The Sensitivity of the Rate of Transient Climate Change to Ocean Physics Perturbations

M. Collins

Hadley Centre for Climate Prediction and Research, Met Office, Exeter, United Kingdom

C. M. Brierley

Department of Meteorology, University of Reading, Reading, United Kingdom

M. MacVean

European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

B. B. B. Booth and G. R. Harris

Hadley Centre for Climate Prediction and Research, Met Office, Exeter, United Kingdom

(Manuscript received 15 May 2006, in final form 26 September 2006)

ABSTRACT

"Perturbed physics" ensembles of Hadley Centre climate models have recently been used to quantify uncertainties in atmospheric and surface climate feedbacks under enhanced levels of CO_2, and to produce probabilistic estimates of the magnitude of equilibrium climate change. The rate of time-dependent climate change is determined both by the strength of atmosphere–surface climate feedbacks and by the strength of processes that remove heat from the surface to the deep ocean. Here a first small ensemble of coupled atmosphere–ocean climate model experiments in which the parameters that control three key ocean physical processes are perturbed is described. It is found that the perturbations have little impact on the rate of ocean heat uptake, and thus have little impact on the time-dependent rate of global warming. Under the idealized scenario of 1% yr^{-1} compounded CO_2 increase, the spread in the transient climate response is of the order of a few tenths of a degree, in contrast to the spread of order of 1° caused by perturbing atmospheric model parameters.

1. Introduction

Uncertainties in the magnitude of future climate change have recently been quantified using "perturbed physics" ensembles of the Hadley Centre climate model (Murphy et al. 2004; Stainforth et al. 2005; Barnett et al. 2006; Webb et al. 2006; Collins et al. 2006; Piani et al. 2005). In these studies, parameters in the atmospheric component of the model are varied within specified ranges, and the atmosphere is coupled either to a simple mixed-layer ocean, or, in one case (Collins et al. 2006) coupled to the same standard parameter dynamical ocean component. The studies thus explore physical climate feedbacks associated with atmospheric and surface processes of which clouds are the leading-order driver of uncertainty (Webb et al. 2006).

The rate of global-mean time-dependent temperature change under a specified forcing scenario is determined jointly by the strength of the physical feedbacks in the atmosphere and surface components of the climate system and the efficiency of processes that remove heat from the surface of the ocean to depth (Gregory and Mitchell 1997). We may parameterize the flux of heat through the ocean surface, F, as being proportional to a constant, κ, multiplied by the global mean temperature change, this being a suitable approximation to make under forcing scenarios of in-

Corresponding author address: Matthew Collins, Hadley Centre for Climate Prediction and Research, Met Office, FitzRoy Road, Exeter, EX1 3PB, United Kingdom.
E-mail: matthew.collins@metoffice.gov.uk

DOI: 10.1175/JCLI4116.1

TABLE 1. Ocean model parameter values used in the perturbed physics ensemble experiments and key quantities that determine the rate of global mean warming. The first column indicates the experiment name (FA indicates that flux adjustments are applied). The along-isopycnal diffusion coefficient takes a constant value everywhere in HadCM3 and is indicated in the second column. The background vertical diffusivity (third column) has a vertical profile with the first number in the column indicating the surface value and the second the value at the bottom of the ocean (see Table A of Gordon et al. 2000). The HadCM3 mixed-layer scheme is a Kraus–Turner type controlled by the "fraction" parameter (fourth column), which scales the calculation of the wind mixing energy and the depth parameter (fifth column), which controls decay length for its penetration. These parameters are known to control processes responsible for vertical heat transport in ocean models. The sixth column gives the TCR, the 20-yr averaged global mean temperature change at the time of CO_2 doubling in the 1% yr^{-1} CO_2 increase experiment. The seventh column gives the effective atmospheric feedback parameter and the eighth column the ocean heat uptake parameter [see Eq. (1) and text for information on how these are calculated]. For the last three columns, the std dev in the calculation expected from natural variability (computed from all the control experiments) is shown. The values in some columns are shown to 2 decimal places to highlight small differences.

	Isopycnal diffusivity ($m^2\ s^{-1}$)	Background vertical diffusivity profile ($\times 10^{-5}\ m^2\ s^{-1}$)	Mixed-layer parameters, fraction, depth (m)		TCR $\sigma = 0.04$ (K)	λ $\sigma = 0.02$ ($W\ m^{-2}\ K^{-1}$)	κ $\sigma = 0.02$ ($W\ m^{-2}\ K^{-1}$)
Std dev	1000	1–15	0.7	100	2.07	1.17	0.63
FA std dev 1					2.17	1.08	0.63
FA std dev 2					2.16	1.07	0.65
FA std dev 3					2.13	1.10	0.64
LowISO	200	1–15	0.7	100	2.17	1.14	0.57
HighISO	2000	1–15	0.7	100	2.07	1.19	0.61
LowLAM	1000	1–15	0.3	100	2.16	1.16	0.57
MedLAM	1000	1–15	0.5	50	2.11	1.14	0.62
LowVDiff	1000	0.5–4	0.7	100	2.28	1.07	0.55
HighVDiff	1000	2–50	0.7	100	1.82	1.31	0.74
FA HighVDiff					2.03	1.14	0.69
Atmosphere physics (range)					1.56 to 2.61	0.85 to 1.75	0.57 to 0.76

creasing greenhouse gases (e.g., common socioeconomic scenarios or simple compound increases in CO_2) and which is justified a posteriori (see Fig. 2b). Hence we may write

$$\Delta T = \frac{Q}{\lambda + \kappa}, \tag{1}$$

where ΔT is the global mean temperature change at a given time, Q is the radiative forcing at that time, λ is the atmospheric feedback parameter, and κ is the ocean heat uptake efficiency (Raper et al. 2002). Uncertainties in the transient response of the climate system are determined by the physical processes involved in setting both λ and κ.

Here we report on the first small ensemble of coupled atmosphere–ocean model simulations of climate change in which parameters in the ocean component of the model are systematically varied, thus potentially impacting the rate of ocean heat uptake and the rate of warming. To isolate the impact of different oceanic processes, we follow Murphy et al. (2004) by perturbing parameters one at a time. We also focus on global mean quantities in order to understand the leading-order impact of the perturbations on future climate change.

2. Experiments and perturbations

We use version 3 of the Hadley Centre Coupled Model (Gordon et al. 2000) employed in previous perturbed physics studies (e.g., Collins et al. 2006) with the standard parameter settings in the atmosphere and the inclusion of an interactive sulfur cycle. Experts in ocean modeling were consulted and a list of ocean parameters produced, together with likely ranges (Brierley 2007). Those experts also indicated the parameters that would be likely to have the greatest impact, leading to the parameters that control three ocean physical processes being perturbed: the diffusivity of tracers along isopycnal surfaces, the calculation of the depth profile of wind-mixing energy in the ocean mixed layer, and the vertical diffusivity of tracers (Table 1).

Figure 1 illustrates the experimental design. In each simulation, the model ocean component was initialized from the Levitus and Boyer (1994) analysis of the observed temperature and salinity, and a state of no motion. Each member was then run for 500 yr in "spinup" mode with constant preindustrial concentrations of greenhouse gases and sulfate emissions. No flux adjustments were employed in these perturbed experiments, resulting in a varying degree of drift away from the initial state. The reason for the increase in ocean heat

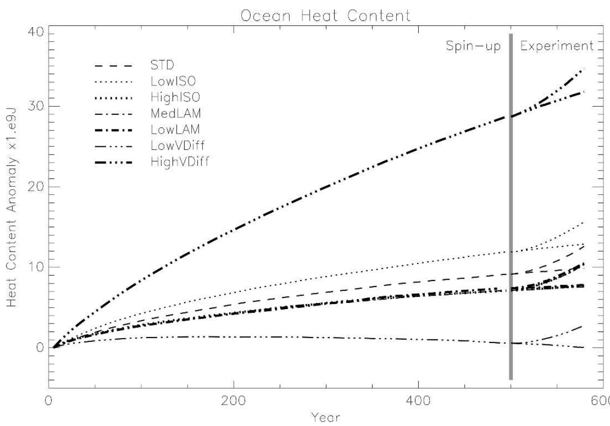

Fig. 1. Anomalies in ocean heat content [computed with respect to the Levitus and Boyer (1994) analysis of ocean temperatures] from the ensemble of ocean physics ensemble experiments. For each member, 500 yr of spinup was performed with fixed preindustrial greenhouse gases and other forcing agents. Each spinup was then extended for 80 yr to produce a control experiment and an additional experiment with CO_2 increases at a rate of 1% yr^{-1} compounded was performed. Parameter perturbations are indicated in the figure legend and correspond to those given in Table 1. For the HighISO, LowLAM, and MedLAM experiments (see Table 1 for definitions), the evolution of the heat content in the spinup phase is very similar.

content in comparison with the relatively small drift seen in the original Third Hadley Centre Coupled Ocean–Atmosphere GCM (HadCM3) control experiment (Gordon et al. 2000) is the replacement of the prescribed sulfate aerosol distribution with that determined by the interactive sulfur cycle [this was done for consistency with the study of Collins et al. (2006)]. Because the model then generates its own three-dimensional aerosol fields in place of previously prescribed fields, there is a positive top-of-atmosphere (TOA) radiative imbalance, with approximately 1.5 W m^{-2} less outgoing than incoming radiation and a corresponding initial warming and drift in each member (see Collins et al. 2006; Table 1). Aerosol emissions remain fixed at preindustrial values in all of the experiments described below, and experiments with the atmosphere component of the model coupled to a mixed-layer ocean give climate sensitivities that are indistinguishable with interactive and noninteractive schemes.

Following this spinup phase, a further 80 yr of control experiment were run with constant CO_2, together with an experiment with a CO_2 increase of 1% yr^{-1} compounded (hereafter the 1% scenario). While no experiment is in true equilibrium, the drift in total ocean heat content in the control phase is small in comparison with the signal seen in the 1% scenario experiments. In addition, the relevant surface and atmosphere global-mean variables show no significant drift (see Fig. 2).

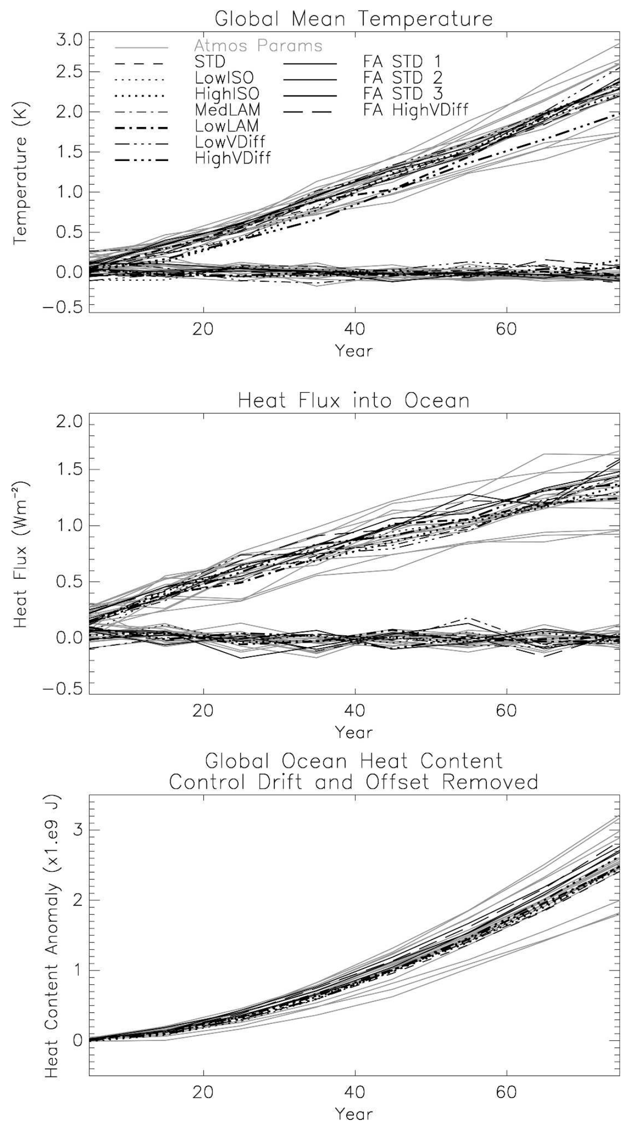

Fig. 2. Time series of global-mean quantities taken from the control and 1% experiments. Gray lines are from the atmosphere physics ensemble and black lines are from standard model and ocean physics ensembles with the parameter perturbation indicated in the legend (see Table 1). (top) 1.5-m temperature from control and 1% experiments. (middle) Heat flux per unit area of the earth's surface from the atmosphere into the ocean from control and 1% experiments. (bottom) Ocean heat content from the 1% experiments expressed in terms of anomalies with respect to the corresponding control experiment (thus removing the small impact of control climate drift).

The 500-yr spinup attempts to produce control states with relatively small residual trends and at the same time limit the drift away from the observed initial state, minimizing as far as possible the influence of mean-state biases.

For comparison, we also use global-mean quantities from a 16-member HadCM3 ensemble in which atmosphere, surface, and sea ice parameters have been varied (Collins et al. 2006). In this ensemble, flux adjustments are employed to correct for top-of-the-atmosphere radiation imbalances that result from the physics perturbations, and to improve the credibility of the simulations in terms of their projections of regional climate change. We also perform two more experiments with standard atmosphere and ocean parameter values but with slight modifications to the Haney-phase temperature and salinity relaxation coefficients [this greatly improves the SST biases seen in Collins et al. (2006)]. The use of this atmosphere–surface physics ensemble allows us to assess the relative importance of uncertainties in the processes that determine λ and κ in setting the rate of time-dependent climate change. In what follows, we refer to the Collins et al. (2006) ensemble as the "atmosphere physics" ensemble, the experiments shown in Fig. 1 as the "ocean physics" ensemble, and all experiments with standard parameter values (whether flux adjusted or not) as the "standard model."

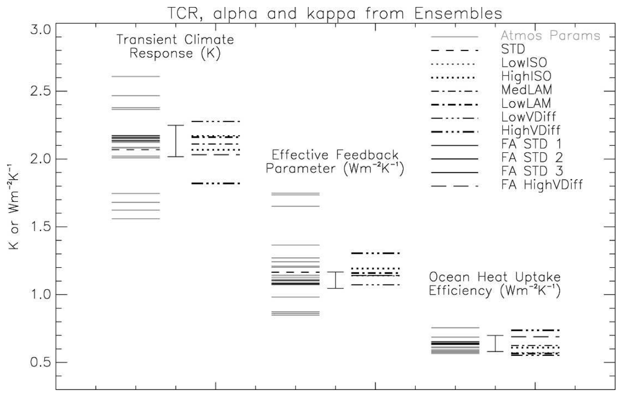

FIG. 3. Graphical representation of the range of the terms in Eq. (1) in the atmosphere and ocean physics ensembles (as indicated on the legend). (left) The transient climate response. (middle)The effective feedback parameter, λ. (right) The ocean heat uptake efficiency, κ. In each case the "error bar" indicates the mean and ±2 std devs of the uncertainty in the estimate of the quantity that would be expected from natural variability. Uncertainty estimates are calculated from nonoverlapping 20-yr sections of all of the control experiments and are centered on the standard model estimates of the respective quantity.

3. Impact on global mean climate change

Figure 2 shows a number of global-mean quantities from both the atmosphere physics and the ocean physics ensemble. In terms of the rate of global-mean temperature rise, the perturbations to the ocean parameters appear to have little impact in comparison with atmosphere parameter perturbations. They produce a very small ensemble spread in ΔT, the same being true of the anomalous flux of heat into the ocean, F, and the rate of rise of ocean heat content. The only exception appears to be the experiment with high vertical diffusivity.

The information contained in Fig. 2 may be quantified by diagnosing the terms in Eq. (1) over the 20-yr period straddling the time of CO_2 doubling at year 70 of the 1% scenario experiments (see, e.g., Raper et al. 2002). The feedback parameter is computed as

$$\lambda = \frac{Q_{2X} - N_{2X}}{\Delta T_{2X}}, \tag{2}$$

where Q_{2X} is the radiative forcing at doubled CO_2, N_{2X} is the 20-yr average TOA flux anomaly, and ΔT_{2X} is often known as the transient climate response (TCR), the 20-yr average global-mean temperature anomaly. We assume that Q_{2X} is the same in each experiment, taking the value of 3.8 W m^{-2} calculated explicitly from an atmosphere–mixed layer experiment. Each model version uses the same radiation component and, as shown in Fig. 1a of Webb et al. (2006), three structurally different versions of the Hadley Centre model in which this same radiation component is used have near-identical global mean radiative forcing. Anomalies are calculated with respect to the relevant 80-yr control average. The ocean heat uptake efficiency is calculated as

$$\kappa = \frac{F_{2X}}{\Delta T_{2X}}, \tag{3}$$

where anomalies in the global-mean flux of heat from the atmosphere to the ocean, F_{2X}, are expressed per unit area of the earth's surface. While λ is generally relatively time invariant in such 80-yr experiments (although time dependence is seen in longer experiments with larger forcing; e.g., Senior and Mitchell 2000; Raper et al. 2002), the κ parameter does have a time dependence that is inversely proportional to the length of time from the start of the experiment. Nevertheless, the κ approach provides a conceptually simple metric that facilitates comparison with other studies. A graphical representation of the variations in TCR, λ, and κ is presented in Fig. 3 and numerical values are given in Table 1.

As reported in Collins et al. (2006), perturbations to the atmosphere component of the model impact the magnitude of atmospheric and surface climate feedbacks and, as a consequence, the TCR. The range in the atmosphere-physics ensemble shown in Fig. 3 is similar to the range seen in the most recent group of models collected for the fourth assessment of the Intergovernmental Panel on Climate Change (see Collins et al. 2006, their Fig. 7). Perturbations to the atmosphere component (with the ocean component fixed) make little change to the ocean heat uptake efficiency, and what little spread there is in the magnitude of κ makes

TABLE 2. Ranges of "hypothetical" TCR in degrees calculated using Eq. (1), the values of λ and κ given in Table 1, and a fixed radiative forcing of 3.8 W m^{-2}. Ranges are computed from the atmosphere physics ensembles (row 1), the ocean physics ensemble (row 2), and the ocean physics ensemble excluding the experiments with high vertical diffusivity. Column 2 shows the range calculated using the values of λ and κ computed from the ensemble experiments, column 3 the range calculated by substituting the standard model λ in the calculation, and column 4 by substituting the standard model κ. Values are shown to 2 decimal places to highlight small differences.

	All variations in λ and κ	Assuming standard model λ	Assuming standard model κ
Atmosphere	1.63–2.69	2.04–2.27	1.59–2.55
Ocean	1.86–2.34	2.06–2.29	1.95–2.22
Ocean (excluding HighVDiff expts)	2.11–2.33	2.20–2.29	2.07–2.22

an almost negligible contribution to the spread in TCR (Tables 1 and 2).

Perhaps surprisingly, it is also the case that the perturbations to the ocean component make little impact on the ocean heat uptake efficiency and, as a consequence, the TCR. With the exception of the experiment with high vertical diffusivity (discussed below), Fig. 3 and Table 1 shows that the range of κ is consistent with that seen in the ensemble with perturbed atmosphere parameters. The corresponding spread in the TCR (again, excluding the HighVDiff experiment; see Table 1) is similarly small—only a few tenths of a degree.

The only perturbation that does seem to have an impact on the TCR is that with high vertical diffusivity. In this experiment, there is an increase of the order of a few tenths of a W m^{-2} K^{-1} in the ocean heat uptake efficiency, κ, in comparison with the standard model version, but there is also a similar magnitude increase in the atmospheric feedback parameter, λ (Table 1). Both changes contribute to a reduction in the TCR in comparison with the standard model. We hypothesize that the relatively larger drift away from the observed initial state in this experiment (Fig. 1) results in a significantly different control climate and therefore different magnitudes of atmosphere–surface feedback processes under enhanced CO_2. To test this hypothesis, we repeat the high vertical diffusivity experiment using flux adjustments in order to keep the control experiment climatology close to that of the standard model. In this experiment, λ is consistent with the standard model λ, and κ is closer to that of the standard model but still marginally higher, indicating that the perturbation does have some influence on the processes that determine ocean heat uptake. Nevertheless, the impact of the perturbation on the TCR is still small in comparison with perturbations made to atmospheric parameters.

4. Discussion and future work

There are three potential caveats to this work: first the experts consulted may have been overly conservative in their specification of the ranges of the parameters perturbed; second there may be other ocean component parameters that are important; and third the one-by-one nature of the perturbations may mask some nonlinear interactions of processes, which could produce significant spread in κ and the rate of climate change. Reconsultation with the experts and examination of the literature reveals the first of these to be unlikely. The second is possible, although there are no obvious candidates. The third is also possible and can only really be checked by performing simultaneous parameter perturbation experiments. Nevertheless, the broadening of the frequency distribution of climate sensitivity seen in the simultaneous atmospheric perturbation studies (Stainforth et al. 2005; Webb et al. 2006) in comparison with that in the single-parameter perturbation study (Murphy et al. 2004) is a result of nonlinear interactions between individual processes that, on their own, are known to have a significant impact on climate sensitivity. The degree of nonlinearity needed to amplify physical processes that, on their own, have little impact on ocean heat uptake efficiency would have to be considerable.

The obvious oceanic process not influenced by the ocean component parameter perturbations we have chosen is the high-latitude convection, which appears (from Gregory 1999, 2000) to have an important, and possibly controlling, role. Convective instability in HadCM3 is removed using the Rahmstorf (1993) scheme globally, with the Roussenov et al. (1995) scheme applied in the sills separating the Greenland–Iceland–Norway Seas from the Atlantic (in order to improve the properties of the dense water that overflows these sills). While it may be possible to perturb some of the options associated with this part of the code, the generic effect of ocean convection schemes is to instantaneously mix columns of water that have become unstable (as a result of surface heat loss or salinification through brine release from sea ice). Introducing a time lag into the ocean convection scheme might improve the representation of that process but is unlikely to have a large effect on the rate of ocean heat uptake because of the disparate time scales.

The ranges in the key properties discussed in this perturbed-parameter ensemble are smaller than those reported in multimodel studies (Raper et al. 2002; Sokolov et al. 2003), suggesting that structural aspects of ocean models are of leading-order importance. For example, Russell et al. (2006a,b) assess the role of the Southern Ocean in recent AOGCMs and find a rather wide range of control states that affect the storage of heat in this key region under climate change. Using an approach based on optimal detection and attribution, Forest et al. (2006) show that the ocean effective diffusivity in many of the current generation of AOGCMs is inconsistent with observations—although in their study, HadCM3 is one of the better models, being more consistent with the data than many others. One corollary of this study is that the choices made when building the ocean component of a coupled model, together with mean climate biases, are likely to be of central importance in setting the rate of ocean heat content and may not be "tuned out" by changing the input parameters of the model.

Here we only report on the outcome of the study in terms of global mean temperature change. While the impacts of the perturbations are small in comparison with natural variability and atmosphere-model parameter uncertainties, larger ensembles or longer experiments under different forcing scenarios may yet reveal significant impacts. The next stage of the work will be to understand why the simulations show only small changes in ocean heat uptake efficiency and global mean temperature change. In addition, regional patterns of climate change may be impacted by the perturbations, and we still have not exhausted the list of parameters that could be perturbed, nor have we examined nonlinearities by perturbing parameters simultaneously.

Acknowledgments. We are very grateful to the input from the Hadley Centre Ocean Group and a number of international experts for their help in determining the parameters and their ranges and in interpreting the results. We are grateful also to Jonathan Gregory and Mark Webb for their insightful comments. The work was supported by the U.K. Department of the Environment, Food and Rural Affairs under Contract PECD/7/12/37, by the European Community ENSEMBLES (GOCE-CT-2003-505539) project under the Sixth Framework Programme, and by the U.K. Natural Environment Research Council.

REFERENCES

Barnett, D. N., S. J. Brown, J. M. Murphy, D. M. H. Sexton, and M. J. Webb, 2006: Quantifying uncertainty in changes in extreme event frequency in response to doubled CO_2 using a large ensemble of GCM simulations. *Climate Dyn.,* **26,** 489–511.

Brierley, C., 2007: Ocean model uncertainty and time-dependent climate projections. Ph.D. thesis, University of Reading, 219 pp.

Collins, M., B. B. B. Booth, G. R. Harris, J. M. Murphy, D. M. H. Sexton, and M. J. Webb, 2006: Towards quantifying uncertainty in transient climate change. *Climate Dyn.,* **27,** 127–147.

Forest, C. E., P. H. Stone, and A. P. Sokolov, 2006: Estimated PDFs of climate system properties including natural and anthropogenic factors. *Geophys. Res. Lett.,* **33,** L01705, doi:10.1029/2005GL023977.

Gordon, C., C. Cooper, C. A. Senior, H. Banks, J. M. Gregory, T. C. Johns, J. F. B. Mitchell, and R. A. Wood, 2000: The simulation of SST, sea ice extents and ocean heat transport in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dyn.,* **16,** 147–168.

Gregory, J. M., 1999: Comparison of heat uptake by the ocean in HadCM2 and HadCM3. Internal Hadley Centre Rep. 8, 5 pp.

——, 2000: Vertical heat transports in the ocean and their effect on time-dependent climate change. *Climate Dyn.,* **16,** 501–515.

——, and J. F. B. Mitchell, 1997: The climate response to CO_2 of the Hadley Centre coupled AOGCM with and without flux adjustment. *Geophys. Res. Lett.,* **24,** 1943–1946.

Levitus, S., and T. P. Boyer, 1994: *Temperature.* Vol. 4, *World Ocean Atlas 1994,* NOAA Atlas NESDIS 4, 117 pp.

Murphy, J. M., D. M. H. Sexton, D. N. Barnett, G. S. Jones, M. J. Webb, M. Collins, and D. A. Stainforth, 2004: Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature,* **430,** 768–772.

Piani, C., D. J. Frame, D. A. Stainforth, and M. R. Allen, 2005: Constraints on climate change from a multi-thousand member ensemble of simulations. *Geophys. Res. Lett.,* **32,** L23825, doi:10.1029/2005GL024452.

Rahmstorf, S., 1993: A fast and complete convection scheme for ocean models. *Ocean Modell.,* **101,** 9–11.

Raper, S. C. B., J. M. Gregory, and R. J. Stouffer, 2002: The role of climate sensitivity and ocean heat uptake on AOGCM transient temperature response. *J. Climate,* **15,** 124–130.

Roussenov, V. M., E. Stanev, V. Artale, and N. Pinardi, 1995: A seasonal model of the Mediterranean Sea general circulation. *J. Geophys. Res.,* **100,** 13 515–13 538.

Russell, J. L., K. W. Dixon, A. Gnanadesikan, R. J. Stouffer, and J. R. Toggweiler, 2006a: The Southern Hemisphere westerlies in a warming world: Propping open the door to the deep ocean. *J. Climate,* **19,** 6382–6390.

——, R. J. Stouffer, and K. W. Dixon, 2006b: Intercomparison of the Southern Ocean circulations in IPCC coupled model control simulations. *J. Climate,* **19,** 4560–4575.

Senior, C. A., and J. F. B. Mitchell, 2000: The time-dependence of climate sensitivity. *Geophys. Res. Lett.,* **27,** 2685–2688.

Sokolov, A. P., C. E. Forest, and P. H. Stone, 2003: Comparing oceanic heat uptake in AOGCM transient climate change experiments. *J. Climate,* **16,** 1573–1581.

Stainforth, D. A., and Coauthors, 2005: Uncertainty in predictions of the climate response to rising levels of greenhouse gases. *Nature,* **433,** 403–406.

Webb, M. J., and Coauthors, 2006: On uncertainty in feedback mechanisms controlling climate sensitivity in two GCM ensembles. *Climate Dyn.,* **27,** 17–38.