Uncertainty in the Oceanic Heat and Carbon Uptake and Their Impact on Climate Projections

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Abstract

The impact of uncertainty in the rate of heat and carbon uptake by the deep ocean on climate response to increases in greenhouse gas concentrations is studied by means of numerical simulations with the two-dimensional (2D) climate-chemistry model developed in the framework of the MIT Joint Program on the Science and Policy of Global Change. This model incorporates parameterizations of most physical processes, includes fully interactive atmospheric chemistry and calculates carbon uptake by the ocean and, therefore, simulates the main nonlinear interactions taking place in the climate system. At the same time, it is much more computationally efficient than coupled atmosphere-ocean general circulation models. Results of the simulations with calculated CO_2 concentrations are compared with those of simulations with a prescribed CO_2 increase. This comparison shows that the uncertainty in the increase in global mean surface temperature due to uncertainty in the rate of oceanic heat uptake is enhanced by taking into account the related uncertainty in oceanic carbon uptake, while the uncertainty in sea level rise is decreased.

Introduction

Results of climate change simulations with different coupled atmosphere-ocean general circulation models (AOGCMs) show significant disagreements in the rates of the surface warming and sea level rise in response to changes in greenhouse gas (GHG) concentrations. These disagreements are, in part, due to differences in the rate of the penetration of heat into the deep ocean. Since AOGCMs are computationally very expensive, most uncertainty studies have been performed with simplified models of different kinds, such as, for example, upwelling-diffusion/ energy balance (UD/EB) models. The climate model used in this study, in contrast to EB models, includes parameterizations of the main physical processes taking place in the climate system. At the same time, it is computationally rather efficient.

A number of studies on the impact of uncertainty in the rate of oceanic heat uptake on climate change have been carried out in recent years (Wigley and Raper, 1993; Harvey, 1994; Sokolov and Stone, 1997). All these studies have been performed with prescribed changes in atmospheric CO_2 or given radiative forcing. However, the CO_2 concentration in the atmosphere is not a pure external parameter for the climate system, but depends on the sources and sinks of carbon, including carbon uptake by the deep ocean. Therefore, use of prescribed forcing does not permit the evaluation of the total impact of the uncertainty in the rate of oceanic uptake. In this paper, results of simulations with the two-dimensional (zonally averaged) climate-chemistry model, which includes fully interactive chemistry, transport of chemical species (Wang, *et al*., 1997), and calculates carbon uptake by the ocean (Prinn, *et al.*, 1997), are compared with that of simulations with prescribed GHG concentrations. As will be seen from that comparison, taking into account uncertainty in the rate of carbon uptake, while increasing the uncertainty in surface warming, offsets somewhat the uncertainty in the ocean's thermal expansion associated with different rates of oceanic heat uptake.

The MIT 2D Climate-Chemistry Model

The atmospheric part of the MIT 2D climate-chemistry model is a modified version of the zonal mean statistical-dynamical model developed at the Goddard Institute for Space Studies (GISS) (Yao and Stone, 1987; Stone and Yao, 1987 and 1990), which is based on the GISS GCM (Hansen *et al.,* 1983). As a result, most of the model's parameterizations of physical processes are identical to those used in the GISS GCM. A number of modifications have been made to the model at MIT to make it more suitable for climate change studies (Sokolov and Stone, 1995 and 1997; Prinn, *et al.,* 1997). The main difference between the GISS and the MIT 2D models is that in the GISS 2D model the terrestrial surface is assumed to be ocean only, while the MIT model includes real land/ocean distribution.

The atmospheric model is coupled to a zonal mean mixed layer ocean model similar to that developed at GISS (Hansen, *et al.,* 1984). 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 (Hansen, *et al*., 1984). Zonally averaged values of diffusion coefficients calculated from the measurements of the tritium distribution in the ocean have been chosen as "standard" ones. The global average value of the diffusion coefficients, denoted as K_v, equals 2.5 cm^2/s for these standard values.

The atmospheric chemistry model (Wang, *et al*., 1997; Prinn, *et al*., 1997) currently has 25 chemical species including CO_2, CH_4, N_2O, O_3, CO, H_2O, NO_x, HO_x, SO_2, sulfate aerosol, and chlorofluorocarbons. The mixing ratios of chemical species are predicted by solving the mass conservation equations including chemical and surface sources and sinks. These equations include convergence due to transport (advection, eddy diffusion, and convection) except for very reactive atoms, free radicals, or molecules which are assumed to be unaffected by transport due to their very short lifetimes. There are 41 gas-phase and 12 heterogeneous reactions in the current model. Emissions of CO_2, CH_4, N_2O, chlorofluorocarbons, CO, NO, and SO_2 are included in this model.

The air-to-sea flux of carbon is proportional to the CO_2 concentration gradient between the atmosphere and oceanic surface and the local surface wind speed (Liss and Merlivat, 1986; Tans, *et al.*, 1990). Invading CO_2 is assumed to come into a chemical equilibrium with dissolved carbonate and bicarbonate ions that is dependent on temperature, alkalinity, and the concentrations of boric, silicic, and phosphoric acids (Peng, *et al.*, 1982). Total inorganic carbon, comprised of dissolved CO_2, carbonate, and bicarbonate, is treated as a single inert tracer for the purposes of mixing and transport by oceanic circulation. The carbon uptake by the deep ocean is simulated in a way similar to that for heat in the climate model. The north-south transport of carbon by the ocean is parameterized by horizontal diffusion, with coefficients depending on depth. Values of the horizontal diffusion coefficients have been chosen so as to give a mixing time changing from 25 years for the mixed layer to 500 years for the deepest ocean layer.

A comparison of the results of simulations of present-day climate and atmospheric composition with observations shows that the MIT 2D climate-chemistry model reasonably reproduces the main features of zonally averaged atmospheric circulation (Sokolov and Stone, 1995 and 1997; Prinn, *et al.,* 1997), distributions of different chemical species in the atmosphere and carbon content in the ocean mixed layer.

The sensitivity, ΔT_{eq}, of the MIT 2D model (defined as equilibrium response of the global mean surface temperature to a doubling of CO_2 concentration) is equal to 3 ˚C and lies in the range

of the values obtained in the simulations with AGCMs (IPCC, 1996). The zonal mean pattern of the 2D model response (Sokolov and Stone, 1997) is also similar to that produced by AGCMs. Model versions with different sensitivities were obtained by imposing a cloud feedback that depends on the increase in surface air temperature (Hansen, *et al.,* 1993). Changes in precipitation, evaporation, radiation balance at the surface, and other variables in the simulations with different versions of the 2D model, as well as their dependencies on the surface warming, are consistent with the results produced by AGCMs with different sensitivities.

The transient behavior of different AOGCMs can be matched by choosing appropriate values for ΔT_{eq} and rate of heat diffusion into the deep ocean (Sokolov and Stone, 1997). In spite of its simplified representation of the deep ocean, the 2D climate model reproduces both the increase of surface air temperature and the sea level rise due to the thermal expansion of the ocean as simulated by different AOGCMs quite well. It is important to note that a unique choice of parameters allows us to reproduce of the behavior of a given AOGCM for a variety of forcings for time period of 100–150 years.

Results of Climate Change Simulations with Different Rates of Oceanic Carbon and Heat Uptake

Here the results of simulations with prescribed greenhouse gas concentrations are compared with the results of simulations carried out with the coupled climate-chemistry model, in which those concentrations were predicted from given emissions. Simulations with prescribed greenhouse gas concentrations were performed with just the climate component of the model. Such a comparison allows us to evaluate the impact of uncertainty in both heat and carbon uptake by the deep ocean and their interaction.

Greenhouse gases emissions used in the simulations with the climate-chemistry model were calculated by the Emissions Prediction and Policy Analysis (EPPA) model (Yang, *et al.*, 1996; Prinn, *et al.*, 1997). Parameters used in the standard version of the EPPA model produce CO_2 emissions close to those assumed in the IPCC scenario IS92a (IPCC, 1992). The climate model version with sensitivity 2.5 °C ("best guess" of the IPCC) has been used in all these simulations. Diffusion coefficients with $K_v = 5$ cm^2/s (*i.e.* doubled "standard" values) were chosen as the middle of the range for the ocean heat uptake. The rate of heat uptake produced by the 2D model for these values of diffusion coefficients is similar to that of the UD/EB model used in IPCC (1996). The diffusion coefficients for carbon are 1.5 times larger than those for heat. This increase is needed to obtain an oceanic carbon uptake close to the current best estimate and might be justified as accounting for an additional carbon uptake associated with the "biological pump." Because of the above choice of parameters, radiative forcing (Fig. 1) and surface warming (Fig. 2) in the "control" simulation of this study are quite close to the middle of the range of predictions given by IPCC (1996), while sea level rise due to the thermal expansion is about 30% less.

Low and high values of coefficients for heat diffusion used in this study were obtained by dividing/multiplying "middle-of-the-range" values by five, thereby preserving the zonal structure of oceanic uptake. Values of K_v for these two sets of coefficients are 1 and 25 cm^2/s, respectively. The magnitude of oceanic carbon uptake obtained in the beginning of the simulations with these different diffusion coefficients, *i.e.*, 0.9, 1.9 and 2.9 GtC per year respectively, are in a good agreement with the range of values (2 ± 0.8 GtC/yr) given by IPCC (1996). As shown by Sokolov and Stone (1997), $K_v = 25$ cm^2/s is the value required to match the behavior of the Max Planck

Institute AOGCM while $K_v = 1$ cm^2/s is somewhat larger than the value implied by warming produced by the National Center for Atmospheric Research AOGCM. Thus, the range of the rate of heat uptake by the deep ocean used in the simulations with the 2D model is consistent with that implied by the existing AOGCMs.

The simulations with the climate-chemistry model have been carried out from 1977 to 2100. To ensure agreement with the observed CO_2 level during an initial stage of the simulations different values of the terrestrial carbon uptake were used in the simulations with different K_v. Two additional simulations, results of which are shown by the thin lines in Figures 2 and 3, have been performed with the climate model forced by the greenhouse gas concentrations obtained in the simulation with the climate-chemistry model with $K_v = 5$ cm^2/s. Diffusion coefficients with $K_v = 1$ and 25 cm^2/s have been used in these latter two simulations for the ocean heat uptake. For convenience in comparison with IPCC projections, all variables are shown as differences from their values in 1990.

An increase/decrease in the rate of carbon uptake by the deep ocean led to a decrease/increase in the atmospheric CO_2 concentration and, as a result, in the radiative forcing (Fig. 1). These changes in the radiative forcing led to an increase in the overall impact of the change in the rate of oceanic uptake on the surface warming, compared to that in the simulations with prescribed concentrations (Fig. 2). At the same time, changes in the rate of carbon and heat uptake by the ocean have impacts of different signs on sea level rise. On the one hand, larger heat uptake produces larger thermal expansion of the deep ocean for a given forcing. On the other hand, an increase in the carbon uptake leads to smaller forcing and, therefore, smaller thermal expansion. The net effect of these two competing factors is a decrease in the uncertainty in the sea level rise due to thermal expansion (Fig. 3) associated with the uncertainty in the oceanic uptake, compared to the fixed forcing case. The magnitude of this decrease is somewhat larger in the case of fast heat and carbon uptake by the deep ocean. It also, apparently, depends on the ratio of the rates of heat and carbon uptakes.

Conclusions

Results of our simulations show that taking into account uncertainty in the rate of oceanic carbon uptake, in addition to uncertainty in heat uptake, can significantly affect the resulting uncertainty in the surface warming and thermal expansion of the deep ocean. In general, including uncertainty in carbon uptake into consideration leads to an increase in uncertainty in surface temperature change and decrease in uncertainty in sea level rise. However, since the sensitivity of surface warming and sea level rise to changes in the rate of oceanic heat uptake depend strongly on the value of ΔT_{eq} (see, for example, Sokolov and Stone, 1997), the above results might be quantitatively different for different values of model sensitivity, as well as for different greenhouse gases emissions.

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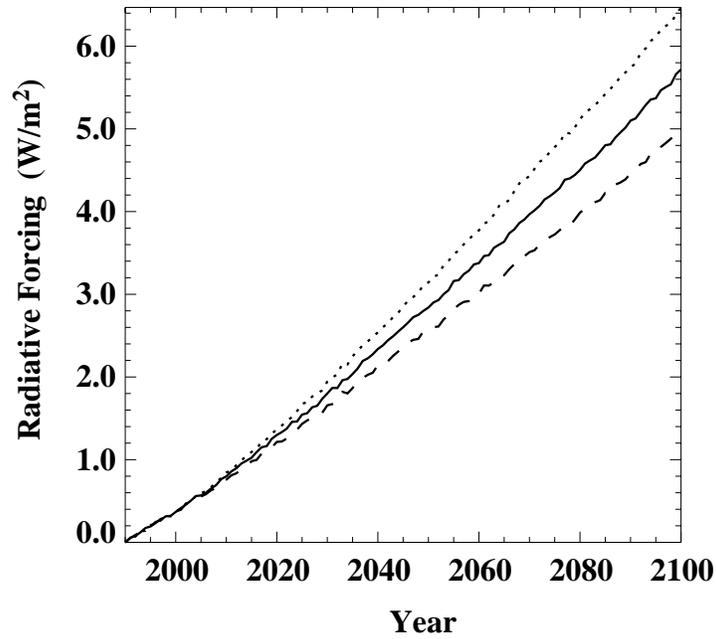
Figure 1. Global mean total radiative forcing due to increase in greenhouse gas and aerosol concentrations in the simulations with the coupled climate-chemistry model with $K_v = 1$ (dotted line), 5 (solid line) and 25 (dashed line) cm^2/s.
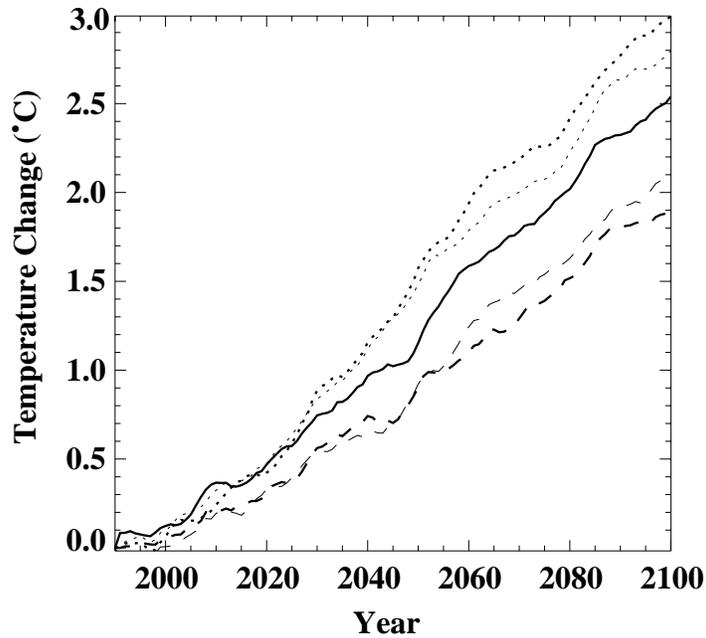
Figure 2. Global mean surface temperature change in the simulations with the coupled climate-chemistry model with $K_v = 1$ (thick dotted line), 5 (thick solid line) and 25 (thick dashed line) cm^2/s, and in the simulations with the climate model with prescribed greenhouse gas concentrations with $K_v = 1$ (thin dotted line) and 25 (thin dashed line) cm^2/s.
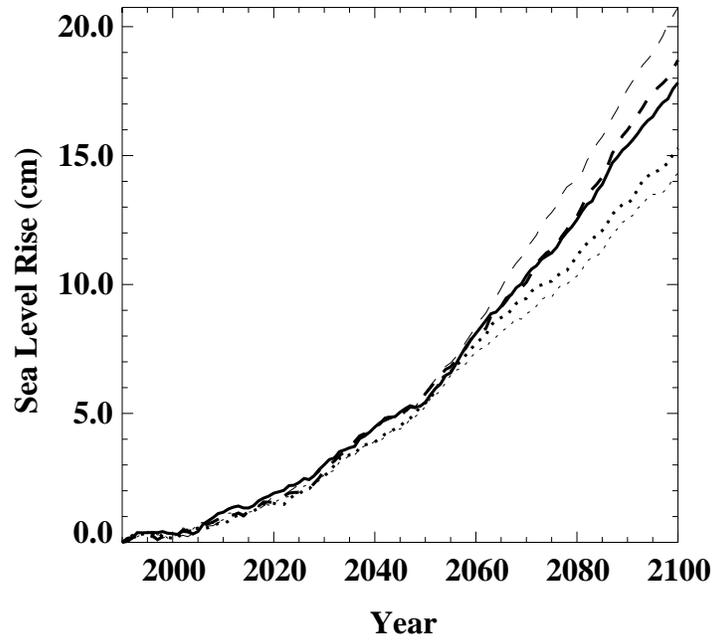
Figure 3. Global mean sea level rise due to thermal expansion of the deep ocean in the simulations with the coupled climate-chemistry model, as in Figure 2, with $K_v = 1$ (thick dotted line), 5 (thick solid line) and 25 (thick dashed line) cm^2/s, and in the simulations with the climate model with prescribed greenhouse gas concentrations with $K_v = 1$ (thin dotted line) and 25 (thin dashed line) cm^2/s.