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An update on the thermosteric sea level rise commitment to global warming

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Abstract

The equilibrium thermosteric sea level rise caused by global warming is evaluated in several coupled climate models. The thermosteric sea level rise is found to be well approximated as a linear function of the mean ocean temperature increase in the models. However, the mean ocean temperature increase as a function of the mean surface temperature increase differs between the models. Our models can be divided into two branches; models with an Atlantic meridional overturning circulation that increases with warming have large mean ocean temperature increases and vice versa. These two different branches give estimates of the equilibrium thermosteric sea level rise per degree of surface warming that are respectively 98% and 21% larger than the estimate given in the IPCC Fifth Assessment Report. Our estimates of the equilibrium thermosteric sea level rise are also used to infer an equilibrium sea level sensitivity, a parameter akin to the often used equilibrium climate sensitivity metric.

1. Introduction

Sea level rise is a serious consequence of anthropogenic climate change, having the potential to increase the cost of coastal flooding damage by orders of magnitude already toward the end of the century (Vousdoukas *et al* 2018). These immediate concerns as well as the great computational cost of running long integrations with global climate models has lead much of the sea level research to focus on the time period until the end of the century (Church *et al* 2013). However, it is well known that sea level rise will continue for centuries even if the increase in global surface temperature is halted, because of the long time scales associated with an equilibration of the ocean and the ice sheets (Meehl *et al* 2005, Levermann *et al* 2013).

The IPCC Fifth Assessment Report (AR5) based its assessment of the equilibrium sea level commitment to global warming on the work by Levermann *et al* (2013), where they found a committed sea level rise of 2.3 m per °C of surface warming of which 0.42 m$°C^{-1}$ was ascribed to thermosteric sea level rise. The assessment by Levermann *et al* (2013) of the equilibrium thermosteric sea level rise was in turn based on integrations of climate models of intermediate complexity that were first presented in AR4 (Solomon *et al* 2007). These numbers for the thermosteric sea level rise commitment to global warming have thus not been updated for a long time, and they are based on models that are far more idealized than our current generation of climate models. The aim of this paper is to present an updated assessment of the thermosteric sea level rise commitment to global warming, using an analysis of data from more comprehensive climate models that have been run to steady state.

Integrations of coupled climate models in warming scenarios to steady or near steady state are rare, so to assemble a variety we have used data from experiments where different forcings are applied to achieve the warming. We have also mixed data from models where we have access to the full data sets, with others where we only know reported mean temperature increases in the atmosphere and ocean. The methods section details the models used, and how these different data sources can be used to get a coherent picture of thermosteric sea level rise projections.

The forcing as well as the models used in our analysis are thus all rather different, but as we will see in the result section they all have a similar equilibrium thermosteric response to ocean warming. A key reason for this is that ocean warming in coupled climate models appear to often be quite uniform with depth. This was first found by (Li *et al* 2013) in an integration forced with $4xCO_2$, and later by Hieronymus *et al* (2019) in several integrations forced with changes in the oceanic background diffusivity. The thermosteric sea level rise caused by a depth independent heating is easy to estimate, as we show in the methods section of this paper. Moreover, the fact that many different models show a depth independent heating can be utilized to simplify the estimates of equilibrium ocean heat uptake, because one can then expect the mean ocean temperature increase to be a simple function of the surface temperature increase.

The uncertainty in future sea level rise is very large on long time scales owing to uncertainties both in the response of the climate system to greenhouse gas emissions and in future emission pathways. For the equilibrium response of the surface air temperature to greenhouse gas emissions this uncertainty has often been discussed using the metric of the equilibrium climate sensitivity. That is, the equilibrium surface air temperature change in °C associated with a doubling of the atmospheric CO_2 concentration. We believe that a similar framework would be useful also for the discussion of future sea level rise. The current paper introduces such a framework for the thermosteric sea level rise, and it is a step toward the introduction of a sea level sensitivity metric.

2. Methods and models

2.1. Models

The climate model integrations we consider in our analysis are: the steady state integration with $2xCO_2$ of CCSM3 by Danabasoglu and Gent (2009) hereafter referred to as DG09, the $4xCO_2$ integration of ECHAM5/MPIOM by (Li *et al* 2013), which is hereafter referred to as L13, the CCSM3 simulation of the transient climate evolution of the last 21 000 years (TraCE) (Liu *et al* 2009), which is forced by orbital as well as greenhouse gas and melt water forcing and the six steady state simulations with CM2G by Hieronymus *et al* (2019), where climate change is induced by changing the ocean background diffusivity. Those simulations are referred to as H19 hereafter. These are all integrations known to the author of this paper, where coupled climate models are run to a near steady state in both a baseline and a warming scenario, but it might not be an exhaustive list of all available ones.

From the L13 and DG09 we only have the reported mean ocean and atmosphere temperature increases, while we have access to the gridded variables from TraCE and H19. For the TraCE simulations we have looked at the difference between two periods with very small ocean heat uptakes, occurring 20 kyr BP and 1 kyr BP. That is, our estimate is basically a computation of the thermosteric sea level rise occurring from the last glacial maximum (LGM) to the preindustrial.

2.2. Methods

We evaluate the thermosteric sea level rise following Griffies and Greatbatch (2012). The ocean models used here are all employing the volume conserving Boussinesq approximation, and the thermosteric effect is therefore calculated indirectly from the model's potential temperature (T), salinity (S) and density (ρ) fields using the equation of state from Jackett and McDougall (1995).

The sea level rise is estimated according to equations (75) and (219) of Griffies and Greatbatch (2012), giving

$$\begin{aligned}\frac{\partial\eta_{non-bouss\ steric}}{\partial t} &\approx -\frac{V}{A}\frac{\partial\ln(\langle\rho\rangle)}{\partial t}\\ &\approx -\frac{V}{A}\left(-\alpha_{eff}\frac{\partial\langle T\rangle}{\partial t}+\beta_{eff}\frac{\partial\langle S\rangle}{\partial t}\right.\\ &\left.+\frac{1}{(\rho c_{sound}^2)_{eff}}\frac{\partial\langle p\rangle}{\partial t}\right)\\ &\approx -\frac{V}{A}\left(-\alpha_{eff}\frac{\partial\langle T\rangle}{\partial t}+\langle\beta\rangle\frac{\partial\langle S\rangle}{\partial t}\right),\end{aligned} \quad (1)$$

where $\eta_{non-bouss\ steric}$ is the steric sea level change that is not directly quantified by the Boussinesq models, V is the ocean volume, A is the ocean surface area, $\langle\rangle$ indicates an average over the whole ocean volume, $\alpha = -\rho^{-1}\partial_T\rho$ is the thermal expansion coefficient, $\beta = \rho^{-1}\partial_S\rho$ the haline contraction coefficient, c_{sound} is the speed of sound, p is pressure and the eff subscript indicated that these are effective or best-fit parameters. The ocean surface area and volume are both taken from Eakins and Sharman (2010) in all our calculations, to minimize the influence of different grids being used in different models. The second row of equation (1) shows that the non-Boussinesq steric effect can be divided into a thermosteric part, a halosteric part and a third term that is proportional to the mean pressure change. The mean pressure change is small as long as the change in ocean mass is small, and this part is hereafter ignored. In the third row we also approximate β_{eff} with $\langle\beta\rangle$, since fractional changes in β in the ocean are small compared to those in α (Hieronymus and Nycander 2013). For example, increasing T from 3 °C to 6 °C at $S = 35$ g kg^{-1} and $p = 2000$ dB increases α by 21%, while the same temperature change decreases β by only 1%.

To calculate the thermo- and halosteric sea level rise from oceanic T, S and ρ fields we integrate equation (1) in time giving

$$\ln(\langle\rho(t_2)\rangle) - \ln(\langle\rho(t_1)\rangle) \approx -\alpha_{eff}\Delta\langle T\rangle + \langle\beta\rangle\Delta\langle S\rangle, \quad (2)$$

where t_1 and t_2 are two points in time, Δ indicates the difference in a given variable between the times t_2 and t_1 and both $\langle\beta\rangle$ and α_{eff} are assumed to be constants. Equation (2) can be used to estimate α_{eff} from the output of a climate model where the ocean has taken up heat. The parameter α_{eff} links a mean ocean temperature change to a thermosteric sea level rise, so it is the parameter we need it to estimate the

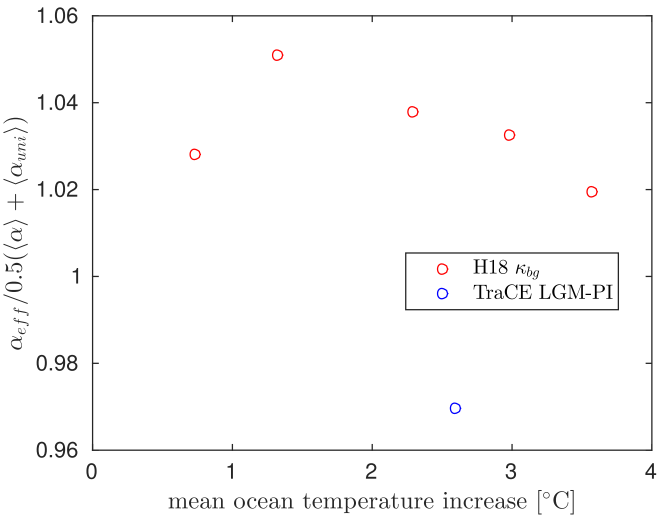

Figure 1. Comparison of α_{eff} estimated using equation (3) and calculated using equation (2). The estimates are done using T, S and p from the H19 and TraCE runs. α_{uni} here is defined as α after a uniform temperature increase (i.e. $\alpha_{uni} = \alpha(S, T + \Delta T, p)$).

thermosteric sea level rise in DG09 and L13. More generally, having a good approximation for α_{eff} is useful since one can then estimate the thermosteric sea level rise that would occur for a given value of $\Delta\langle T\rangle$.

The next step is therefore to derive an estimate of α_{eff} based on the current fields of T, S and p. L13 and H19 found the equilibrium ocean temperature increase to be relatively uniform with depth, as was discussed in the introduction. One might therefore presume that α_{eff} could be approximated as

$$\alpha_{eff} \approx \frac{\langle\alpha(S,\, T,\, p)\rangle + \langle\alpha(S,\, T + \Delta T,\, p)\rangle}{2}, \tag{3}$$

where $\langle\alpha(S,\, T,\, p)\rangle$ is evaluated with the current T, S and p field and $\langle\alpha(T + \Delta T)\rangle$ is evaluated by uniformly adding ΔT to the current T field, while keeping the S and p fields unchanged. A comparison of α_{eff} estimated using equation (3) and calculated using equation (2) is shown in figure 1. The figure shows that the approximation of α_{eff} is good to within about 5% in the TraCE and H19 experiments. The thermosteric sea level rise is a linear function of α_{eff} for a given ΔT (see equation (4) further down), so the same accuracy applies also to the sea level rise.

The ocean warming in H19 and TraCE is considerably less spatially uniform than that of the CO_2 induced warming in L13, while the degree to which the warming is uniform in DG09 is not known to us. A natural assumption, given that equation (3) is derived assuming a spatially uniform warming, is thus that equation (3) should be more accurate for pure CO_2 induced climate change than it is for that in the H19 and TraCE runs. Moreover, the large diffusivity changes in H19 and the strong freshwater forcing in TraCE are significantly outside of the range expected in coming climate change, and we therefore expect also future climate climate change to have an equilibrium warming that is more spatially homogeneous than that in the H19 and TraCE runs. The thermosteric sea level rise from our ongoing climate change can thus be approximated as

$$\Delta\eta_{thermo} \approx \frac{V}{A}\frac{\langle\alpha(S,\, T,\, p)\rangle + \langle\alpha(S,\, T + \Delta T,\, p)\rangle}{2}\langle\Delta T\rangle. \tag{4}$$

To complete this analysis we shall estimate the influence of uncertainties in the basic state. That is, we shall estimate the influence uncertainties in the preindustrial distribution of S, T and p has on our estimate of thermosteric sea level rise. To this end we have calculated $\langle\alpha\rangle$ from the preindustrial control runs of the seven Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor *et al* (2012)) models identified by Sen Goupta *et al* (2013) as having the smallest sea level drift. Figure 2 shows $\langle\alpha\rangle$ as a function $\langle T\rangle$ in those models. The individual models $\langle\alpha\rangle$ differ from the ensemble mean by a maximum of about 5%, and the difference between them is almost entirely owing to them having different $\langle T\rangle$ (the linear fit has a mean absolute residual of 4.7×10^{-7} °C^{-1} and $R^2 = 0.987$). The sea level rise a given, CO_2 forced, increase in $\langle T\rangle$ would give from the preindustrial can thus be estimated from equation (4) using an ensemble mean $\langle\alpha\rangle$ with an error of a few percent owing primarily to uncertainties in the real preindustrial value of $\langle T\rangle$, and secondarily to uncertainties in the estimate of α_{eff} owing to the approximations utilized in equation (3).

3. Results

The methods section establishes a simple connection between the thermosteric sea level rise and changes in the mean ocean temperature. Figure 3 shows the thermosteric sea level rise calculated from the near steady state integrations detailed in the data section as a function of the increase in mean ocean temperature.

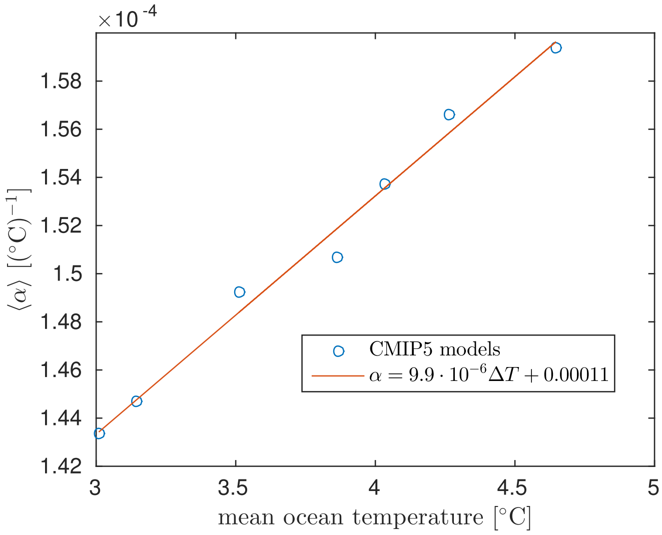

Figure 2. $\langle\alpha\rangle$ as a function $\langle T\rangle$ in the seven CMIP5 models with the smallest mean sea level drift in their preindustrial control runs: CMCC-CMS, GFDL-ESM2M, GFDL-ESM2G, HadGEM2-CC,IPSL-CM5A-LR,IPSL-CM5A-MR and MRI-CGCM3.

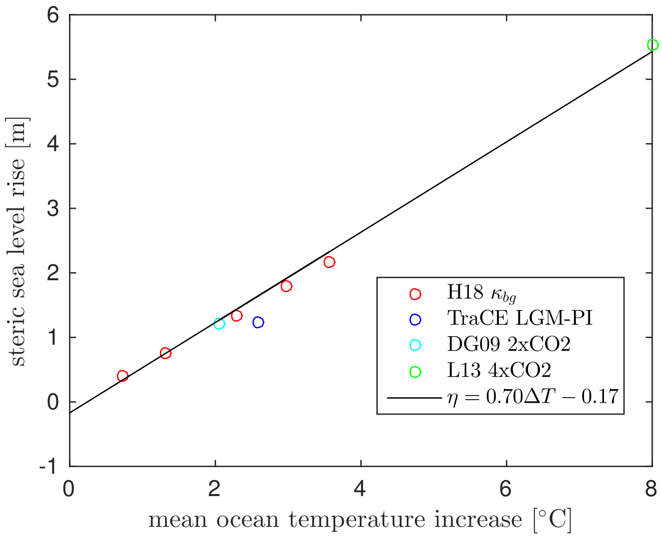

Figure 3. Thermosteric sea level rise as a function of mean ocean temperature increase in our near steady state integrations. The thermosteric sea level rise in L13 and DG09 is calculated from equation (4) using the ensemble mean $\langle\alpha\rangle$ from the CMIP5 models with the smallest mean sea level drift in their preindustrial control runs. The sea level rise in H19 is calculated directly from the first row of equation (1), since they have no mean salinity changes. The thermosteric sea level rise in TraCE is calculated from the difference between the total steric and halosteric term as in equation (2). V and A are assumed constant and equal in all integrations.

To test the various approximations derived in the methods section we calculate the sea level rise in the different integrations according to equations (1) and (2) when the S and T and p fields are known to us and from equation (4) when only $\langle \Delta T\rangle$ is known. The different methods agree rather closely on an equilibrium sea level rise of 0.7 m per °C of mean ocean warming. The biggest mismatch occurs for the TraCE simulation, and the difference is due to the colder volume mean temperature in the LGM ocean as compared with the preindustrial, which gives a smaller α_{eff}, see figure 2. Because of this obvious difference we excluded the TraCE simulation when fitting the line. The mean absolute residual excluding the TraCE simulation, but including the origin as a point, is 0.09 m and $R^2 = 0.996$. The residual for Trace is 0.40 m.

Another noteworthy point is that our estimate of the equilibrium sea level rise in L13 is 5.53 m, while the authors of L13 give an estimate of 5.8 m. This difference of slightly less than 5% is probably partly caused by our lack of knowledge of the actual T, S and p field in the integration, and of the approximations used in equation (3). However, the authors of L13 estimated their thermosteric sea level rise directly from an integration on the models native grid, so the A and V used in our and their estimate is also different. The small difference between our estimate and that in L13 is a

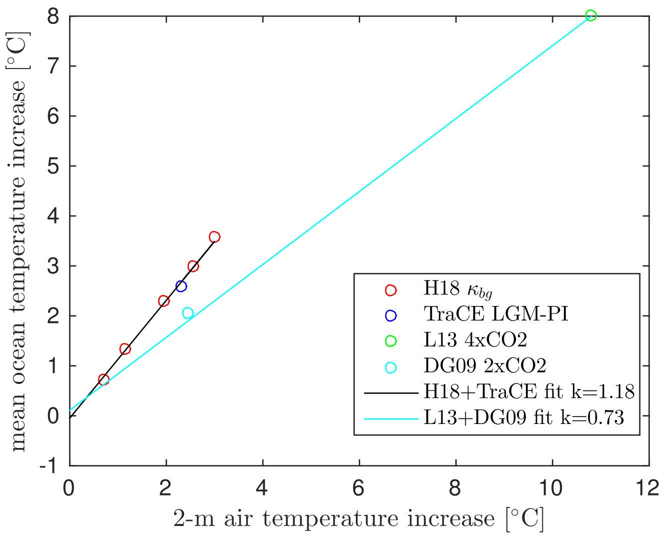

Figure 4. Volume mean ocean temperature increase as a function of the increase in the 2 m air temperature. The increase in the 2 m air temperature in TraCE is estimated from the SST increase using a linear relationship between increases in 2 m air temperature and SST found from H19 and L13, because of the large perturbations to the orography caused by the continental scale ice sheets of the LGM.

testament to the fidelity of the simple estimate given in equation (4), especially given that L13 is the integration considered here that has the biggest warming.

Having established that thermosteric sea level rise can be approximated as a linear function on the increase in mean ocean temperature in our climate models, the next step is to link the mean ocean temperature increase to the more easily knowable mean surface temperature increase. Figure 4 shows the mean ocean temperature increase as a function of the increase in the 2 m air temperature in our different integrations. The 2 m air temperature for TraCE is estimated as $\Delta T(2\ \mathrm{m}) = 1.25\Delta\mathrm{SST}$, a regression derived from the H19 and L13 runs that models $\Delta T(2\ \mathrm{m})$ as a function of ΔSST in those simulations with errors smaller than 0.06 °C. This is done because of the large perturbations to the orography caused by the continental scale ice sheets of the LGM, which would otherwise affect the comparison of 2 m temperature.

There are two clearly distinguishable branches of ocean heat uptake in figure 4. The uptake is much larger in the branch consisting of H19 and TraCE than in that with DG09 and L13, where the warming is induced solely by CO_2 increases. The branch consisting of the TraCE and H19 simulations is unlikely to be a good analogue for our current warming period, where the warming is forced primarily by emissions of greenhouse gases. However, the two CO_2 induced warming runs also have their deficiencies. There is, for example, no addition of melt water from ice sheets in either of them even though there is considerable warming in both of them. Recent research has shown a strong influence of melt water forcing on the transient evolution of coupled climate models (Golledge *et al* 2019). We will come back to what distinguishes these two branches in terms of changes in the general circulation in the discussion and conclusions section.

The thermosteric sea level rise is 0.83 m per °C of surface warming in the branch with the higher ocean heat uptake and 0.51 m per °C of surface warming in that with the lower. Figure 5 shows the thermosteric sea level rise in these two branches as a function of increases in mean surface air temperature, and also the spread induced by the uncertainty in α_{eff}. The spread owing to uncertainties in α_{eff} is here assessed by calculating the sea level rise from equation (4) using all seven near steady state preindustrial control simulations from the CMIP5 models in the calculation of α_{eff}, instead of just using the ensemble mean. The differences in thermosteric sea level rise that is due to the existence of the two branches is much larger than that due to uncertainties in the value of the preindustrial α_{eff}. The problem of pinning down the equilibrium thermosteric sea level commitment of global warming is thus essentially a problem of determining the real oceans equilibrium temperature response to global warming, a task that will ultimately require long integrations with coupled climate-ice sheet models.

4. Discussion and conclusions

New estimates of the equilibrium thermosteric sea level commitment of global warming was derived from an analysis of near steady state integrations of several coupled climate models with different forcing agents causing the global warming. All models are reasonably consistent with an equilibrium thermosteric sea level rise of 0.7 m per °C of mean ocean warming, starting from a preindustrial basic state. However, the relationship between the mean surface air temperature increase and the mean ocean temperature increase

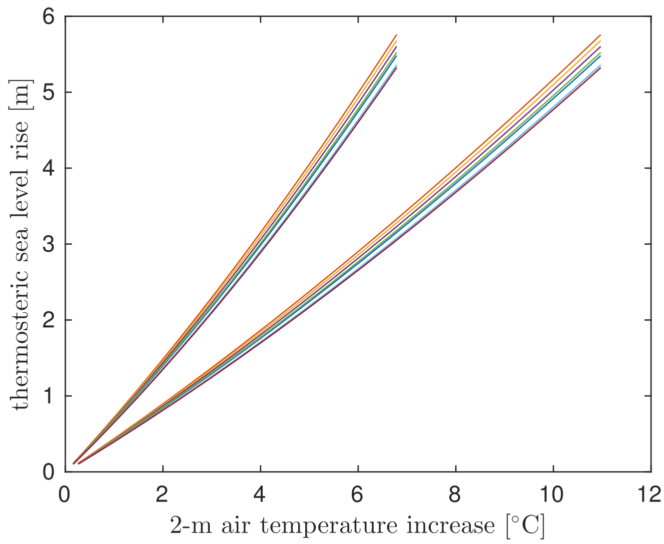

Figure 5. Thermosteric sea level rise as a function of the increase in surface air temperature for the two branches of ocean heat uptake. The sea level rise is calculated according to equation (4) using either $\langle T \rangle = 1.18T\,(2\text{ m})$ or $\langle T \rangle = 0.73T\,(2\text{ m})$. The seven different lines in each branch represent $\alpha' s$ calculated from the seven least drifting CMIP5 preindustrial control integrations.

showed two distinct branches leading to a projected thermosteric sea level rise of either 0.83 m or 0.51 m per °C of surface warming. Both branches give a considerable upward revision of the previous estimate of 0.42 m per °C of surface warming derived by Levermann *et al* (2013), based on work from AR4 (Solomon *et al* 2007), that was used in AR5 (Church *et al* 2013). The higher value derived here is also firmly outside of the range of 0.2–0.63 m°C^{-1} given by Levermann *et al* (2013).

The branch with the higher ocean heat uptake is unlikely to be a good analogue for our current warming period since the warming in H19 is due to artificially increasing the ocean mixing, while that in TraCE has orbital and freshwater forcing that is very different from today's. However, the TraCE simulation is the only warming simulation considered here that actually has a freshwater influx to the ocean from melting ice sheets. Every realistic warming scenario of the amplitudes considered here would be associated with a strong melt water flux into the ocean, although not as great as that in TraCE since the our planet's current ice sheets contain less water than those we have lost since the LGM did. Levermann *et al* (2013), for example, modelled a near complete disappearance of the Greenland ice sheet for a global surface temperature increase of 2 °C. Thus, even though the experiments in the lower heat uptake branch are clearly our best analogous for the ongoing climate change, neither of our integrations have all the relevant forcing. This problem can ultimately only be resolved by integrating more and more complex climate models to steady state. What we can do already today, however, is to look at changes in the general circulation in the different integrations and see whether any of those could explain the differences.

A good candidate for such a change is the Atlantic meridional overturning (AMOC) amplitude. Our two different branches of ocean heat uptake have markedly different AMOC changes per °C of warming. DG09 report a decrease in the AMOC amplitude of 14%, while L13 report a decrease in the AMOC of 46%. The AMOC decrease per °C of warming in these CO_2 induced warming simulations is thus very similar. Moreover, the AMOC in TraCE is reported to increase by 46% (Liu *et al* 2009), while the AMOC in the H19 simulation with the ocean warming that is closest to that in TraCE increased by 39%, so these simulations also have a similar AMOC change per °C of warming. Thus, the mean ocean temperature increases more than the mean surface temperature in the simulations where the AMOC amplitude increases, and vice versa. The AMOC is responsible for the spreading of the relatively warm North Atlantic Deep Water (NADW), and a strong AMOC is typically a deep AMOC (Marshall *et al* 2017). A deeper and stronger AMOC is thus consistent with an increase in the volume of warm NADW at the expense of that of cold Antarctic deep water, which could explain the higher equilibrium temperature increases in the integrations with increasing AMOCs. The relationship between the AMOC amplitude and the ocean heat uptake is, however, complex, and a weakening of the overturning has been seen to promote ocean heat uptake in transient simulations (Krasting *et al* 2016). The issue is also complicated by the fact that the AMOC just like the ocean heat uptake are emergent properties, and can thus both influence and be influenced by the each other.

Not much is known about the equilibrium response of the AMOC to global warming. The transient response of the AMOC to melt water additions in the Northern Hemisphere is a decreasing amplitude (Jungclaus *et al* 2006). However, the equilibrium response to such an addition is not known, and neither is the response to significant melt water additions from Antarctica. There is some evidence from idealized models as well as physical reasoning that the AMOC amplitude should increase with surface warming (see e.g. Toggweiler and Russell (2008), Jansen (2017) and Jansen *et al* (2018)), while the results of DG09 and L13 suggest that it should decline. It thus appear that some support for the AMOC response in both our branches can be found from earlier experiments and theory. Moreover, the AMOC in our current generation of climate models is strongly dependent on parametrized processes (Saenko 2006, Jayne 2009, Marshall *et al* 2017, Hieronymus *et al* 2019), whose fidelity in modeling equilibrium climate change is hard to assess. In conclusion, even though we consider the lower branch more plausible than the upper, one should also consider that the lower branch could need an upward revision if the AMOC reduction with global warming is found to be overestimated by those models.

The equilibrium climate sensitivity to a doubling of CO_2 expressed as the surface air temperature change in °C associated with a doubling of the atmospheric CO_2 concentration is an often used climate metric (Gregory *et al* 2004, Andrews *et al* 2012, Winton *et al* 2013). AR5 gave a likely range for this parameter of 1.5 °C–4.5 °C. We believe it would be useful to have a similar bound on the equilibrium sea level rise caused by a doubling of the atmospheric CO_2 concentration, and our new values of the equilibrium thermosteric sea level rise is a step toward assessing such a sensitivity. Using the equilibrium climate sensitivity range from AR5 we get an equilibrium thermosteric sea level sensitivity range of 0.77–2.30 m for the low- and 1.24–3.72 m for the high ocean heat uptake branch.

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