LETTERS

Influence of the Thermohaline Circulation on Projected Sea Level Rise

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ABSTRACT

A zonally averaged three-basin ocean–atmosphere model is used to investigate mean steric sea level rise in global warming scenarios. It is shown that if the North Atlantic deep water formation stops due to global warming, steric sea level rise is much larger for the same global mean atmospheric temperature increase than if the thermohaline circulation remains near the present state. In the equilibrium, global mean steric sea level rise depends linearly on the global mean atmospheric temperature increase. The influence of different subgrid-scale ocean mixing parameterizations on steric sea level rise is investigated.

1. Introduction

There is evidence from observations and models that sea level has risen during the last 100 years due to the increase in global mean air temperature (see IPCC 1996, chapter 7 for a review). Future warming is expected to cause an increase in sea level of 0.2 to 0.86 m by the year 2100, with a ''best guess'' of 0.49 m. The main factors contributing to changes in sea level are changes related to oceanic thermal expansion, glaciers and small ice caps, the large ice sheets of Greenland and Antarctica, and possible changes in ground-water storage. More than half of the projected sea level rise (0.28 of 0.49 m in the year 2100) is expected to be due to oceanic thermal expansion (IPCC 1996). Here we investigate changes in sea level due to this thermal expansion component of global sea level rise and the uncertainties associated with potential circulation changes.

Several types of models have been employed for estimates of ocean thermal expansion, from simple 1D upwelling diffusion energy balance models (Raper et al. 1996), 2D zonally averaged energy balance models (de Wolde et al. 1995, 1997), or the subduction model of Church et al. (1991) to complex 3D atmosphere–ocean GCMs (e.g., Mikolajewicz et al. 1990). Using new parameterizations of the subgrid-scale ocean mixing processes (Redi 1982; Gent and McWilliams 1990), some models simulate reduced convection, improved stratification, and changes in the Southern Ocean overturning circulation, leading to a reduced ocean heat uptake in global warming scenarios (e.g., Hirst et al. 1996; Power and Hirst 1997; Wiebe and Weaver 1999). In a recent study, Weaver and Wiebe (1999) suggest that, based on horizontal diffusion parameterizations, previous Intergovernmental Panel on Climate Change projections of long-term changes in sea level may overestimate the thermal expansion component. They find equilibrium steric sea level rise to be more than two times lower when using more realistic parameterizations for subgrid-scale ocean mixing.

The aim of this paper is to present new results from a zonally averaged coupled ocean–atmosphere model to show how changes in sea level are linked to changes in the atmospheric temperature, to the thermohaline circulation, and to ocean mixing parameterizations. Focussing on the equilibrium changes in sea level due to global warming, we find simple dependences that give a consistent view of our results and the results of Weaver and Wiebe (1999).

2. Model description

We use the zonally averaged three-basin ocean model of Wright and Stocker (1991), with the closure scheme described by Wright et al. (1998). The ocean model consists of three rectangular basins representing the Atlantic, Pacific, and Indian Oceans, connected by an Antarctic circumpolar basin, the Southern Ocean. The geometry is identical to that used by Stocker and Wright (1996). The ocean model is coupled to a one-dimensional, zonally and vertically averaged energy balance model of the atmosphere (Stocker et al. 1992) including an active hydrological cycle (Schmittner and Stocker

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1999). The three different subgrid-scale ocean mixing parameterizations used are the same as those described in detail in Knutti et al. (2000). Briefly, we use the version HOR with the traditional horizontal–vertical diffusion scheme (horizontal diffusivity K_H = 1000 m^2 s^{-1}, constant vertical diffusivity $K_V = 5 \times 10^{-5}$ m^2 s^{-1}), the version ISO with an isopycnal diffusion scheme (isopycnal diffusivity K_I = 1000 m^2 s^{-1}, diapycnal diffusivity $K_D = 5 \times 10^{-5}$ m^2 s^{-1}), and the model version GM, which is identical to ISO but with an additional eddy-induced advection (Gent and McWilliams 1990) (Gent–McWilliams parameter κ = 500 m^2 s^{-1}). The model configuration, all parameters, and the spinup of the model as well as the simulation of the global warming scenarios are identical to those described in detail by Knutti et al. (2000). For the global warming scenarios we assume an exponential increase in atmospheric CO_2, corresponding to a linear increase in the radiative forcing. Once double preindustrial CO_2 concentration (560 ppm) is reached, CO_2 is kept constant and the model is integrated until an equilibrium state is reached (usually 5000 yr). Changes in global mean sea level due to thermal expansion are calculated from the changes in the in situ density distribution (Gregory 1993).

3. Results

Most coupled ocean–atmosphere models show a reduction of the North Atlantic overturning when global warming scenarios are calculated, and several studies have indicated the possibility of a permanent reorganization of the thermohaline circulation when deep water formation stops completely in the North Atlantic (e.g., Manabe and Stouffer 1994; Stocker and Schmittner 1997). Major changes in the temperature and salinity distribution are simulated in this case. To investigate the effect of such a circulation reorganization on global mean sea level, we calculated two global warming scenarios [doubling of preindustrial atmospheric CO_2 with an increase rate of 1% (yr^{-1})] with prescribed climate sensitivities for the GM model version. The climate sensitivities are specified as an additional radiative forcing of 3.69 and 3.70 W m^{-2} for doubling CO_2 (see Schmittner and Stocker 1999 for details), leading to an atmospheric temperature increase of 1.84° and 1.85°C, respectively (Fig. 1a). The sensitivities are chosen around a bifurcation point: in the first case, the Atlantic overturning is reduced but recovers after a few hundred years. In the second case, the circulation collapses permanently (Fig. 1b). The global mean atmospheric temperature increase is almost identical in both cases, but steric sea level rise is much larger, and the time to reach a new equilibrium is about twice as long if the circulation collapses (Fig. 1c). Qualitatively, the same result is found for all mixing parameterizations (HOR, ISO, and GM) and for different parameter settings. To understand this behavior, a second series of experiments was performed. For each model spinup, 60 global warming scenarios with different climate sensitivities and CO_2 increase rates were integrated to equilibrium. For each of these scenarios, the equilibrium values of global mean sea level rise versus global mean atmospheric temperature increase are plotted in Fig. 2. We show only the results for HOR and GM, but a similar dependence is found for all mixing parameterizations and parameter sets. In the cases where the Atlantic circulation recovers after the warming (open symbols), sea level rise in our model is approximately proportional to the atmospheric temperature increase. When a completely different circulation pattern establishes, a linear dependence is still observed, but the reorganization results in an additional contribution on the order of 0.5 m to the sea level rise. For the HOR version, two types of reorganizations are observed where North Atlantic deep water (NADW) formation stops. The additional contribution to sea level rise is even larger for the case where no deep water formation occurs in any basin (filled triangles pointing

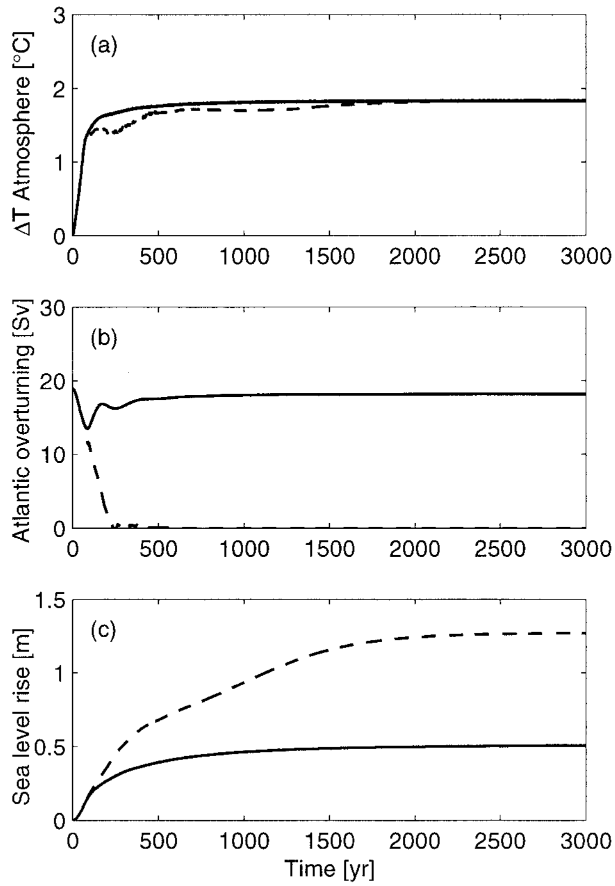

FIG. 1. (a) Global mean atmospheric temperature increase (°C), (b) Atlantic deep overturning [Sverdrups ≡ 10^6 m^3 s^{-1} (Sv)], and (c) global mean sea level rise (m) vs time in two almost identical global warming experiments using the model version with a Gent–McWilliams mixing scheme. If the Atlantic deep overturning collapses (dashed lines), steric sea level rise is much larger for the same atmospheric temperature increase than if the overturning recovers (solid lines).

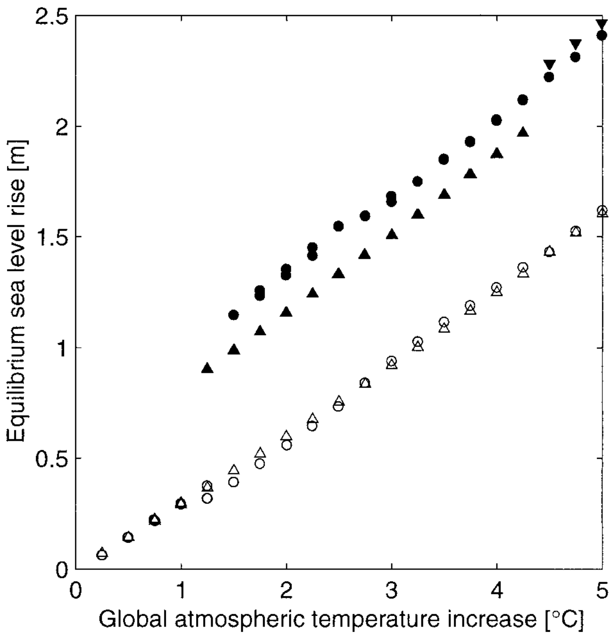

FIG. 2. Global mean sea level rise (m) vs global atmospheric temperature increase (°C) in global warming scenarios. Each point represents the equilibrium state of one scenario. Triangles denote horizontal mixing (HOR) for the cases where (a) NADW formation recovers after the warming (open triangles), (b) NADW formation stops and NPDW formation establishes (filled triangles pointing up), and (c) where no NADW or NPDW formation occurs (filled triangles pointing down). Circles denote Gent–McWilliams mixing (GM) for the cases where (a) NADW formation restores (open circles) and (b) where NADW formation stops and NPDW formation establishes (filled circles).

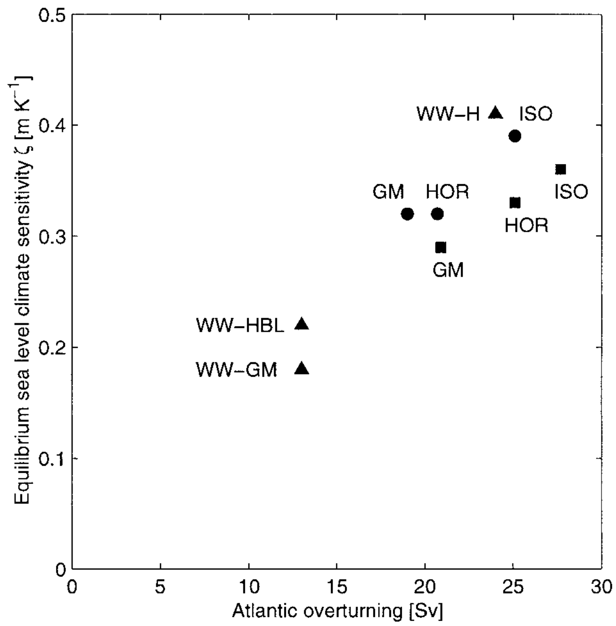

FIG. 3. Equilibrium sea level climate sensitivity ζ (m K^{-1}) vs Atlantic deep overturning (Sv) of the spinup for different model versions. We define ζ as the global mean sea level rise at equilibrium divided by the atmospheric mean temperature increase after the warming. The results for the standard parameter set used in this study are marked with circles, those for a parameter set used in earlier studies (Schmittner and Stocker 1999) are marked with squares. In both cases the three versions, horizontal mixing (HOR), isopycnal mixing (ISO), and Gent–McWilliams parameterization (GM), are indicated. Triangles denote the results of Weaver and Wiebe (1999).

down) than if a shallow cell of North Pacific deep water (NPDW) formation develops (filled triangles pointing up). For the GM version, we observe only the reorganization leading to NPDW formation (filled circles). At least in our model and in the examined range, equilibrium sea level rise Δz can therefore be approximated by a linear dependence on the atmospheric mean temperature increase ΔT_{atm}:

$$\Delta z = \zeta \Delta T_{\mathrm{atm}} + c,$$

where ζ denotes an ''equilibrium sea level climate sensitivity'' in units m K^{-1}; it is given by the slope of a linear fit to the results shown in Fig. 2 for the case when the modern circulation pattern is maintained.

Next we investigate the values and sensitivities of the two parameters c and ζ. The additional contribution c is determined by the transition of the thermohaline circulation between different steady states. For the results in Fig. 2, we obtain $c = 0.45$ m (HOR, filled triangles pointing up) and $c = 0.63$ m (GM, filled circles) for the transition from NADW formation to shallow NPDW formation. An interesting result is obtained when we start with the steady state of the model and apply a freshwater pulse in the North Atlantic to enforce a collapse of the Atlantic circulation. Although no atmospheric warming occurs, an increase in sea level of $c = 0.55$ m (HOR) and $c = 0.74$ m (GM) is observed, consistent with the results for the global warming experiments. The additional increase in sea level, c, is mainly due to the increased ocean heat uptake in the case of an NADW formation collapse due to a temporary reduced surface temperature and therefore reduced emission of longwave radiation. Less than 10% of the additional sea level rise is caused by the nonlinear dependence of density on temperature and salinity; in the case of an NADW formation collapse, we observe a warming mainly in the upper 1000 m of the Atlantic. As the thermal expansion coefficient $\alpha = -\rho^{-1}\partial\rho/\partial T$ is larger for higher temperatures, this leads to considerable expansion in the upper Atlantic.

Parameter ζ characterizes the sensitivity of global mean sea level in a specific model version to changes in atmospheric mean temperature. We believe this to be one of the most important quantities when comparing changes in sea level in different model versions. Note that we now compare sea level sensitivities of different model spinups, differing in either ocean mixing parameterizations or parameter settings. In Fig. 3, we compare ζ for the different ocean mixing parameterizations by plotting ζ versus the Atlantic overturning of the corresponding spinup steady state. The three ocean mixing versions HOR, ISO, and GM obtained with standard parameter settings are marked with circles. To test the robustness of our result, we calculated ζ for the same mixing parameterizations, but with ocean parameters used in previous studies (Schmittner and Stocker 1999) (squares). In both cases, a strong dependence of ζ on the strength of the thermohaline circulation is observed. These results indicate that an enhanced thermohaline circulation leads to higher values of ζ because of a stronger coupling of the atmosphere and surface ocean to the deep ocean and to a more effective transport of excess heat to the deep ocean, which results in higher sea level rise.

Rather small differences in steric sea level rise between the different ocean mixing parameterizations are found in our global warming simulations. Our results are seemingly inconsistent with those of Weaver and Wiebe (1999, hereafter WW), who observe that sea level rise in a $2 \times CO_2$ scenario is two times lower when using more realistic Gent–McWilliams mixing (WW–GM hereafter) or HBL mixing (notation as in WW: variable vertical diffusivity, WW–HBL hereafter) parameterizations instead of the classic horizontal–vertical diffusion parameterization (constant vertical diffusivity $K_V = 10^{-4}$ m^2 s^{-1}, WW–H hereafter). However, a consistent picture is obtained when we estimate ζ for the experiments of WW (note that ζ is determined from one single experiment) and compare them with our results (see Fig. 3). Their values for ζ differ by about a factor of 2 for the different mixing versions, but there are large differences in the Atlantic thermohaline circulation as well. For the WW–HBL and WW–GM versions, they observe an Atlantic overturning of only 13 Sv compared to 24 Sv in the WW–H version. An extrapolation of our results in Fig. 3 is in agreement with the low ζ values WW find for their GM and HBL versions. We conclude from these results that the sensitivity of sea level to changes in atmospheric temperature for a particular model version is not necessarily affected by the mixing parameterization that is used, but it may be predominantly determined by the strength of the thermohaline circulation. There is, however, a strong relation of the Atlantic overturning strength to the way ocean mixing is parameterized and to various parameters used in these mixing schemes (e.g., vertical or diapycnal diffusivity, Gent–McWilliams parameter) (Knutti et al. 2000).

4. Summary and discussion

We have shown in a series of model experiments that sea level rise from thermal expansion in global warming scenarios is affected by the thermohaline circulation in two different ways. First, equilibrium sea level rise depends linearly on the atmospheric temperature increase with the slope ζ related to the strength of the circulation. The values for ζ estimated in different studies cover a large range from about 0.2 to 0.5 m K^{-1}, with the average of our model results indicating a best estimate of about 0.3 m K^{-1} (see Fig. 3). Second, our experiments suggest that a permanent reorganization of the thermohaline circulation pattern could lead to a comparatively large additional contribution to sea level rise of order 0.5 m. Furthermore, we have confirmed previous studies that showed that changes in sea level depend on the way subgrid-scale mixing processes in the ocean are parameterized. However, quantitative results in our experiments are different from those of WW. We suggest that if their GM and H versions had similar Atlantic overturning, differences in projected sea level rise could be significantly smaller. Our results indicate that the equilibrium sensitivity of global mean sea level to atmospheric temperature changes is indirectly affected by the mixing parameterization via the strength of the thermohaline circulation, with a stronger circulation leading to higher sea level rise for the same warming scenario. A precise picture of the modern thermohaline circulation pattern and of expected circulation changes in the future is therefore crucial to reduce the uncertainty in projected sea level rise.

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REFERENCES

Church, J. A., J. S. Godfrey, D. R. Jackett, and T. J. McDougall, 1991: A model of sea level rise caused by ocean thermal expansion. *J. Climate,* **4,** 438–456.

de Wolde, J. R., R. Bintanja, and J. Oerlemans, 1995: On thermal expansion over the last hundred years. *J. Climate,* **8,** 2881–2891.

——, P. Huybrechts, J. Oerlemans, and R. S. W. van de Wal, 1997: Projections of global mean sea level rise calculated with a 2D energy-balance climate model and dynamic ice sheet model. *Tellus,* **49A,** 486–502.

Gent, P. R., and J. C. McWilliams, 1990: Isopycnal mixing in ocean circulation models. *J. Phys. Oceanogr.,* **20,** 150–155.

Gregory, J. M., 1993: Sea level changes under increasing atmospheric CO_2 in a transient coupled ocean–atmosphere GCM experiment. *J. Climate,* **6,** 2247–2262.

Hirst, A. C., H. B. Gordon, and S. P. O'Farell, 1996: Global warming in a coupled climate model including oceanic eddy-induced advection. *Geophys. Res. Lett.,* **23,** 3361–3364.

IPCC, 1996: *Climate Change 1995, The Science of Climate Change.* Cambridge University Press, 572 pp.

Knutti, R., T. F. Stocker, and D. G. Wright, 2000: The effects of subgrid-scale parameterizations in a zonally averaged ocean model. *J. Phys. Oceanogr.,* in press.

Manabe, S., and R. J. Stouffer, 1994: Multiple-century response of a coupled ocean–atmosphere model to an increase of atmospheric carbon dioxide. *J. Climate,* **7,** 5–23.

Mikolajewicz, U., B. D. Santer, and E. Maier-Reimer, 1990: Ocean response to greenhouse warming. *Nature,* **345,** 589–593.

Power, S. B., and A. C. Hirst, 1997: Eddy parameterization and the oceanic response to global warming. *Climate Dyn.,* **13,** 417–428.

Raper, S. C. B., T. M. L. Wigley, and R. A. Warrick, 1996: Global sea level: Past and future. *Rising Sea Level and Subsiding Coastal Areas,* J. D. Milliman, Ed., Kluwer Adacemic, 384 pp.

Redi, M. H., 1982: Oceanic isopycnal mixing by coordinate rotation. *J. Phys. Oceanogr.,* **12,** 1154–1158.

Schmittner, A., and T. F. Stocker, 1999: The stability of the thermohaline circulation in global warming experiments. *J. Climate,* **12,** 1117–1133.

Stocker, T. F., and D. G. Wright, 1996: Rapid changes in ocean circulation and atmospheric radiocarbon. *Paleoceanography,* **11,** 773–796.

——, and A. Schmittner, 1997: Influence of CO_2 emission rates on the stability of the thermohaline circulation. *Nature,* **388,** 862–865.

——, D. G. Wright, and L. A. Mysak, 1992: A zonally averaged, coupled ocean–atmosphere model for paleoclimate studies. *J. Climate,* **5,** 773–797.

Weaver, A. J., and E. C. Wiebe, 1999: On the sensitivity of projected oceanic thermal expansion to the parameterisation of sub-grid scale ocean mixing. *Geophys. Res. Lett.,* **26,** 3461–3464.

Wiebe, E. C., and A. J. Weaver, 1999: On the sensitivity of global warming experiments to the parameterisation of sub-grid scale ocean mixing. *Climate Dyn.,* **15,** 875–893.

Wright, D. G., and T. F. Stocker, 1991: A zonally averaged ocean model for the thermohaline circulation. Part I: Model development and flow dynamics. *J. Phys. Oceanogr.,* **21,** 1713–1724.

——, ——, and D. Mercer, 1998: Closures used in zonally averaged ocean models. *J. Phys. Oceanogr.,* **28,** 791–804.