MIT Joint Program on the Science and Policy of Global Change

Evaluating the Use of Ocean Models of Different Complexity in Climate Change Studies

Andrei P. Sokolov, Stephanie Dutkiewicz, Peter H. Stone and Jeff Scott

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Abstract

The study of the uncertainties in future climate projections requires large ensembles of simulations with different values of model characteristics that define its response to external forcing. These characteristic include climate sensitivity, strength of aerosol forcing and the rate of ocean heat uptake. The latter can be easily varied over a wide range in an anomaly diffusing ocean model (ADOM). The rate of heat uptake in a three-dimensional ocean general circulation model (OGCM) is, however, defined by large number of factors and is far more difficult to vary. Necessity to obtain a realistic ocean circulation places additional constraints, making it impossible to cover the range of values suggested by observations. As a result, a simpler model like an ADOM needs to be used in uncertainty studies.

To evaluate the performance of the ADOM on different time scales we compare results of simulations with two versions of the MIT Integrated Global System Model (IGSM): one with a ADOM and the second with a full three-dimensional OCGM. Our results show that through the 20th and 21st century, the version of the IGSM with ADOM is able to reproduce important aspects of the climate response simulated by the version with the OCGM. However, the inability of the ADOM to depict feedbacks associated with the changes in the ocean circulation significantly affects its performance on the longer timescales. In particular, the ADOM overestimates sea level rise due to thermal expansion of the deep ocean. It also rather poorly depicts long term changes in oceanic carbon uptake, leading to underestimation of the atmospheric CO_2 concentrations. Thus, the IGSM version with ADOM can be used to obtain probability distributions of changes in many of the important climate variables through the end of 21st century. On the other hand, studying longer-term climate change requires the use of the OGCM.

Contents

1. INTRODUCTION

Projections of climate change over the next century are complicated by significant uncertainties in the climate system properties that determine the response to transient forcing, such as climate sensitivity and the rate at which the deep ocean absorbs heat and CO_2. There are additional uncertainties in the forcing itself, especially in the indirect forcing by aerosols (IPCC, 2001). Unfortunately, the available observations for the 20th century can only place limited constraints on these key quantities (Andronova & Schlesinger, 2002; Gregory *et al.*, 2002; Forest *et al.*, 2002, 2005). Existing coupled atmosphere-ocean-land general circulation models (GCMs) also differ significantly in both climate sensitivity and rate of heat uptake (IPCC, 2001; Raper *et al.*, 2002; Sokolov *et al.*, 2003). An important source of these differences among models is the lack of commonly accepted parameterizations for sub-grid-scale processes. For instance, the different representation of cloud processes between models is a major source of the discrepancies between their climate sensitivities (Cess *et al*., 1989; Colman, 2003). The heat uptake by the deep ocean also depends on the representation of small-scale processes (Stone, 2004). Dalan *et al*. (2005), for example, showed that changing the value of the coefficient for vertical diffusion can lead to significant changes in the simulated ocean circulation which affect the rate of oceanic heat uptake.

Because of the above discussed uncertainties, there is no single best climate model or best set of key climate parameters for projecting climate change. An alternative approach is to produce probability distributions for the changes in the most important climate variables. Such probabilistic approaches are also more useful for policy makers than a single model result. However, even with much greater computational power than is available today, it will not be possible to perform such probabilistic studies using state-of-the-art AOGCMs. Therefore, such studies are usually carried out with models of intermediate complexity (Claussen *et al.*, 2002).

The MIT Integrated Global System Model (IGSM), described by Prinn *et al.* (1999) and updated in Sokolov *et al.* (2005), was designed to be used in this sort of probabilistic framework. The IGSM provides the flexibility and computational speed required for uncertainty analysis while still including the representations for all the major components of the climate system.

Forest *et al*. (2002) used the first version of the IGSM to produce probability distributions for the climate sensitivity, the rate of heat uptake by the deep oceans, and the net forcing due to aerosols. In that study observed temperature changes over the 20th century were compared with results of simulations in which these model parameters were varied. This work was then combined with an analysis of uncertainty in anthropogenic greenhouse gas emissions (Webster *et al*., 2002) to produce a probabilistic forecast of climate change for the 21st century (Webster *et al*., 2003).

The IGSM consists of a two-dimensional (zonally averaged) statistical-dynamical atmospheric model with interactive chemistry coupled to a model of terrestrial ecosystem and an ocean model. In the first version of the IGSM (IGSM1, Prinn *et al.,* 1999) the oceanic component of the climate system was represented by a zonally averaged mixed layer anomaly-diffusing ocean model (ADOM) (Sokolov & Stone, 1998).

The second version of the IGSM (IGSM2, Sokolov *et al.*, 2005) was developed in two different configurations: with either a two-dimensional (latitude-longitude) ADOM (IGSM2.2) or with a three-dimensional ocean GCM (IGSM2.3).

The ADOM has several advantages: it is computationally efficient and it is flexible. The rate of heat mixing into the deep ocean can be varied over a wide range just by changing the coefficient of effective diffusion of the heat anomalies. Versions of the IGSM2.3 with different rates of heat uptake can be produces by changing the vertical/diapycnal diffusion coefficients (Dalan *et al.*, 2005). However, changing the diffusion coefficient in a 3D model can alter the ocean circulation as a whole, in particular the strength of North Atlantic overturning (Dalan *et al.*, 2005). The necessity to obtain an ocean circulation consistent with observation restricts the range of acceptable vertical diffusion coefficients.

As shown by Sokolov *et al.* (2003), the MIT 2D climate model with the mixed layer/ADOM can (with an appropriate choice of the vertical diffusion coefficient and climate sensitivity) simulate the behavior of different coupled AOGCMs, in terms of surface warming and sea level rise, on time scales of about 100-150 years. The simple anomaly-diffusing ocean model works well because the mixing of the heat into deep ocean is a linear response to the forcing on century time-scales in typical global warming simulations (*e.g*., Keen & Murphy, 1997; Huang *et al.*, 2003). Thus the mixed layer/ADOM seems to be an appropriate tool for studying uncertainty in possible climate change for time scales from a few decades to a century. However, in some cases much longer simulations are required to fully evaluate the impact of proposed economic policies, for instance stabilization of atmospheric greenhouse gas concentrations. Feedbacks associated with changes in the ocean circulation, not simulated by the ADOM, may become crucially important on the longer time scales. The goal of this study is to investigate on what time scales a simplified ocean model can capture the climate response of a 3D model and when the use of the 3D OGCM is required.

The model components, and especially the difference in the two versions of the ocean, are described in Section 2. Section 3 provides a comparison of results between the IGSM2.2 and IGSM2.3 for different future emission scenarios, for different climate sensitivities, and for different time scales. Conclusions are provided in Section 4.

2. MODEL COMPONENTS

The IGSM is a fully coupled model of the Earth climate system which allows simulation of critical feedbacks between components. The second version of the IGSM (IGSM2, Sokolov *et al.*, 2005) includes the following components:

- An atmospheric dynamics, physics and chemistry model, which includes a sub-model of urban chemistry,
- Either mixed layer/ADOM, or 3D general circulation ocean model, both with carbon cycle and sea-ice sub-models,
- A set of coupled land models, the Terrestrial Ecosystem Model (TEM), a Natural Emissions Model (NEM), and the Community Land Model (CLM), that encompass the global, terrestrial water and energy budgets and terrestrial ecosystem processes.

The time steps used in the various sub-models range from 20 minutes for atmospheric dynamics to one month for TEM, reflecting differences in the characteristic timescales of the various processes simulated by the IGSM. The atmospheric and ocean sub-model are briefly described below. Descriptions of the other components of the IGSM2 can be found in Schlosser & Kicklighter, 2005; Liu, 1996; Wang *et al.*, 1998; Wang, 2004; and Xiao *et al.*, 1997 and 1998. A comparison between the old version, IGSM1, and the newer version, IGSM2 can be found in Sokolov *et al.* (2005).

2.1 Atmospheric Dynamics and Physics

The MIT two-dimensional (2D) atmospheric dynamics and physics model (Sokolov and Stone, 1998) is a zonally averaged statistical-dynamical 2D model that explicitly solves the primitive equations for the zonal mean state of the atmosphere and includes parameterizations of heat, moisture, and momentum transports by large scale eddies based on baroclinic wave theory (Stone

& Yao, 1987, 1990). The model's numerics and parameterizations of physical processes, including clouds, convection, precipitation, radiation, boundary layer processes, and surface fluxes, are built upon those of the Goddard Institute for Space Studies (GISS) GCM (Hansen *et al.*, 1983). The radiation code includes all significant greenhouse gases (H_2O, CO_2, CH_4, N_2O, CFCs and O_3) and eleven types of aerosols. The model's horizontal and vertical resolutions are variable, but in the standard version of IGSM2 it has 4º resolution in latitude and eleven levels in the vertical.

The MIT 2D atmospheric dynamics and physics model allows up to four different types of surface in the each grid cell (ice free ocean, sea-ice, land, and land-ice). The surface characteristics (*e.g.*, temperature, soil moisture, albedo) as well as turbulent and radiative fluxes are calculated separately for each kind of surface. The atmosphere above is assumed to be well mixed horizontally in each latitudinal band. The area weighted fluxes from the different surface types are used to calculate the change of temperature, humidity, and wind speed in the atmosphere. The atmospheric model's climate sensitivity can be changed by varying the cloud feedback (Sokolov & Stone, 1998; Sokolov, 2005).

2.2 Ocean Component

In the older IGSM1 (Prinn *et al.*, 1999), a zonally (longitudinally) averaged mixed layer ocean model with 7.8º latitudinal resolution was used. In the new IGSM2 the ocean component has been replaced by either a 2D (latitude-longitude) mixed layer anomaly-diffusing ocean model (hereafter denoted as IGSM2.2) or a fully 3D ocean GCM (denoted as IGSM2.3).

2.2.1 The two-dimensional mixed layer anomaly diffusing ocean model

The ocean component of the IGSM2.2 consists of a Q-flux mixed layer model with horizontal resolution of 4º in latitude and 5º in longitude, and a 3000 m deep anomaly diffusing ocean model beneath. The mixed layer depth is prescribed based on observations as a function of time and location (Hansen *et al.*, 1983). In addition to the temperature of the mixed layer, the model also calculates the averaged temperature of the seasonal thermocline and the temperature at the annual maximum mixed layer depth (Russell *et al.*, 1985). Diffusion in the deep ocean model is applied to the difference in the temperature at the bottom of the seasonal thermocline relative to its value in a present-day climate simulation (Hansen *et al.*, 1984; Sokolov & Stone, 1998). Since this diffusion represents a cumulative effect of heat mixing by all physical processes, the values of the diffusion coefficients are significantly larger than those used in sub-grid scale diffusion parameterizations in OGCMs. The spatial distribution of the diffusion coefficients used in the diffusive model is based on observations of tritium mixing into the deep ocean (Hansen *et al.*, 1988). For simulations with different rates of oceanic heat uptake, the coefficients are scaled by the same factor in all locations.

The coupling between the atmospheric and oceanic components takes place every hour. Fluxes of sensible and latent heat are calculated in the atmospheric model by bulk formulas with turbulent exchange coefficients dependent on the Richardson number. The atmosphere's turbulence parameterization is also used in the calculation of the flux derivatives with respect to surface temperature. To account for partial adjustment of near surface air temperature to changes in fluxes, the derivatives are calculated under the assumption that the exchange coefficients are fixed. A more detailed discussion of technical issues involved in the calculations of these fluxes and their derivatives, is given in Kamenkovich *et al*. (2002). The heat flux (F_H) at the longitude-latitude point (i, j) is calculated as:

$$F_H(i,j) = F_{HZ}(j) + \frac{\partial F_{HZ}}{\partial T}(j)(Ts(i,j) - Tsz(j)) \tag{1}$$

where

$F_{HZ}(j)$ and $\partial F_{HZ} / \partial T (j)$ are the zonally averaged heat flux and its derivative with respect to surface temperature, and

$Ts(i,j)$ and $Tsz(j)$ are the surface temperature and its zonal mean.

The mixed layer model also includes a specified vertically-integrated horizontal heat transport by the deep oceans, a so-called "Q-flux", allowing zonal as well as meridional transport. This flux is calculated from a simulation in which sea surface temperature (SST) and sea-ice distribution are relaxed toward their present-day climatology with relaxation coefficient of 300 $Wm^{-2}K^{-1}$, which corresponds to an e-folding time scale of about 15 days for a 100 m deep mixed layer. Relaxing SST and sea-ice on such short time scale, while being virtually identical to specifying them, avoids problems with calculating the Q-flux near the sea-ice edge. The use of a 2D (longitude-latitude) mixed layer ocean model instead of the zonally averaged one used in IGSM1 has allowed a better simulation of both the present day sea-ice distribution and sea-ice changes in response to increasing radiative forcing (Sokolov *et al*., 2005).

A thermodynamic ice model is used for representing sea-ice. This model has two ice layers and computes ice concentration (the percentage of area covered by ice) and ice thickness.

The IGSM2.2 includes the same ocean carbon model (Holian *et al*., 2001) as the IGSM1. Formulation of carbonate chemistry in this model is similar to Peng *et al.* (1987). Vertical and horizontal transports of the total dissolved inorganic carbon are parameterized by diffusive processes. The values of the horizontal diffusion coefficients are taken from Stocker *et al.* (1994), and the coefficient of vertical diffusion of carbon (Kvc) depends on the coefficient of vertical diffusion of heat anomalies (Kv). In IGSM1, Kvc was assumed to be proportional to Kv (Prinn *et al.*, 1999; Sokolov *et al.*, 1998). This assumption, however, does not take into account the vertical transport of carbon due to the biological pump. In the IGSM2.2 Kvc is defined as follows:

$$Kvc = Kvco + r\,Kv \tag{2}$$

where the values of $Kvco$ and r were estimated by comparing results of the simulations with the IGSM2.2 and IGSM2.3 (see Section 3.1 for details).

2.2.2 The 3D ocean general circulation model

The 3D ocean component is a major advance in the capabilities of the IGSM. The IGSM1 atmospheric model (with lower resolution than in the IGSM2) had previously been coupled to the MOM2 ocean GCM for studies of ocean response to climate change (Kamenkovich *et al*., 2002, 2003; Dalan *et al*., 2005a,b; Huang *et al*., 2003a,b). This version has also been used in a number of model intercomparison studies (Gregory *et al*., 2005; Petoukhov *et al*., 2005; Stouffer *et al*., 2005). However, as detailed by Dutkiewicz *et al*. (2005), the 3D ocean-seaice-carbon cycle component of the IGSM2.3 is now based on the 3D MIT ocean general circulation model (Marshall *et al*., 1997a,b). As configured for the IGSM2.3, the MIT ocean model has realistic bathymetry, and 4º by 4º resolution in the horizontal with fifteen layers in the vertical (ranging from 50 m at the surface to 500 m thick at depth). Mesoscale eddies, which are not captured in this coarse resolution, are represented by the Gent and McWilliams (1990) parameterization. Embedded in the ocean model is a thermodynamic sea-ice model based on the 3-layer model (two ice layers and a snow layer) of Winton (2000) and the LANL CICE model (Bitz & Lipscome, 1999).

The ocean model has a biogeochemical component with explicit representation of the cycling of carbon, phosphate, dissolved organic phosphorus, and alkalinity. The physical ocean model velocities and diffusion are used to transport these tracers; in addition chemical and biological processes are parameterized. Air-sea exchange of CO_2 follows Wannikof (1992), and carbonate chemistry is calculated following Najjar and Orr (1998), Millero (1995), and the DOE Handbook (1994). There is also a parameterization of the export of organic carbon from the surface waters: biological productivity is modelled as a function of available nutrient (phosphate) and photosythetically available radiation (see Dutkiewicz *et al.*, 2005). A fraction of the biological production in the sunlit surface layers enters a dissolved organic pool that has an e-folding timescale of remineralization of 6 months (following Yamanaka & Tajika, 1997). The remaining fraction of the productivity is instantaneously exported as particulate matter to depth (Yamanaka & Tajika, 1996), where it is remineralized according to the empirical power law relationship of Martin *et al.* (1987). There is also a representation of the calcium carbonate cycle following the parameterization of Yamanaka and Tajika (1996).

The coupling between the atmospheric and 3D oceanic sub-models takes place once a day. The atmospheric model calculates 24-hour averaged surface heat, freshwater and momentum fluxes, and passes these to the ocean model. After receiving these fluxes, the ocean and sea-ice sub-models are integrated for 24 hours (two ocean tracer time steps). At the end of this period, sea surface temperatures, surface sea-ice temperatures, and sea-ice coverage are passed back to the atmospheric sub-model.

The atmospheric sub-model provides heat and fresh-water fluxes separately for open ocean and sea-ice, as well as derivatives with respect to surface temperature. Total heat and fresh-water fluxes for the oceanic sub-model can therefore vary by longitude as a function of ocean sea surface temperature, *i.e*., warmer ocean locations undergo greater evaporation and receive less downward heat flux (similar to the procedure represented in Equation 1). Wind stresses from the atmospheric sub-model are weaker than observations, especially in the Southern Ocean. The oceanic sub-model therefore uses the technique of anomaly coupling: the mean wind stresses, including zonal variations, are taken from the climatology of Trenberth *et al.* (1989), while the anomalies are taken from the atmospheric sub-model. The oceanic sub-model requires adjustments to the atmospheric heat and freshwater fluxes in order to replicate the ocean sea surface temperature and salinity for the later part of the 20th century. The adjustments are calculated as part of the ocean sub-model spin-up. These adjustments are then held fixed for a pre-industrial (year 1860) spin-up of several thousand years and then are also held fixed for the 1860-onward simulation. In this 3D configuration, the ocean-carbon-atmospheric component must be spun-up for several thousand years to reach a pre-industrial (1860) steady state for each set of model parameters (*e.g.*, vertical diffusion). More details of the ocean-carbon-seaice sub-model and its coupling to the atmosphere are provided by Dutkiewicz *et al*. (2005).

3. SIMULATIONS OF THE PAST AND FUTURE CLIMATE

As discussed above, there are significant uncertainties in the characteristics of climate models defining their response to changes in radiative forcing. To obtain probability distributions for the future climate a large number of climate change simulations must be carried out. For example, the distributions presented by Webster *et al.* (2003) are based on the results of 250 simulations with different values of climate sensitivity, strength of aerosol forcing and the rate of oceanic heat and carbon uptake. **Figure 1** shows the probability density function for the effective diffusion coefficient suggested by observations (Forest *et al*., 2005).

The IGSM2.3 version was spun-up to steady state equilibrium for year 1860 atmospheric composition with three different values for ocean vertical diffusion coefficients (*Kz*), namely 0.2, 0.4 and 0.6 cm^2/s. Global mean values of the effective diffusion coefficients (*Kv*) for the IGSM2.2 required to match the behavior of these three versions of the IGSM2.3 were determined from simulations with 1% per year increase in the atmospheric CO_2 concentration using the approach described in Sokolov *et al.*, (2003) and are shown in the Figure 1 by black circles.

Changes in the diffusion coefficient in our current 3D ocean model setup affect ocean circulation as a whole: the strength of the meridional overturning circulation (MOC) in the North Atlantic in the simulations with these three versions is 9, 14 and 17 Sv, respectively. Further

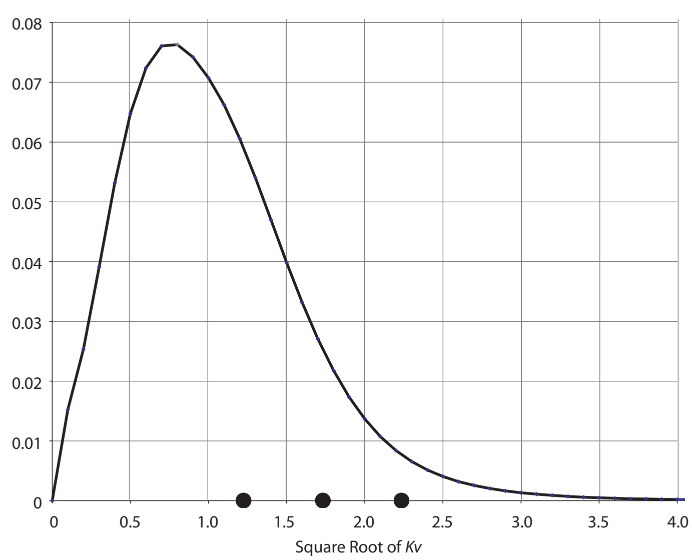

Figure 1. Probability density function for the effective anomaly diffusion coefficient from Forest *et al*., (2005) and values corresponding to the three versions of the IGSM2.3 with different values of vertical diffusion coefficient (large dots).

decrease in the vertical diffusion coefficient leads to an unrealistically weak MOC. Thus it is impossible to produce versions of the IGSM2.3 with the rates of heat uptake in the lower portion of the required range (*i.e.* below median, see Figure 1), at least without additional changes in the structure of the ocean model. Therefore use of the IGSM2.3 in the uncertainty studies is limited. It is worth noting that for the AOGCMs analyzed by Sokolov *et al.* (2003) values of the effective vertical diffusion coefficients also lie in the upper part of the distribution shown in Figure 1.

The climate response of the MIT climate model with ADOM was previously compared with the responses of different coupled AOGCMs only in simulations with prescribed changes in atmospheric CO_2 concentration. The existence of two versions of the IGSM2 that differ only by the ocean sub-component allows us to conduct a more detailed comparison and to define time scales on which a mixed layer anomaly-diffusing ocean model can reproduce behavior of the more sophisticated 3D ocean model.

3.1 Simulations Design

The climate change simulations considered here start in year 1861 from the end of the corresponding spin-up simulation and are conducted in two stages: a simulation with historical forcings and a future climate projection. During the first stage, from 1861 to 1990, the model is forced by the observed changes in greenhouse gas concentrations (Hansen *et al*., 2002), tropospheric and stratospheric ozone (Wang & Jacob, 1998), the solar constant (Lean, 2000), sulfate aerosols (Smith *et al*., 2004), and volcanic aerosols (Sato *et al*., 1993). For this historical forcing stage, carbon uptake by the ocean and terrestrial ecosystems are calculated but not fed back to the atmospheric model. Based on data for anthropogenic carbon emissions and atmospheric CO_2 concentrations, the net land plus ocean carbon uptake should equal about 4.1 GtC per year for the 1980s. In these experiments, the difference between the model actual total land-ocean uptake and this observed value is determined and this additional sink/source is then kept constant during the subsequent forward stage of the simulations.

In the second-stage of the simulations, which begins in 1991, the full version of IGSM2 is forced by the greenhouse gas emissions. Historical greenhouse gas emissions are used through 1996 and emissions projected by the MIT Emissions Predictions and Policy Analysis model (EPPA, Paltsev *et al.*, 2005) from 1997. In this future climate stage of the simulations, all components of the IGSM2 were fully interactive; concentrations of all gases and aerosols were calculated by the atmospheric chemistry sub-model based on anthropogenic and natural emissions and the terrestrial and oceanic carbon uptake provided by the corresponding sub-components.

In this study, two different emission scenarios are used: a “reference” no policy case (Paltsev *et al.*, 2005) and a “stabilization” scenario. In the first scenario (REF) greenhouse gas emissions grow at a rather high rate up to year 2100. To compare model responses under strong forcing, simulations with this scenario were continued until year 2200 with emissions being fixed at their 2100 values. In the second case (STAB), emissions were constructed to ensure stabilization of different greenhouse gases and thereby radiative forcing over a few hundreds years. Simulations with the stabilization scenario were carried out through year 2400. Carbon dioxide emissions for these two scenarios are shown in **Figure 2**.

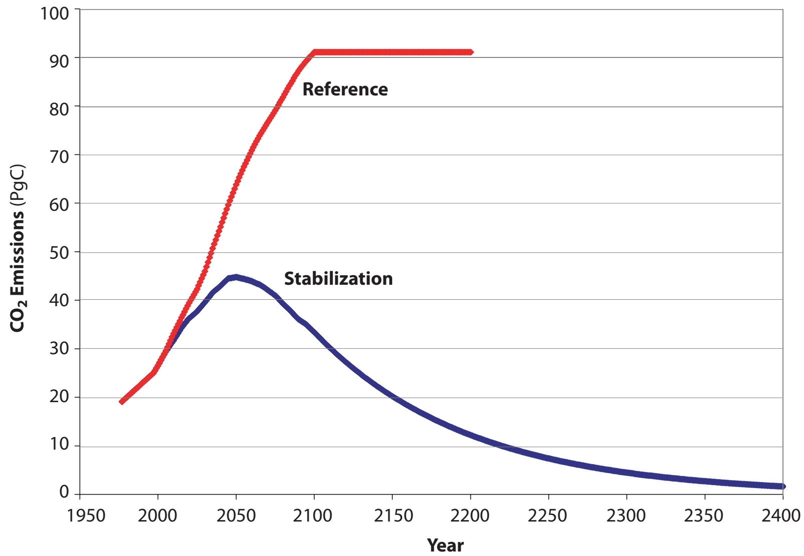

Figure 2. CO_2 emissions in the reference and stabilization simulations.

For a thorough comparison of the climate responses simulated by the IGSM2.2 and IGSM2.3, three simulations with each version of the IGSM were conducted for each of the two emission scenarios. These three simulations differ in some of the parameters that they use: values of these parameters are provided in **Table 1**. Climate sensitivities (*S*) and the strengths of the aerosol forcing were chosen so as to ensure consistency between simulated and observed climate for 20th century (**Figure 3** and Table 1). Climate sensitivity is defined as an equilibrium sensitivity for CO_2 doubling for the IGSM2.2 and as an effective climate sensitivity (Murphy, 1995) at the time of CO_2 doubling for the IGSM2.3. For the IGSM2.2 the sensitivities defined in these two ways are practically identical.

Values of the parameters in the equation for *Kvc* (Equation 2) were estimated so as to ensure consistency of the oceanic carbon uptakes in the historical stage of simulations with the versions of the IGSM2.2 and the IGSM2.3 with similar rates of heat uptake. The values of *Kvco* and *r* that satisfy this requirement are 2.85 cm^2/s and 0.6 respectively.

Table 1. Parameters settings in the simulations with the IGSM2.2 and IGSM2.3.

Simulation	Model	Emission scenario	Climate sensitivity (^0C)	Aerosol forcing for 1980s (Wm^{-2})	Vertical diffusion coefficient (cm^2s^{-1})	Effective diffusion coefficient (cm^2s^{-1})
REF31	IGSM2.3	REF	1.5	–0.1	0.2	
REF32	IGSM2.3	REF	2.0	–0.35	0.4	
REF33	IGSM2.3	REF	3.0	–0.7	0.6	
REF21	IGSM2.2	REF	1.5	–0.1		1.5
REF22	IGSM2.2	REF	2.0	–0.35		3.0
REF23	IGSM2.2	REF	3.0	–0.7		5.0
STAB31	IGSM2.3	STAB	1.5	–0.1	0.2	
STAB32	IGSM2.3	STAB	2.0	–0.35	0.4	
STAB33	IGSM2.3	STAB	3.0	–0.7	0.6	
STAB21	IGSM2.2	STAB	1.5	–0.1		1.5
STAB22	IGSM2.2	STAB	2.0	–0.35		3.0
STAB23	IGSM2.2	STAB	3.0	–0.7		5.0

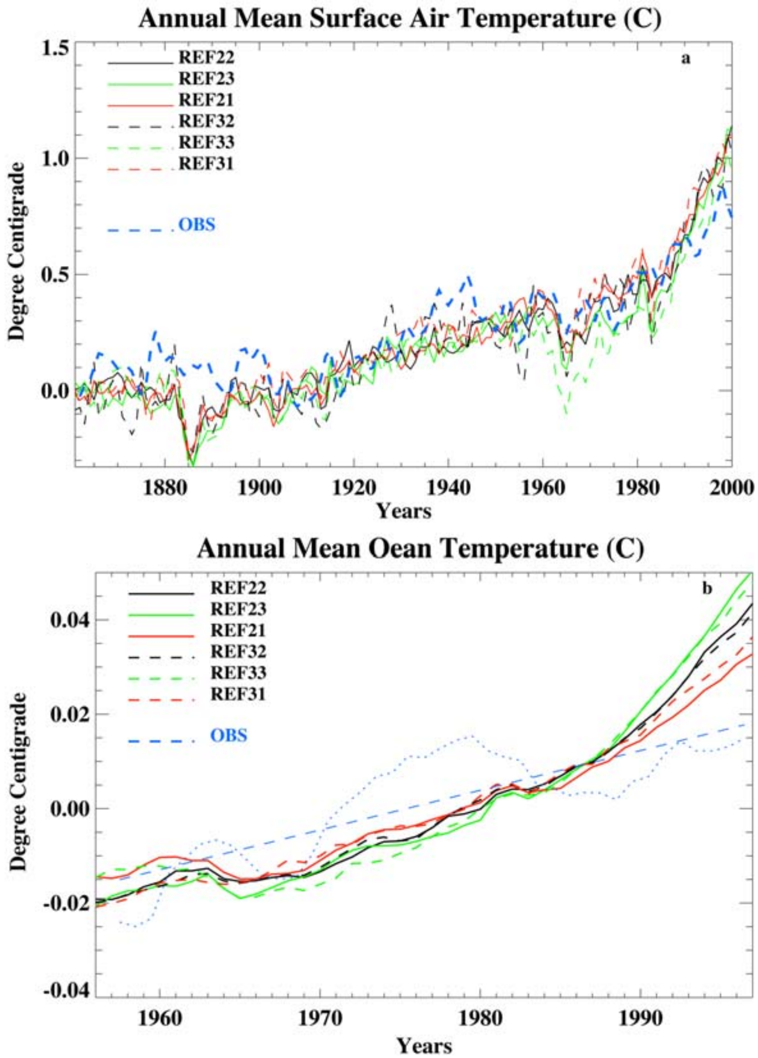

Figure 3. Changes in **(a)** global mean annual mean surface air temperature and **(b)** ocean temperature for top 3000 meters in simulations with IGSM2.2 and IGSM2.3. Observations are from Jones (2003) and Levitus *et al.* (2005), respectively. Dotted blue observations line on bottom panel shows five year means and dashed blue line estimated linear trend.

3.2 Results

The two versions of the IGSM produce similar warming trends in the historical forcing stage (Figure 3), illustrating that he IGSM2.2 matches the response of the IGSM2.3 in simulations with multiple anthropogenic and natural forcings. The apparent overestimation of the warming trend in the late 20th century, especially in the ocean, is probably caused by the fact that the models are forced by observed forcings only through 1990. Therefore the impact of the Pinatubo eruption in 1991 is not taken into account.

The IGSM2.2 reproduces reasonably well the changes in the annual global mean surface air temperature (SAT) projected by the IGSM2.3 for all combinations of parameters and for both emission scenarios (**Figure 4**). SAT increases predicted by the two versions of the model agree in the corresponding simulations within 0.5ºC. Moreover zonally averaged distributions of

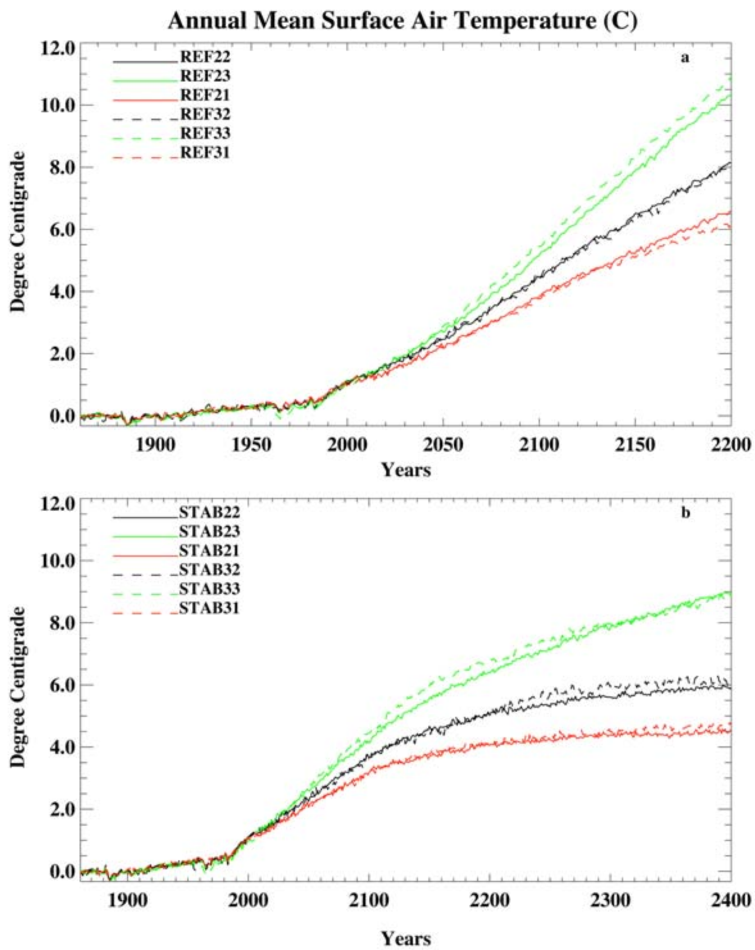

Figure 4. Changes in global mean annual mean surface air temperature in simulations with **(a)** reference and **(b)** stabilization emission scenarios.

changes in temperature in the last decade of 21st century as simulated by IGSM2.2 and IGSM2.3 (**Figure 5**a and 5c) are overall very close except in the polar regions where slightly different changes in sea-ice cover cause corresponding differences in temperature changes. These zonal distributions are shown for the simulations with reference emission scenarios. Differences are even smaller in the stabilization simulations where the forcing is weaker. The differences in sea-ice cover (Figure 5b) are, to a large part, related to differences in how the flux adjustment is calculated in the IGSM2.2 and IGSM2.3. In the spin-up simulation with the ISGM2.2 both sea surface temperature and sea-ice are relaxed toward the observations, while in the IGSM2.3 spin-up relaxation is applied only to temperature and only from 60ºS to 60ºN. Seaice sub-models used in the IGSM2.2 and IGSM2.3 are also different. As a result, sea-ice cover in the equilibrium pre-industrial climate simulations with the IGSM2.2 and IGSM2.3, as well as sea-ice changes in the simulations discussed here, are somewhat different. In all simulations with the reference emission scenario the IGSM2.2 produces noticeably larger decrease in sea-ice cover (Figure 5b and **Figure 6**a). In the stabilization case large differences occur only between the simulations with high climate sensitivity (Figure 6b).

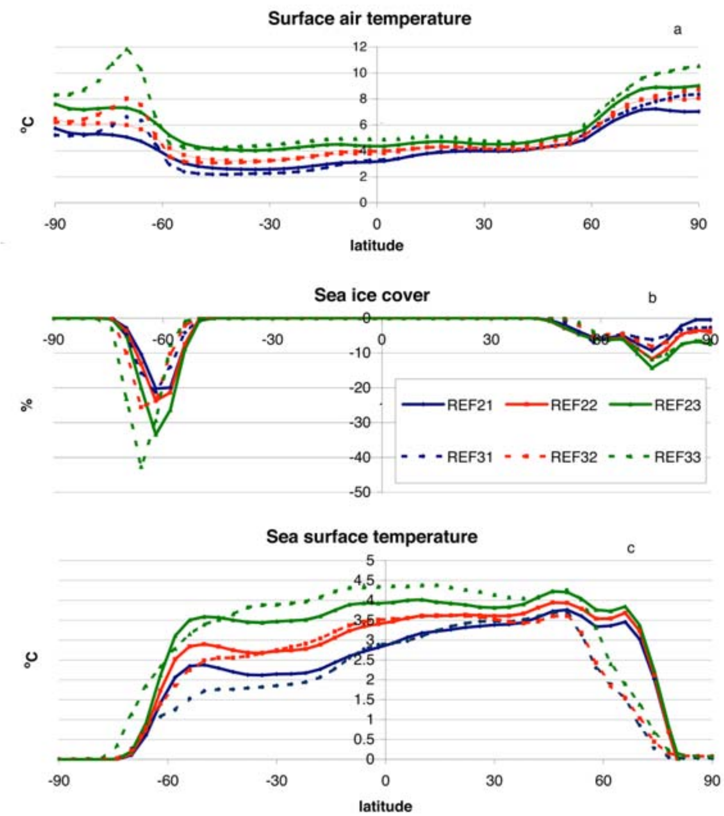

Figure 5. Changes in zonally averaged **(a)** surface air temperature, **(b)** sea-ice cover, and **(c)** sea surface temperature in the simulations with reference emission scenario. Difference between decadal means 2091-2100 and pre-industrial equilibrium climate.

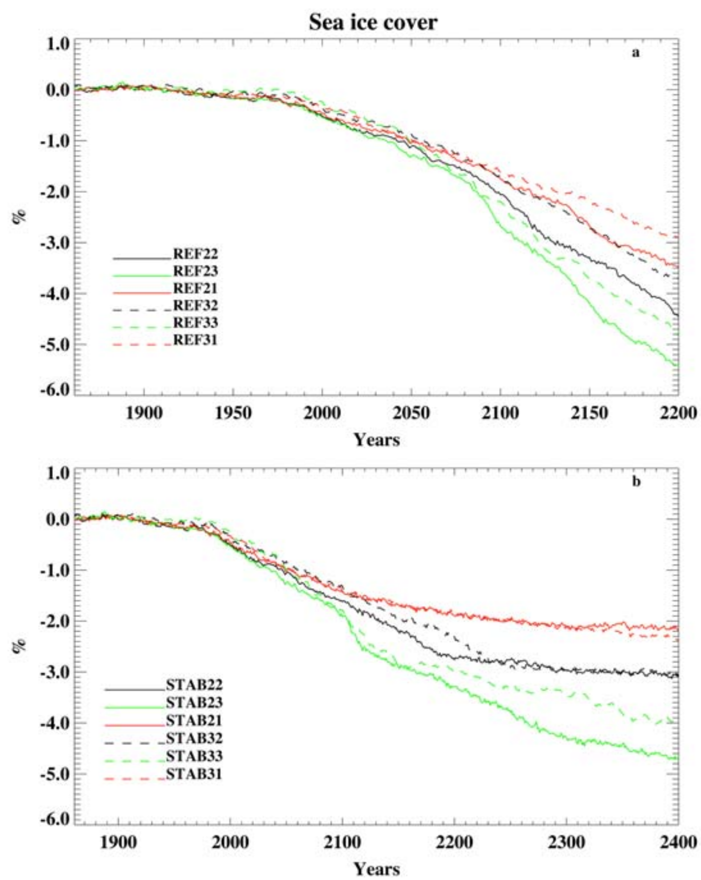

Figure 6. Changes in global mean annual mean sea-ice cover in simulations with **(a)** reference and **(b)** stabilization emission scenarios.

There is a good agreement in sea level rise due to thermal expansion of the ocean as projected by the two versions of the IGSM for the historical forcing stage, and for about 100 years of the future forcing stage. By year 2100 the two versions differ by less than 2 cm in the corresponding simulations (**Figure 7**). However, the IGSM2.2 begins to overestimate increase in sea level after about year 2150. At the end of the simulations with stabilization emissions scenario sea level rise simulated by the IGSM2.2 is about 20-25% larger that that simulated by the IGSM2.3.

Figure 8 shows the zonally averaged temperature changes with depth in the STAB22 (right column) and STAB32 (left column) simulations. In spite of its simplicity, the ADOM reproduces ocean temperature changes from the pre industrial equilibrium state simulated by the 3D ocean model through the middle of the 21st century. However by year 2100 the structure of the deep ocean warming for the two versions of the model begins to look quite different. The IGSM2.2 overestimates the depth of the warming at high latitudes more severely later in the integration. During the second half of the 21st century, an excessive warming at high latitudes is compensated by an under-estimate of tropical warming sustaining a good agreement for the global sea level rise (Figure 7), but later there is no longer enough compensation and an increasing overestimate of the sea level rise occurs.

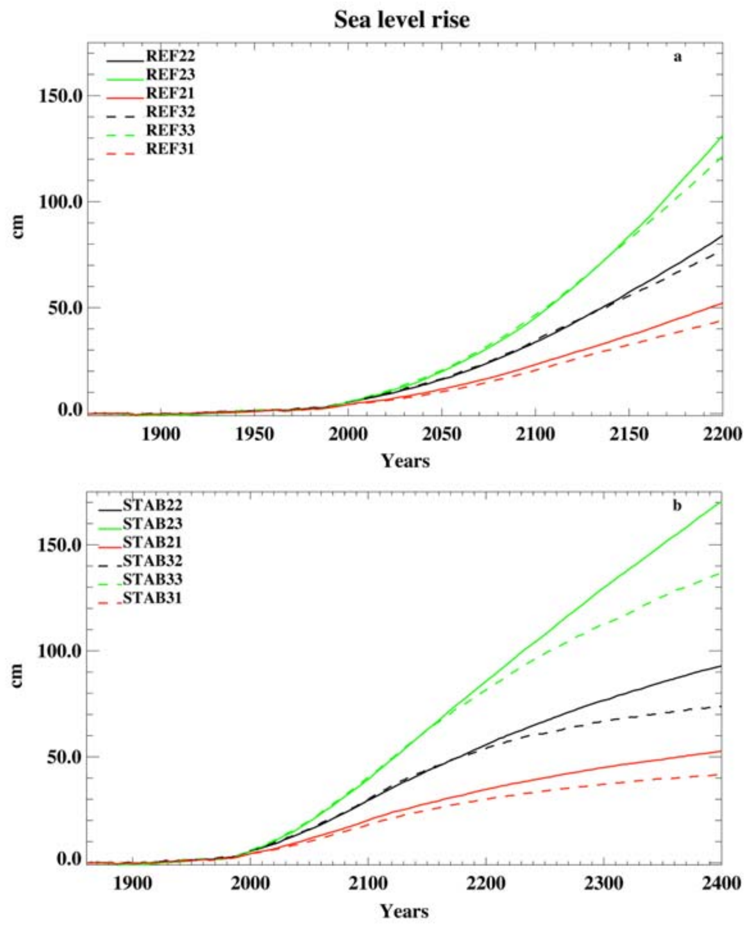

Figure 7. Changes in global mean annual mean sea level rise due to thermal expansion in simulations with **(a)** reference and **(b)** stabilization emission scenarios.

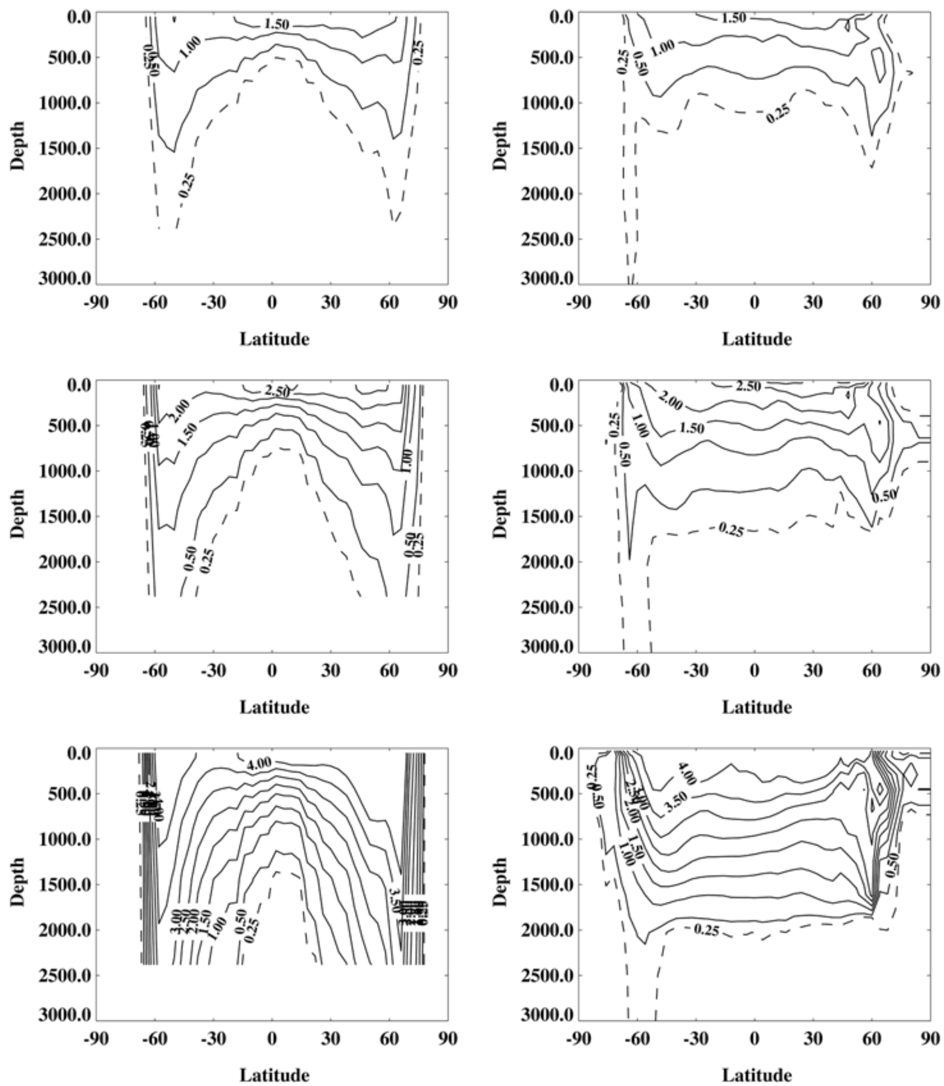

Figure 8. Changes in ocean temperature from the pre-industrial equilibrium averaged over years 2041-2050 (top), 2091-2100 (middle) and 2291-2300 (bottom), in simulations STAB22 (right) and STAB32 (left).

It is interesting to note that mixing of heat to the deep ocean can be approximated by the diffusion of mixed layer temperature anomalies in spite of significant changes in the strength of the meridional overturning circulation occurring during 21st century (**Figure 9**). On the long time scales, though, this assumption does break down.

The ability of the IGSM2.2 to simulate oceanic carbon uptake is even more limited in time. Both versions of the IGSM parameterize the air-sea flux of CO_2 in a similar manner. However, while the 3D ocean model transports carbon away from the surface by ocean dynamical processes and by an explicit (if simple) parameterization of the sinking of organic material, the IGSM2.2 relies entirely on effective diffusion. (Though, the component of vertical diffusion of carbon independent of the diffusion of heat anomalies (Equation 2) can be considered as a very simplified representation of the biological pump.)

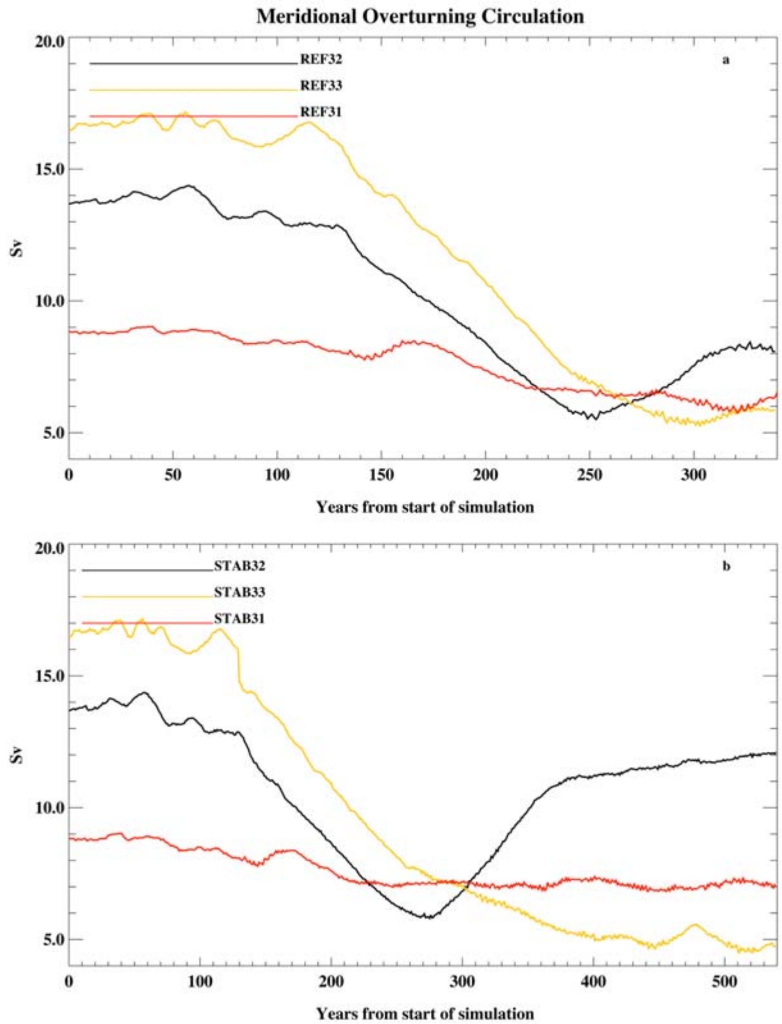

Figure 9. Changes in global mean annual mean meridional overturning circulation in **(a)** simulations with reference and **(b)** stabilization emission scenarios.

As a result of the appropriate choice of parameters defining the vertical diffusion of carbon in the IGSM2.2, carbon uptake by the ocean compares well in simulations with different versions of the model through the 1990s (**Figure 10** and **Table 2**). However, because the IGSM2.2 does not include the feedbacks between changes in ocean circulation, biological productivity and carbon uptake by the ocean there are significant differences in the carbon cycle simulated by the IGSM2.2 and IGSM2.3 in the second stage of the simulations. In the IGSM2.2 simulations with the reference emission scenario, carbon uptake by the ocean continues to increase through year 2100 (Figure 10a), although somewhat more slowly during the latest part of the simulations. In contrast, in the IGSM2.3 simulations uptake reaches a maximum of about 4 GtC/yr around 2070; uptake then starts to decrease even though CO_2 emissions continue to increase. Carbon dioxide is less soluble in warmer water, so the ocean solubility pump becomes less efficient with the increase in the SST and limits carbon uptake by the ocean. This mechanism, cited as a major feedback in the ocean carbon cycle by several authors (*e.g.*, Matear *et al.*, 1999, Chuck *et al.*, 2005), operates in both versions of the model.

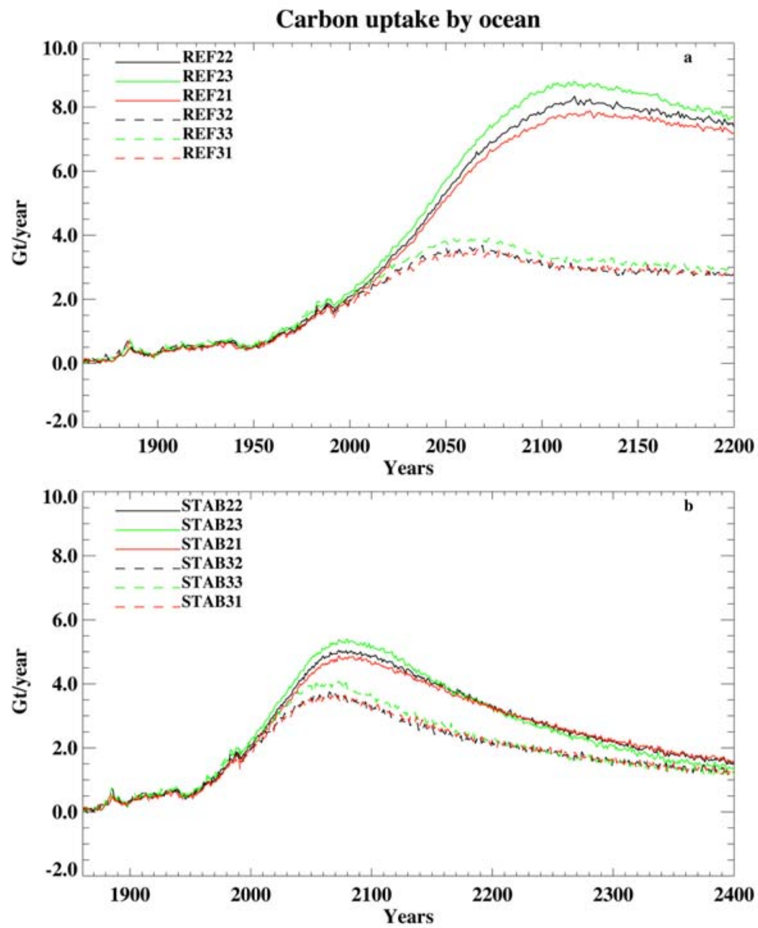

Figure 10. Changes in global mean annual mean oceanic carbon uptake in simulations with **(a)** reference and **(b)** stabilization emission scenarios.

Table 2. Oceanic carbon uptake (GtC per year) averaged over years 1981-1990 in the simulations with the IGSM2.2 and IGSM2.3

Kz/Kv	IGSM2.3	IGSM2.2
0.2/1.5	1.61	1.60
0.4/3.0	1.69	1.69
0.6/5.0	1.87	1.83

Changes to the ocean circulation (Sarmiento *et al*., 1998; Chuck *et al*., 2005; Matear & Hirst, 1999) and potentially decreased biological productivity (Chuck *et al*., 2005) have also been cited to reduce the ability of the ocean to take up carbon. In the 3D model there is a substantial change to the circulation, for instance a slowing of deep water formation as seen in the MOC strength (Figure 9), with particularly large changes seen in the 21st century. This results in lower rate with which additional carbon is removed to depth. This feedback mechanism is not captured by the diffusive model, leading it to overestimate the transport of carbon to depth. The 3D model carbon component also includes the affect of biology in removing carbon from surface waters, and this too changes significantly in the 21st century: as surface waters become more stratified, less nutrient reach the euphotic layer, and global productivity, and therefore carbon export is reduced (see Dutkiewicz *et al.*, 2005). This process, too, is not captured in the diffusive ocean model. The ability of water to take up carbon from the atmosphere reduces markedly when it has a higher dissolved inorganic carbon concentration—thus there is an intensification of the differences between the two ocean models uptake. As a result, by the year 2100, carbon flux into the ocean in the simulations with the IGSM2.2 is more than twice as large as in simulations with the IGSM2.3 in the reference scenario. In the stabilization simulations carbon uptake by the ocean as simulated by the two versions of the IGSM look more similar (Figure 10b), both following the emission pattern, but the above problems with the diffusive model taking carbon away from the surface quicker than the 3D model in the future scenarios still occurs: the IGSM2.2 overestimates the cumulative carbon uptake in these simulations by about 35-40%.

Because of the much smaller ocean-carbon sink simulated by the IGSM2.3, atmospheric CO_2 concentration estimates for 2100 are higher in the IGSM2.3 by about 30-50 ppm (**Figure 11**) than those predicted in the IGSM2.2 in simulations with both emission scenarios; final CO_2 concentrations are higher by about 120-150 ppm. Due to the logarithmic dependency of radiative forcing on CO_2 concentration, the differences in forcing (**Figure 12**) during the 21st century are too small to have an effect on the surface warming or sea level rise produced by the two model versions. Even at the end of the simulations the difference in radiative forcing produced by the

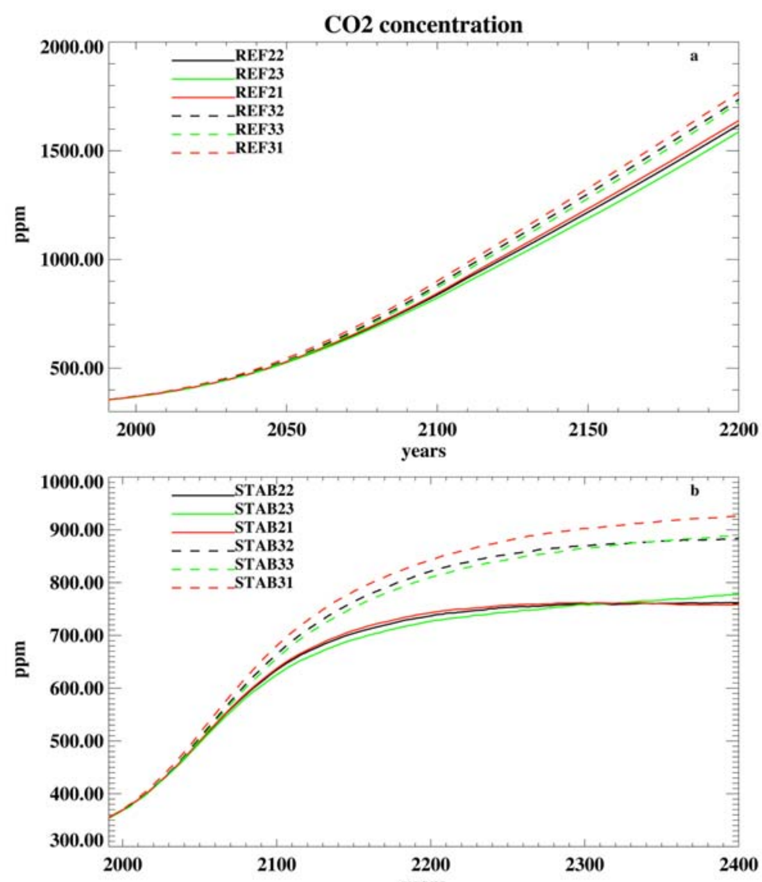

Figure 11. Changes in global mean annual mean atmospheric CO_2 concentration in simulations with **(a)** reference and **(b)** stabilization emission scenarios.

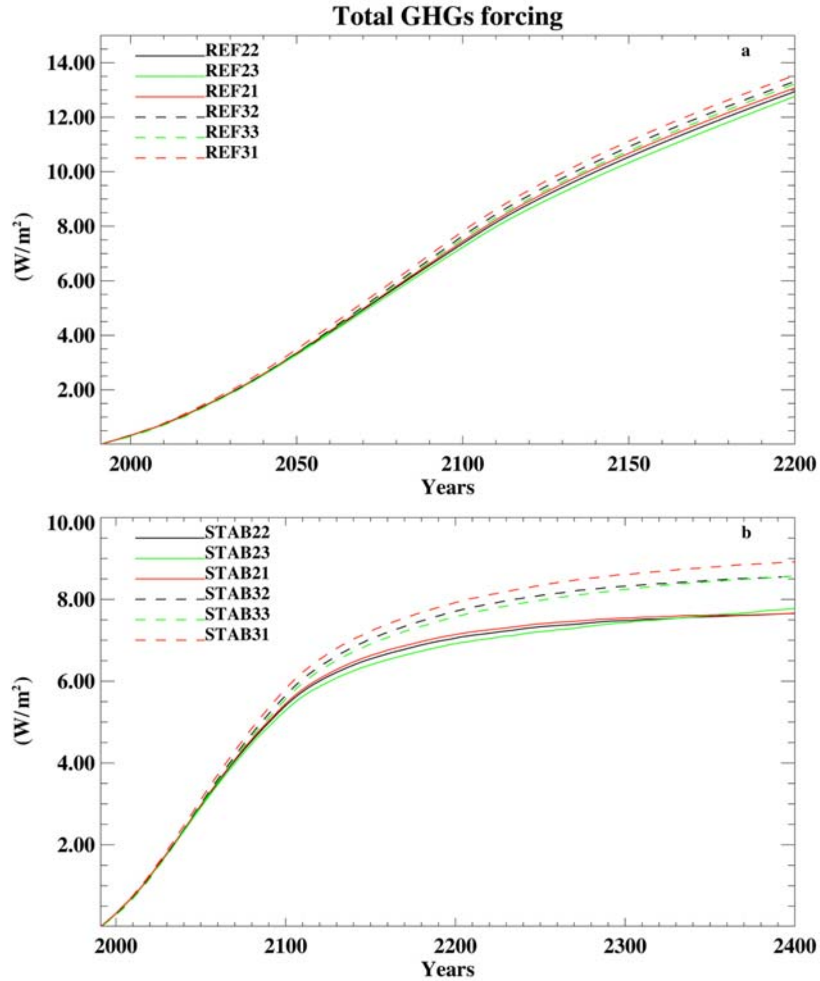

Figure 12. Changes in global mean annual mean radiative forcing due to greenhouse gases in simulations with **(a)** reference and **(b)** stabilization emission scenarios.

IGSM2.2 and the IGSM2.3 is less than 1.5 W/m^2. The difference in the equilibrium surface warming in the simulations with climate sensitivity of 3ºC due to such difference in forcing is slightly more than 1ºC. Difference in the transient warming should be even smaller. In addition, the larger decrease in the sea-ice cover in simulations with the IGSM2.2 (Figure 6) leads to stronger surface albedo feedback. This will compensate for a weaker forcing, making changes in SAT (Figure 4) closer in the corresponding simulations with the IGSM2.2 and IGSM2.3.

It should be noted that the values of climate sensitivity used in the simulations are relatively low. For larger values of sensitivity the impact of the differences in forcing on changes in SAT and other climate variables would be more significant.

4. CONCLUSIONS

The MIT IGSM was designed to provide probabilistic forecasts of future climate under different greenhouse gas emission scenarios. Such forecasts require large ensembles of climate change simulations in which climate system parameters, including rate of heat and carbon uptake by the ocean, must be varied. Changing the rate of ocean uptakes over a wide enough range is easy to achieve in a anomaly diffusing ocean model but is rather difficult in the full 3D ocean GCM, in part due to the necessity to maintain a reasonable circulation. This makes the use of the IGSM version incorporating the 3D OGCM for estimating uncertainty in future climate change problematic.

The goal of this study was to define time scales for which the mixed layer anomaly diffusive ocean model is able to capture the climate response of the 3D ocean GCM. Comparison of climate change simulations with the two versions of the IGSM2 shows that the IGSM2.2 reproduces changes in both surface and ocean temperatures simulated by the IGSM2.3 from pre-industrial time through the end of the 21st century. However, on longer time scales the assumption that changes in the ocean temperature can be described by the diffusion of the mixed layer temperature anomalies breaks down, leading to overestimation of the deep ocean warming and sea level rise due to thermal expansion by the IGSM2.2.

The inability to simulate changes in the ocean circulation and the lack of explicit parameterization of ocean biology, leads the IGSM2.2 to poorly depict the uptake of carbon by the ocean beyond the mid-21st century, and therefore underestimates atmospheric CO_2 concentrations. Associated differences in the radiative forcing simulated by the two versions of the model do not become significant, however, until a few decades later.

It should be kept in mind that the possible impact of climate change on human society is largely defined by changes in surface air temperature and sea level. Therefore, differences in other variables in simulations with different versions of the model are important to the extent to which they affect changes in these two variables.

Results of this study allow us to conclude that the IGSM2.2 is an adequate tool for producing probability distributions of possible changes in surface air temperature and sea level over the 21st century. On the other hand, an estimation of the long-term effects of changes in greenhouse gas emissions, in particular those studies aimed at stabilizing atmospheric greenhouse gas concentrations, will require multi-century simulations. In such simulations the use of the 3D ocean GCM is essential.

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