Global Warming Projections: Sensitivity to Deep Ocean Mixing

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The climatological impact of increases in greenhouse gas concentrations in the atmosphere, despite being a subject of intensive study in recent years, is still very uncertain[1, 2]. One major uncertainty affecting possible climate change that has not received enough attention is the uncertainty in heat uptake by the deep ocean. We analyze the influence of this process and its uncertainty on climate predictions by means of numerical simulations with a 2-dimensional (2D) climate model. In the case of high climate sensitivity, as a result of uncertainty in deep ocean heat uptake, there is more than a factor of two uncertainty in the predicted increase of surface temperature. The corresponding uncertainty in the sea level rise due to thermal expansion is much larger than the uncertainty in the predicted temperature change and is significant even in the case of low climate sensitivity.

The uncertainty in the rate of heat uptake by the deep ocean has not been included in the projections of climate change made by the Intergovernmental Panel on Climate Change (IPCC)[1,2]. However, our results show that this uncertainty plays a very important role in defining the ranges of possible warming and, especially, of sea level rise. To assess the uncertainty we have used a 2-dimensional (zonally averaged) climate model, the MIT 2D model[3,4,5]. This model allows us to perform a much larger number of numerical simulations, than would be possible with a coupled atmosphere ocean general circulation model (AOGCM).

The atmospheric part of the MIT 2D model is a modified version of the zonal mean statistical-dynamical model developed at the Goddard Institute for Space Studies (GISS)[6,7,8], which is based on the GISS GCM[9]. As a result, most of the model's parameterizations of physical processes are identical to those used in the GISS GCM[9]. A number of modifications have been made to the model at MIT to make it more suitable for climate change studies[3,4,5]. Model versions with different sensitivities are obtained by imposing a cloud feedback which depends on the increase in surface air temperature[10]. The range of sensitivity (that is, equilibrium response to the doubling of CO_2 concentration — ΔT_{eq}) suggested by the IPCC[1] (i.e., 1.5 ˚C – 4.5 ˚C) has been used in this study. The atmospheric model is coupled to a zonal mean mixed layer ocean model similar to that developed at GISS[11]. The horizontal heat transport by the ocean is calculated from the results of a climate simulation with the MIT 2D model using climatological sea surface temperature and sea-ice distributions, and is held fixed in the climate experiments. The heat uptake by the deep ocean is parameterized by diffusive mixing of mixed layer temperature perturbations[11]. Zonally averaged values of diffusion coefficients calculated to reproduce measurements of tritium mixing in the ocean have been chosen as "standard" ones[11]. The global average value of the diffusion coefficients, denoted as K, equals 2.5 cm^2s^{-1} for these standard values.

Additional sets of diffusion coefficients, differing from the standard values by a constant, have been calculated by matching the MIT 2D model's transient warming to those produced by different AOGCMs (see Table 1). In the absence of direct measurements of mixing of heat into the deep ocean, this range gives us one estimate of the uncertainty in the effective value of the diffusion coefficients. The transient response of the 2D model with "standard" ocean heat uptake is similar to that obtained in the simulation with the Geophysical Fluid Dynamics Laboratory (GFDL) AOGCM[12] (see Figure 1). Five times larger values of the diffusion coefficients are required to match the delay in warming produced by the Max Planck Institute (MPI) and United Kingdom Meteorological Office (UKMO) AOGCMs[13,14]. (Data for the MPI model have been corrected by taking into account temperature drift in the control simulation.) At the same time, no heat diffusion into the deep ocean is required to reproduce the fast warming produced by the National Center for Atmospheric Research (NCAR) AOGCM[2]. We do not know reasons for these differences, but we note that the amount of deep convective mixing in ocean GCMs is sensitive to the parameterization of subgrid scale mixing[15].

All simulations discussed below have been performed with a 1% per year increase in the CO_2 concentration, while all other forcings were held constant. According to our results, when climate sensitivity is high, even a small change in the rate of heat uptake causes a significant difference in the predicted surface temperature increase. In the simulation with $\Delta T_{eq} = 4.5$ ˚C and $K = 0$ $cm^2 s^{-1}$ the surface temperature increase for years 91 to 100 of the integration, ΔT_{91-100}, is 6.2 ˚C. For heat diffusion with $K = 0.5$ $cm^2 s^{-1}$, ΔT_{91-100} is 4.6 ˚C. Thus, if the rate of heat uptake by the deep ocean is close to that matching the behavior of the NCAR model, the increase of the surface temperature will be significantly higher than the highest estimate of possible warming given by the IPCC[1,2] (Figure 2). In the case of low climate sensitivity the impact of the deep ocean on warming is much smaller (Figure 2).

Our simulations also show a particularly large impact of the rate of heat penetration into the deep ocean on sea level rise due to thermal expansion (Figure 3). The thermal expansion has been calculated from the deep ocean temperature increase using the method of Gregory[16]. Levitus' data[17] have been used for the unperturbed state of the deep ocean. In spite of our model's simplified representation of the deep ocean, it reproduces the thermal expansion of the ocean as simulated by the GFDL AOGCM quite well (see Figure 1b). The uncertainty in sea level rise is quite significant even for climate sensitivity as low as 1.5 ˚C.

One might argue that the low effective values of K implied by the NCAR AOGCM, when combined with a high climate sensitivity, is inconsistent with the modest 0.3 to 0.6 ˚C warming of the past century[2]. Then one could agree with the IPCC's upper bound for projections of global mean temperature over the next century[2]. However, excluding this combination of possibilities would not reduce the uncertainty in projections of sea level rise due to thermal expansion (Figure 3). Also it is not at all obvious that the modest warming to date does exclude this combination, because of the large uncertainties in the cooling caused by increases in tropospheric aerosols[2].

Table 1. Response of different AOGCMs and matching versions of the MIT 2D model to a gradual increase of CO_2 concentration.

Model	ΔT_{eq} (˚C)	ΔT at time of CO_2 doubling (˚C)	Fraction of equilibrium response (%)
GFDL 2D, K = 2.5	3.5	2.3	66
	3.5	2.5	71
UKMO 2D, K = 12.5	2.8	1.7	61
	2.9	1.8	62

MPI 2D, K = 12.5	2.5	1.6	64
	2.5	1.7	68
NCAR 2D, K = 0	4.6	3.8	83
	4.5	3.6	80

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Figure 1a. Global mean surface temperature change caused by a 1% per year increase in CO_2 in the simulations with the MIT 2D model with $K = 2.5\ cm^2s^{-1}$ (solid curves) and the GFDL AOGCM (dashed curves).

Figure 1b. Global mean sea level rise due to thermal expansion caused by a 1% per year increase in CO_2 in the simulations with the MIT 2D model with $K = 2.5\ cm^2s^{-1}$ (solid curves) and the GFDL AOGCM (dashed curves).

Figure 2. Global mean surface temperature change caused by a 1% per year increase in CO_2 in the simulations with $\Delta T_{eq} = 4.5$ ˚C (solid curves, with K = 0, 0.5, 2.5 and 12.5 cms^2s^{-1}, as indicated) and $\Delta T_{eq} = 1.5$ ˚C (dashed curves with K = 0, 2.5 and 12.5 cm^2s^{-1}, as indicated) together with upper and low bounds (shown by straight lines) for the IPCC's projections for the same scenario (IPCC, 1990, Figure 6.8).

Figure 3. Sea level rise due to thermal expansion caused by a 1% per year increase in CO_2 in the simulations with $\Delta T_{eq} = 4.5$ ˚C (solid curves, with K = 0, 0.5, 2.5 and 12.5 cm^2s^{-1}, as indicated) and $\Delta T_{eq} = 1.5$ ˚C (dashed curves with K = 0, 2.5 and 12.5 cm^2s^{-1} as indicated).