MIT Joint Program on the Science and Policy of Global Change

Sensitivity of Climate Change Projections to Uncertainties in the Estimates of Observed Changes in Deep-Ocean Heat Content

A.P. Sokolov, C.E. Forest, and P.H. Stone

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Abstract

The MIT 2D climate model is used to make probabilistic projections for changes in global mean surface temperature and for thermosteric sea level rise under a variety of forcing scenarios. The uncertainties in climate sensitivity and rate of heat uptake by the deep ocean are quantified by using the probability distributions derived from observed 20th century temperature changes. The impact on climate change projections of using the smallest and largest estimates of 20th century deep ocean warming is explored. The impact is large in the case of global mean thermosteric sea level rise. In the MIT reference ("business as usual") scenario the median rise by 2100 is 27 and 43 cm in the respective cases. The impact on increases in global mean surface air temperature is more modest, 4.9 C and 3.9 C in the two respective cases, because of the correlation between climate sensitivity and ocean heat uptake required by 20th century surface and upper air temperature changes. The results are also compared with the projections made by the IPCC AR4's multi-model ensemble for several of the SRES scenarios. The multi-model projections are more consistent with the MIT projections based on the largest estimate of ocean warming. However the range for the rate of heat uptake by the ocean suggested by the lowest estimate of ocean warming is more consistent with the range suggested by the 20th century changes in surface and upper air temperatures, combined with expert prior for climate sensitivity.

Contents

1. INTRODUCTION

There are significant uncertainties in the characteristics of the climate system which define its response to external forcing, such as climate sensitivity, strength of aerosol forcing and the rate of deep ocean heat uptake (*e.g.* Andronova and Schlesinger 2001; Frame *et al*. 2005; Forest *et al*. 2006; Knutti *et al*. 2006). Consequently anthropogenic climate change can be described only in probabilistic terms, even when changes in the concentrations of greenhouse gases (GHGs) and aerosols are prescribed (*e.g.* Knutti *et al*. 2003). To account for such uncertainties, projections of future changes in global mean surface air temperature (SAT) presented in the IPCC AR4 (Meehl *et al*. 2007) are based in part on a multi-model ensemble of simulations with coupled atmosphere-ocean general circulation models (AOGCMs).

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There are, however, well known problems with the use of so-called “ensembles of opportunity” (Tebaldi and Knutti 2007). Among them are difficulties with defining the relative weights of different models and the fact that existing AOGCMs do not cover the full range of uncertainty in climate sensitivity and the rate of oceanic heat uptake. By contrast, earth system models of intermediate complexity can be used effectively for producing probabilistic predictions of future climate changes, due to their computational efficiency and ability to vary the above mentioned characteristics over wide ranges.

Here we use the climate component of the MIT Integrated Global System Model (Sokolov *et al*. 2005) to evaluate the climate response and its associated uncertainty when we prescribe the forcing from four different scenarios. The probability distributions for the uncertain input parameters were obtained by comparing 20th Century temperature changes as simulated by the MIT model with available observations (Forest *et al*. 2006). In particular we use the probability distributions obtained this way when they are combined with an expert prior on climate sensitivity (Forest *et al*. 2006).

Distributions presented by Forest *et al*. (2006) are based on data for the trend in the ocean temperature averaged the 0-3km layer from Levitus *et al*. (2005). There are, however, significant differences between estimates of changes in deep ocean temperature obtained in different studies (Gouretski and Koltermann 2007; Domingues *et al*. 2008). To evaluate the impact of these differences on climate projections, we constructed two additional sets of input parameters distributions and carried out additional ensembles of 21st century climate simulations for two forcing scenarios. We also compare these projections with projections produced by the ensemble of AR4 AOGCMs.

2. MODEL DESCRIPTION

The climate model used in this study, as well as in Forest *et al.* (2006), is a modified version of the model described by Sokolov and Stone (1998). It consists of a 2-dimensional (zonally averaged) statistical-dynamical atmospheric model coupled to an ocean mixed layer model with temperature anomalies diffused below the mixed layer. The atmospheric model is derived from the Goddard Institute for Space Studies (GISS) Model II general circulation model (GCM) (Hansen *et al*. 1983) and uses parameterizations of the eddy transports of momentum, heat and moisture by baroclinic eddies (Stone and Yao 1987, 1990). The model uses the GISS radiative transfer code which contains all radiatively important trace gases as well as aerosols. The surface area of each latitude band is divided into fractions of land, ocean, land-ice and sea-ice, with the surface fluxes and surface temperature computed separately for each surface type. The version used here has 4 degree latitudinal resolution and 11 layers in the vertical. The Q-flux ocean mixed layer model and the thermodynamic sea-ice model have 4 degree by 5 degree latitude-longitude resolution and are described by Hansen *et al*. (1984).

The climate sensitivity of the atmospheric model (S) can be changed by varying the strength of the cloud feedback (Sokolov and Stone 1998), while the rate of deep oceanic heat uptake can be changed by varying the value of the global mean diffusion coefficient (Kv) used to mix ocean temperature anomalies below the mixed layer. In spite of the simplicity of the MIT 2D model, it has been shown to be able, with the appropriate choice of the model's parameters (S, Kv) and the same forcing scenario, to reproduce the behavior of different AOGCMs over a wide range of climate sensitivities and rates of oceanic heat uptakes (Sokolov and Stone 1998; Sokolov *et al*. 2003). Fits for different AOGCMs are obtained using results from their simulations with increasing atmospheric CO_2 concentrations. Reproducing the AOGCM results for other forcing scenarios, such as the SRES scenarios, is more complicated. In some cases different sets of forcing agents were taken into account in the simulations of climate for 20th and 21st centuries with different AOGCMs. In addition, the strengths of aerosol forcing and the efficacies of different forcings vary among models.

As a result differences in the "climate forcing"[1] among AOGCMs (**Figure 1**), are significantly larger than differences in CO_2 forcing (Forster and Taylor 2006). However, if for a particular forcing scenario the "climate forcing" for a given AOGCM is similar to the "climate forcing" simulated by the MIT 2D model, then the version of the MIT model, reproducing the behavior of this AOGCM for changes in CO_2 only, also reproduces its behavior for that forcing scenarios (**Figure 2**).

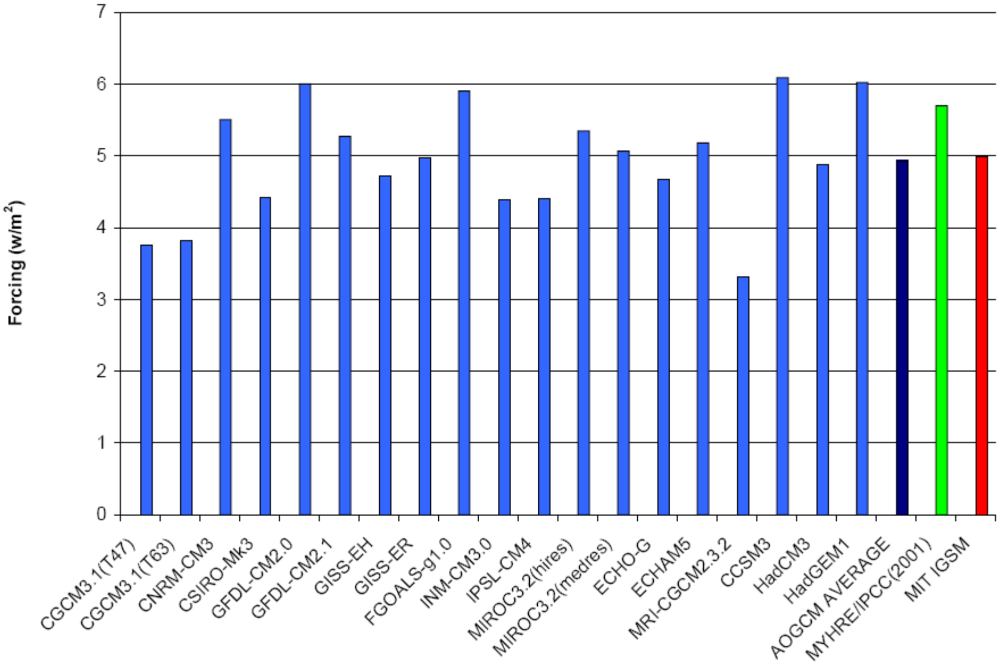

Figure 1. Climate forcing for SRES A1B in the last decade of the 21st century relative to present (1980-1999) for AR4 AOGCMs, MIT IGSM and from Myhre *et al*. (2001).

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[1] "Climate forcing" for a given scenario is calculated from the changes in SAT and heat flux at the top of the atmosphere using the feedback parameter estimated from the simulation with 1% per year CO_2 increase (Forster and Taylor, 2006)

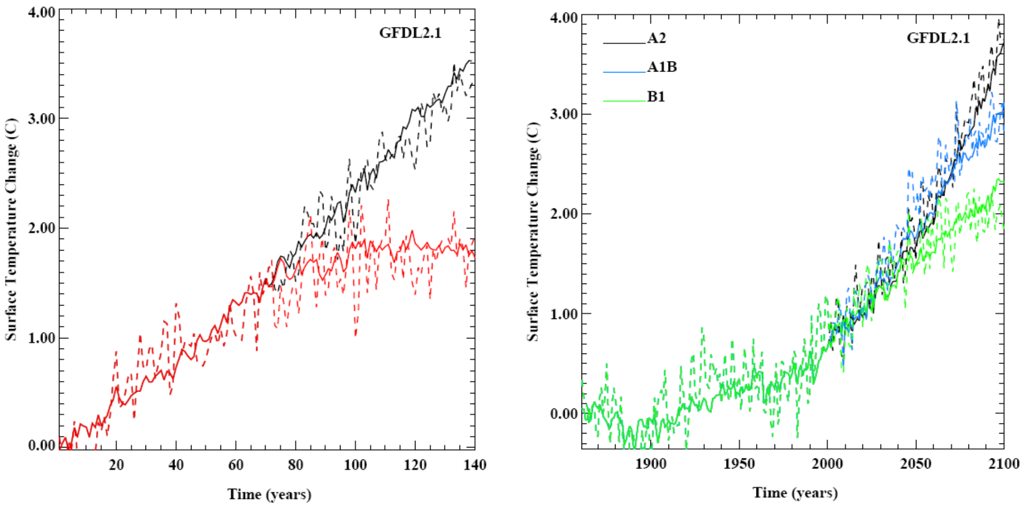

Figure 2. Change in global mean annual mean surface air temperature simulated by the GFDL 2.1 model (dashed lines) and the corresponding version of the IGSM (solid lines) in the simulations with 1% per year CO_2 increase (top) and with SRES A2, A1B and B2 scenarios (bottom).

3. PROBABILITY DISTRIBUTIONS OF INPUT CLIMATE PARAMETERS

Performing probabilistic climate forecast requires knowledge of probability distributions for climate system parameters determining model response to an external radiative forcing. Forest *et al*. (2002) proposed a method for obtaining such distributions based on comparison of the results of 20th century climate simulations with observational records of surface, upper air and deep ocean temperature changes. Distributions presented by Forest *et al*. (2002, 2006 and 2008) were obtained using estimates of changes in deep ocean heat content provided by Levitus *et al*. (2005). However, several other estimates have been published in the last few years (*e.g.* Gouretski and Koltermann 2007; Ishii *et al*. 2006; Carton and Santorelli (2008); Domingues *et al*. 2008). The methods used in different studies vary in their treatment of sub-surface temperature measurements from different types of instruments (MBT, XBT and so on) as well as in the methods used to estimate changes in data-sparse regions. Only three papers, Levitus *et al*. (2005), Gouretski and Koltermann (2007) and Domingues *et al*. (2008) (LAB05, GK07 and DOM08 hereafter) provide observationally based estimates of changes in the ocean heat content for the 0-3000 m layer (**Figure 3**). All the others give results for the upper 700m only. When we re-did our analyses using trends based on just the upper 700 m we found that they did not introduce any constraints on the climate parameters beyond those resulting from using just the upper air and surface temperature data. This lack of impact is due to the strong correlation between upper-ocean and sea surface temperatures and the large natural variability of the upper ocean layers.

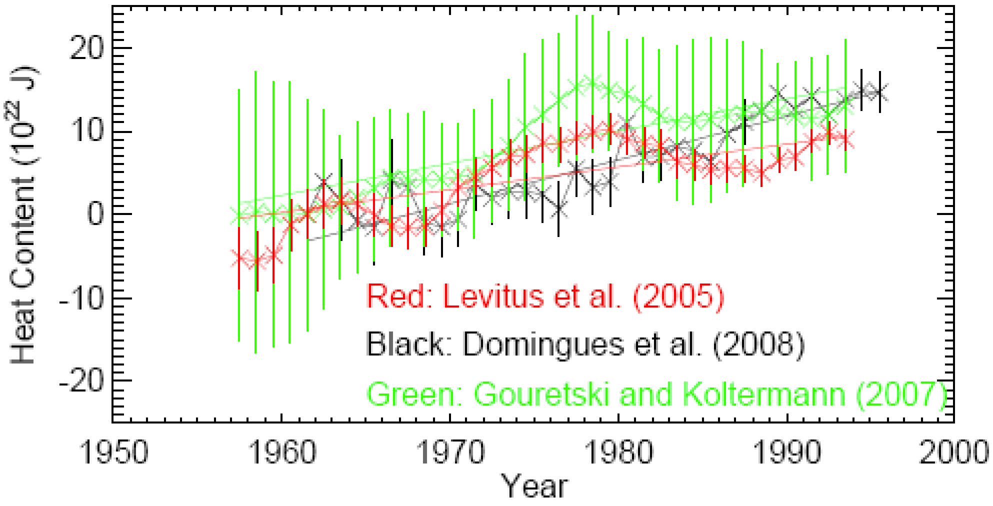

Figure 3. Changes in ocean heat content from LAB05 (red) , GK07 (green) and DOM08 (black) for the 0-3000m layer as estimated by each group. Five year running means were applied to the GK07 data and the errors combined appropriately. The error bars are nominally 1-sigma standard errors but represent different sources of uncertainty in each case.

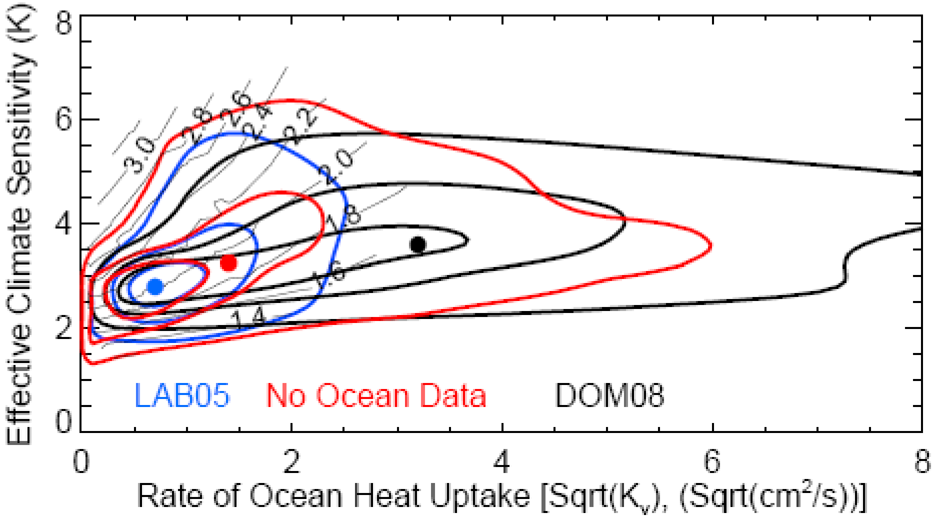

Figure 4. The marginal posterior probability density function for S-Sqrt(Kv) parameter space obtained using data for surface, upper-air and deep-ocean temperatures by LAB05 (blue) andDOM08 (black) and using surface and upper-air temperatures only (No Ocean data) (red). Thick contours denote rejection regions for significance levels of 90%, 50% and 10% respectively. Red dots indicate the median values from respective 1D marginal distributions. Thin contours show values of TCR from a 250-member ensemble of simulations with the input probability distributions based on the LAB05 data.

Figure 4 shows the marginal posterior probability density functions for the S-Sqrt(Kv) parameter space (Sqrt(Kv) = $\sqrt{Kv}$) obtained using the LAB05 and DOM08 estimates for changes in deep ocean temperature and their respective estimates of the uncertainty in the trends[2]. These estimates are respectively the smallest and largest estimates of the 0-3000m trend. We note that each of these trends lie outside the uncertainty range cited for the other trend, and thus the published uncertainty estimates are almost certainly underestimates. Therefore we also include in Figure 4 for comparison the distribution constructed without the use of any ocean data (*i.e.*, No Ocean data, hereafter, NO). We note that the probability distributions for climate parameters obtained using upper-ocean (0-700m) data are almost identical to the NO distribution. The use of the LAB05 and DOM08 analyses strongly affects the range of acceptable values of the rate of oceanic heat uptake (**Table 1**). However, due to the correlation between climate sensitivity and the rate of oceanic heat uptake imposed by the data on surface air temperature, changes in SAT in response to a 1% per year increase in CO_2 concentration in simulations with the median values of S and Kv from the different parameter distributions are not very different (see Figure 4).

Table 1. Percentiles of marginal distributions of Sqrt(Kv) obtained under different assumptions on deep ocean temperature changes.

	2.5%	**5.0%**	**25.0%**	**50.0%**	**75.0%**	**95.0%**	**97.5%**
LAB05	0.12	0.20	0.46	0.73	1.12	1.87	2.16
NO	0.14	0.24	0.75	1.47	2.45	5.39	6.44
DOM08	0.44	0.65	1.87	3.16	4.74	7.00	7.46

4. SIMULATIONS

First we carried out three 250-member ensembles of simulations from year 1860 to year 2000, using different values of the climate sensitivity, the rate of the oceanic heat uptake and the strength of the aerosol forcing for each of the distributions based on the LAB05, NO, and DOM08 results. Different combinations of model parameters controlling these characteristics were chosen using the Latin Hypercube Sampling algorithm (Iman and Helton, 1988) from the probability density functions described in the previous section. The distribution of each model parameter was divided into 250 segments of equal probability and sampling without replacement was performed, so that every segment was used once. Details on the sampling procedure can be found in Webster *et al*. (2003).

In each simulation, the MIT 2D climate model was forced by the observed changes in GHGs, stratospheric aerosols from volcanic eruptions, tropospheric and stratospheric ozone, solar irradiance and changes in vegetation due to land use change. Details of the forcings are given in Forest *et al*. (2006). As can be seen from **Figure 5**, changes in SAT in simulations with median values of climate parameters from all three distributions agree well with observations. Then we carried out a number of 250-member ensembles of simulations for several forcing scenarios

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[2] The LAB05 analysis has recently been updated to take into account the systematic errors in the XBT data noted by GK07. The result, which is available on the NOAA website, is not appreciably different from the LAB05 result.

using different distributions of the climate parameters (**Table 2**). Each simulation was started from the end of the corresponding 20th Century simulation and simulated years 2001-2100. Data for GHG concentrations for the SRES scenarios B1, A1B and A2 scenarios were taken from the web site of the Goddard Institute for Space Studies (http://data.giss.nasa.gov/modelforce/ghgases/GCM_2004.html). In addition to changes in CO_2 (ISAM reference), N_2O, CH_4, CFC-11 and CFC-12, these data include changes in additional trace gases (Hansen and Sato, 2004). Changes in the loading of sulfate aerosols were prescribed according to the IPCC TAR's description (Houghton *et al*. 2001). Changes in black and organic carbon aerosols were not included.

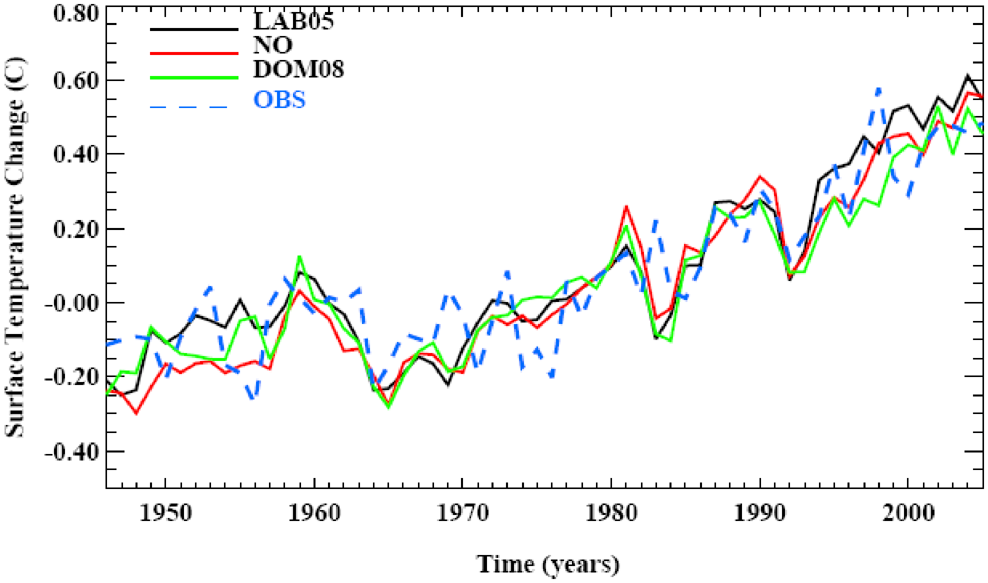

Figure 5. Changes in global-mean annual-mean surface air temperature in simulations with median values of climate parameter from different distributions. Observations are from Jones (2003).

In the simulations with the MIT REF scenario we used GHG and sulfate aerosol concentrations obtained in a reference simulation with the full version of the MIT IGSM2.2 with "business as usual" emissions. Detailed information on this scenario can be found in Prinn *et al*. (2008). It is worth noting that the total radiative forcing and SAT changes in simulations with the MIT REF scenario are close to those in simulations with the SRES A1FI scenario. The chosen set of simulations allows us to explore the dependency of the projected climate changes on both the forcing scenarios and the choice of ocean data.

Table 2. List of simulations with different input parameters and different forcing scenarios.

Input parameters distributions	Forcing scenarios			
	SRES B1	SRES A1B	SRES A2	MIT REF
LAB05	X	X	X	X
NO	-	X	-	X
DOM08	-	X	-	X

5. RESULTS AND DISCUSSION

The use of different pdfs for input climate parameters has a smaller effect on the distributions of projected surface warming than on the distribution of projected sea level rise (**Figure 6, Tables 3 and 4**) because a correlation between the input parameters is imposed by the 20th century surface air temperature data. For example, the mean values of sea level rise in the ensembles with NO and DOM08 input distributions exceed the mean value for LAB05 distribution by 40 and 51%, respectively, while changes in the mean values of the increase in SAT are only 6 and 13%. The choice of input distributions also significantly changes the shape of the probability distribution for projected thermosteric sea level rise. It has been noted in several papers (*e.g.* Knutti *et al*. 2008: Meinshausen *et al*. 2008) that, for the given set of AOGCM models, the shapes of the distributions for SAT increase are similar under different SRES scenarios. Our simulations yielded similar results. Ratios of the different percentiles of the given distribution to the corresponding mean differ only slightly between ensembles with different forcing scenarios (see **Table 5**). At the same time, the ratios of the SAT changes in the simulations with different forcing scenarios for *a given version* of the MIT IGSM are not defined just by the ratios of forcings, but also depend on the values of climate sensitivity and the rate of heat uptake by the ocean.

For each of the ensembles listed in Table 2, the SAT change in a simulation using the median values of the input climate parameters is close to the median value of SAT changes from the corresponding ensemble of simulations. This fact, in combination with the similarity of the statistical properties of the distributions of projected surface warming for different forcing scenarios, allows us to approximate the probability ranges for surface warming under the SRES B1 and A2 scenarios for the NO and DOM08 sets of input parameters without running the corresponding ensembles. Namely, we run simulations with the median values of climate parameters for the remaining scenarios and then used ratios from Table 5 to estimate probability ranges. Those ranges are shown in **Figure 7** by dashed lines.

Table 3. Distributions of temperature changes in the last decade of 21st century relative to the 1981-2000 mean.

		5.0%	**16.7%**	**50.0%**	**Mean**	**83.3%**	**95.0%**
LAB05	B1	1.51	1.69	2.10	2.08	2.37	2.71
	A1B	2.30	2.61	3.17	3.17	3.64	4.11
	A2	3.00	3.43	4.06	4.03	4.55	4.98
	REF	3.62	4.11	4.86	4.83	5.41	6.02
NO	A1B	2.20	2.45	2.94	3.01	3.55	3.86
	REF	3.33	3.76	4.50	4.50	5.23	5.78
DOM08	A1B	2.13	2.31	2.58	2.66	3.00	3.44
	REF	3.16	3.43	3.91	3.99	4.50	5.06

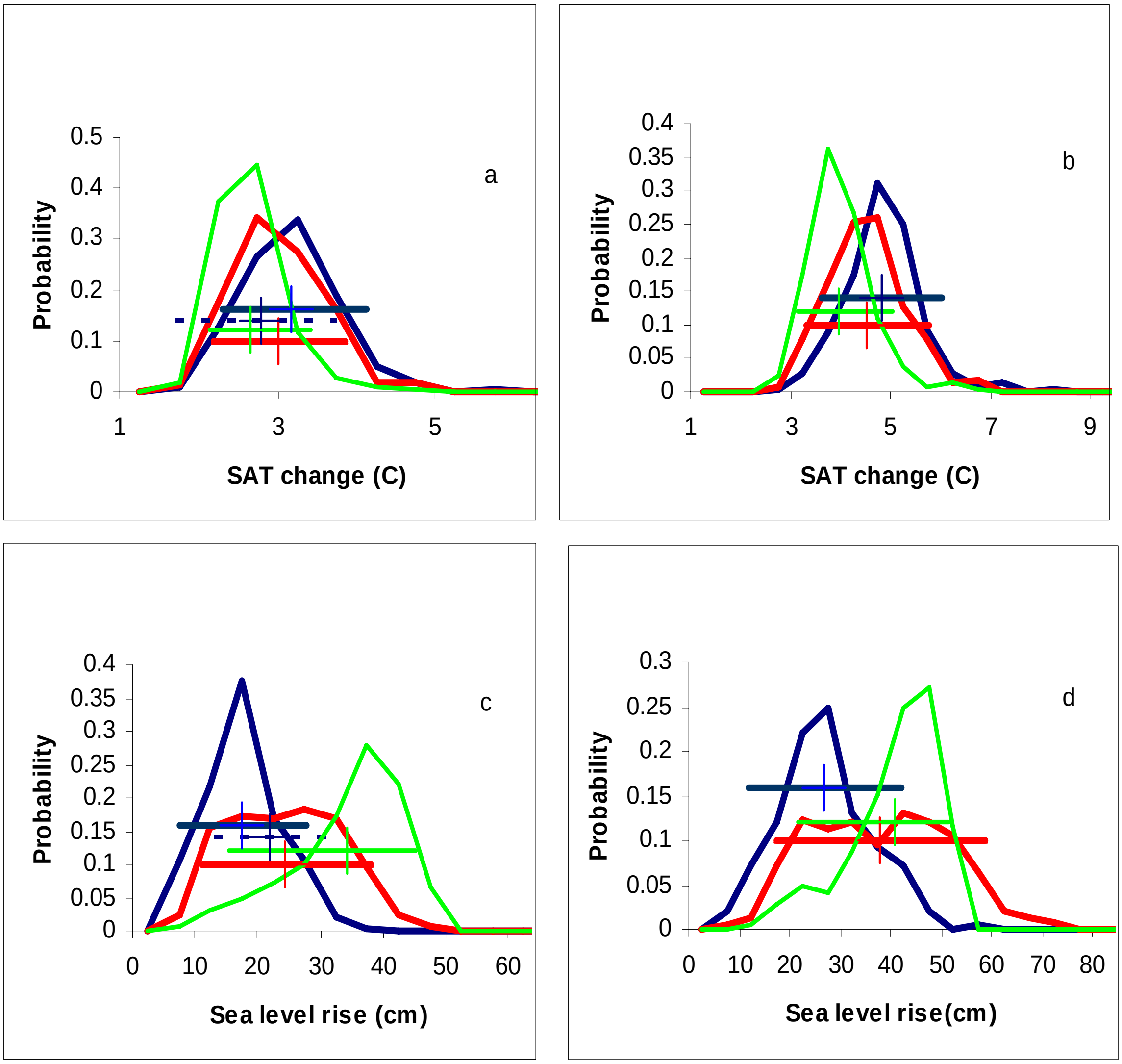

Figure 6. Frequency distributions for SAT increase under SRES A1B (a) and MIT REF (b) scenarios and corresponding thermosteric sea level rise (c and d) in 2091 to 2100 relative to the 1981 to 2000 average in simulations with LAB05 (blue) DOM08 (green) and NO (red) input parameter distributions. Solid horizontal bars show 5-95% ranges from 250-member ensembles of simulations with the MIT model, dashed horizontal bars show 5-95% ranges from the multi-model IPCC AR4 AOGCM ensemble (from figure TS.27 of Solomon *et al* (2007))

Table 4. Distributions of thermosteric sea level rise in the last decade of 21st century relative year to the 1981-2000 mean.

		5.0%	16.7%	50.0%	Mean	83.3%	95.0%
LAB05	B1	5.23	8.85	13.02	12.40	17.85	21.26
	A1B	7.67	12.16	17.45	16.77	23.35	27.60
	A2	10.64	15.80	22.10	21.35	28.65	33.56
	REF	11.80	18.91	26.95	26.11	35.73	42.11
NO	A1B	11.27	14.65	24.40	24.54	33.32	38.07
	REF	17.65	23.10	37.83	37.80	51.45	58.66
DOM08	A1B	15.26	25.73	36.00	34.34	42.76	45.26
	REF	21.50	32.55	42.71	40.82	49.15	51.47

The values of Sqrt(Kv) required for the MIT IGSM to reproduce the results of different AR4 AOGCMs in simulations with 1% per year CO2 increase, range from 0.9 cms$^{-1/2}$ to 2.0 cms$^{-1/2}$. The Sqrt(Kv) values for practically all the AR4 models fall in the upper half of the Sqrt(Kv) range suggested by the pdf using the LAB05 ocean heat content data and in the low half of the range of the Sqrt(Kv) distribution based on the DOM08 results.

As a result, the simulations using the LAB05 input parameter distribution suggest stronger warming than the ensemble of the AR4 AOGCMs (see Figures 6 and 7) -- namely by the end of the 21st century (2091-2100) surface air temperature will increase above the present level (1980-1999) by 1.7C to 2.4C (16.7 to 83.3 percentiles) for B1, 2.6C to 3.6C for A1B and 3.4C to 4.6C for A2. The corresponding increases in the mean are 2.1C, 3.2C and 4.0C respectively. . From the AR4 AOGCM ensemble (also shown in Figures 6 and 7), the mean increases are 1.8C, 2.8C and 3.4C for the B1, A1B and A2 scenarios, respectively. The corresponding ranges for sea level rise due to thermal expansion of sea-water in LAB05 simulations are: 9 cm to 18 cm for B1, 12 cm to 23 cm for A1B and 16 cm to 29 cm for A2 (Table 4).

Table 5. Ratios of the percentiles values to the means for probability distributions shown in Table 3.

		5.0%	16.7%	50.0%	83.3%	95.0%
LAB05	B1	0.72	0.81	1.01	1.14	1.30
	A1B	0.73	0.82	1.00	1.15	1.30
	A2	0.74	0.85	1.01	1.13	1.23
	REF	0.75	0.85	1.01	1.12	1.25
NO	A1B	0.73	0.81	0.98	1.18	1.28
	REF	0.74	0.84	1.00	1.16	1.28
DOM08	A1B	0.80	0.87	0.97	1.13	1.29
	REF	0.79	0.86	0.98	1.13	1.27

The upper bounds of the distributions for SAT increases obtained in the LAB05 ensemble also significantly exceed the upper bounds simulated by the AR4 AOGCMs (Figure 5a). For example, the probability of surface warming exceeding 4.1 C by the end of 21st Century under the A2 scenario is 5% according to the AR4 AOGCM ensemble (Figure TS.27 of Solomon *et al*. (2007)), but 46% according to our results. The SAT changes simulated by the AR4 AOGCMs almost completely lie below the median suggested by our LAB05 projections for the high emissions scenario (A2) (Figure 7b) and below 83.3 percentile for the other two scenarios (Figures 6a and 7a). The larger difference for A2, rather than for the other two scenarios is explained, in part, by the fact that the AR4 simulations for different SRES scenarios were carried out with different sets of AOGCMs. Thus the MIROC3.2 (hires) AOGCM, which produces the highest warming in the simulations for the A1B and B1 scenarios, was not used in the simulations with SRES A2.

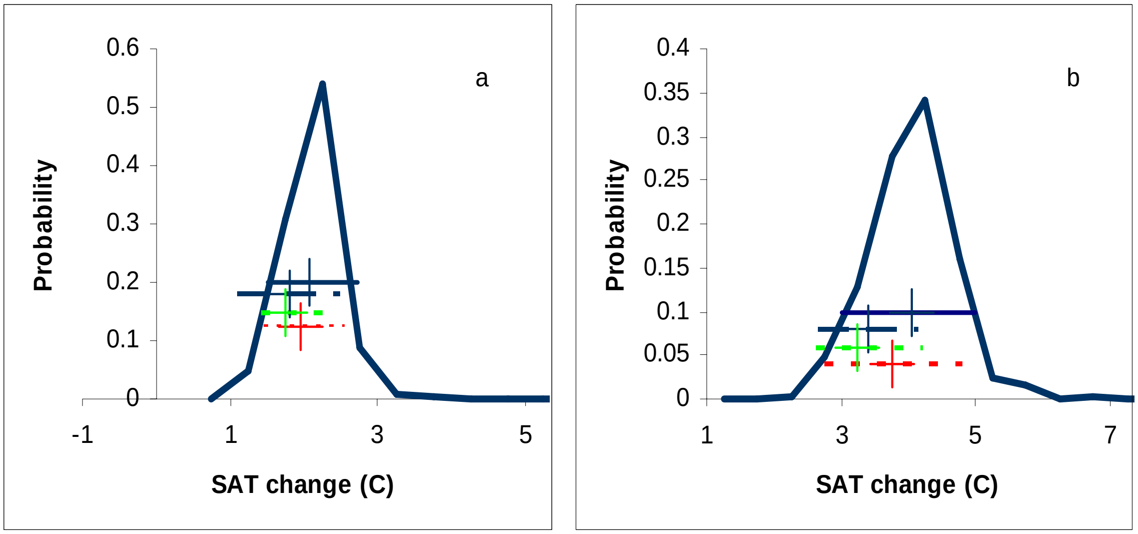

Figure 7. Frequency distributions for SAT increase in 2091 to 2100 relative to the 1981 to 2000 average for the B1 (a) and A2 (b) SRES scenarios in simulations with LAB05 input parameter distribution. Solid horizontal bars show 5-95% ranges from 250-member ensembles of simulations with the MIT IGSM; green and red dashed horizontal bars show 5-95% ranges for DOM08 and NO approximated by scaling (see text for details); blue dashed horizontal bars show 5-95% ranges from the multi-model IPCC AR4 AOGCM ensemble (from figure TS.27 of Solomon *et a*l, 2007)

On the other hand our projections using the DOM08 analysis are more consistent with the AR4 AOGCM projections. However our NO projections are closer to our LAB05-based projections, which indicates that, for the assumed prior for climate sensitivity, the observed changes in surface and upper air temperature are more consistent with the weaker ocean warming trend in the LAB05 analysis than with the stronger trend in the DOM08 analysis.

The differences in forcing between AOGCMs (illustrated in Figure 1) are unlikely to affect our comparison in a significant way for two reasons. First, the climate forcing in the MIT IGSM simulations with mean values of climate sensitivity, rate of oceanic heat uptake and strength of aerosol forcing turned out to be very similar to the forcing averaged over the set of AR4 AOGCMs (see Figure 1). Second, the correlation between TCR, which provides a good measure of model response to an external forcing on time scales of 50-100 years, and the strength of climate forcing for the AR4 AOGCMs is very weak.

As noted above, the use of input distributions based on different estimates of changes in the ocean heat content has a strong effect on the projected sea level rise due to thermal expansion. The range of values produced by the AR4 AOGCMs for the SRES A1B scenario falls in between ranges obtained in the different MIT ensembles (Figure 6c).

6. CONCLUSIONS

Uncertainties in the estimates of the 20th century changes in the deep ocean heat content have a strong effect on projections of the thermosteric sea level rise. The median value of the thermosteric sea level rise under the MIT reference forcing scenario is 41 cm if the DOM08 data is used, but 27 cm if the LAB05 data is used. The effect on SAT increases is more modest because of the correlation between climate sensitivity and ocean heat uptake required by observed 20th century temperature changes. Nevertheless the effect is still significant. The median SAT increase at the end of the 21st century for the MIT reference scenario is 3.9 C if the DOM08 data are used for producing the probability distributions, but 4.9 C if the LAB05 data are used.

For the forcing scenarios used in this study, the statistical properties of the distributions of changes in surface air temperature do not depend on the choice of distribution for input climate parameters (see Table 5). Such similarity in the distributions for projected surface warming is explained by the correlation between S and Sqrt(Kv) imposed by the transient changes in SAT observed during 20th century and by the fact that in all scenarios considered here forcing increases monotonically with time. Distributions for the equilibrium SAT changes under scenarios where the forcing is stabilized will be defined primarily by the input distributions for climate sensitivity.

The estimates of SAT increase produced by the multi-model ensemble of the IPCC AR4 AOGCMs slightly overestimate the results of the MIT ensemble for input distributions based on the DOM08 data, and strongly underestimate the surface warming suggested by the MIT results using the LAB05 data. For the sea level rise due to thermal expansion the situation is the opposite. As noted above, the LAB05 analysis is more consistent with the observed 20th century surface and upper air temperature changes. These results emphasize the necessity for producing reliable estimates for changes of deep ocean heat content.

Acknowledgments

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