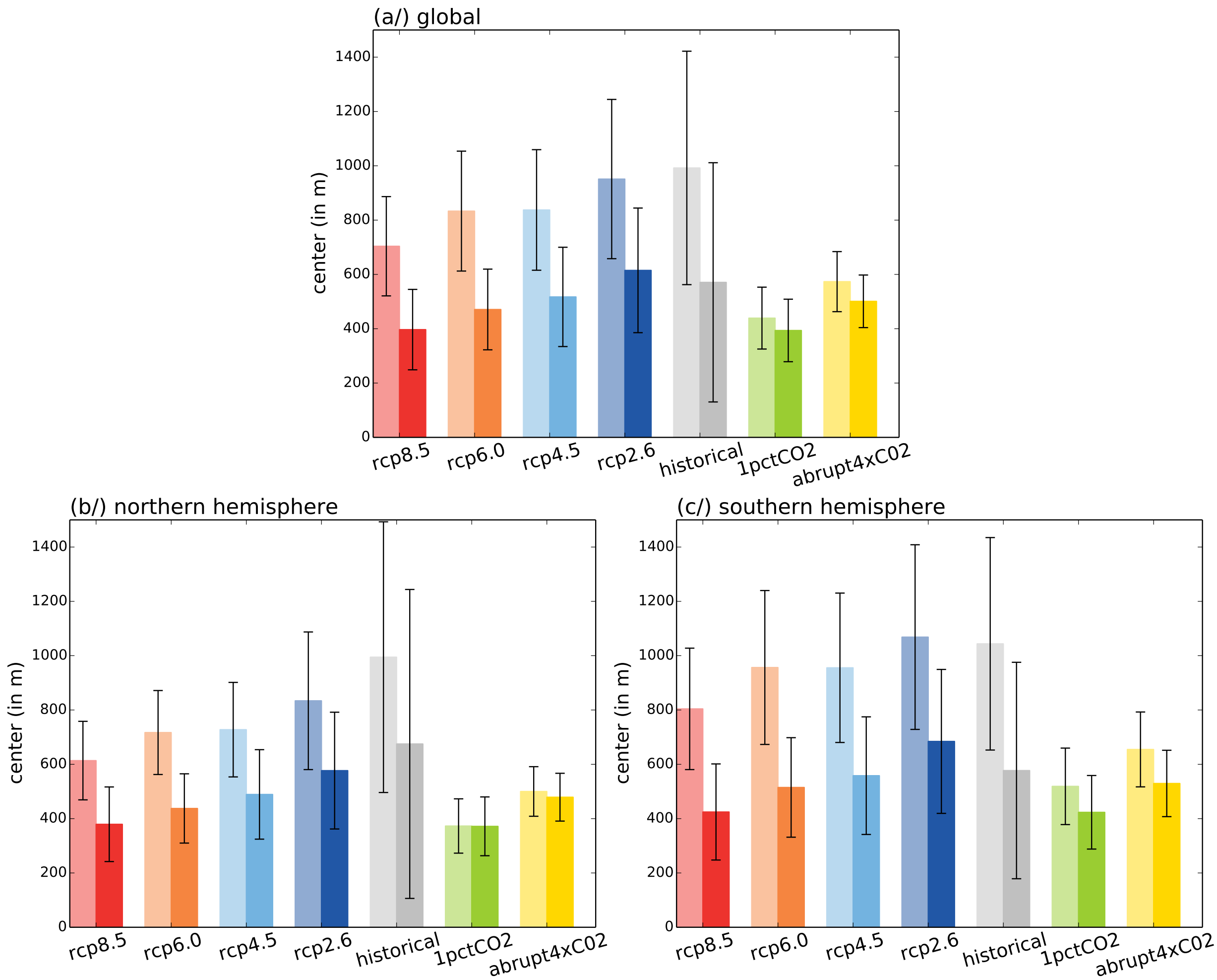

Figure 5. ~~Depth~~ CMIP5 multi-model mean depth and ~~standard deviation~~ SD (in m) where ~~the multi-model ensemble~~ individual model mean (left bar) and median (right bar) depth of thSLR originates for the four RCP scenarios, as well as the historical scenario and the two idealized CO_2-forcing scenarios. Thermal expansion estimates are derived from Equation 2 based on (a/) globally, (b/) northern and (c/) southern hemispherically-averaged vertical potential temperature profiles, followed by a temporal averaging over the last twenty years (see Fig. 3 and 4). Table ~~S4~~ S5 summarizes the estimates.

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