Do deep ocean temperature records verify models?

Richard S. Lindzen
Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

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[1] Recent papers show that deep ocean temperatures have increased somewhat since 1950, and that the increase is compatible with the predictions of coupled GCMs. The inference presented is that this degree of compatibility constitutes a significant test of the models. The present paper assumes that the measurements and their analysis are correct, and uses a highly simplified coupled model (i.e., an energy balance model with a mixed layer diffusive ocean) to examine whether deep ocean temperature behavior from 1950 to 2000 actually distinguishes between models of radically different sensitivity to doubled CO_2. It is found that whenever models are tuned with additional forcing (for example, from aerosols) so as to replicate observed global mean temperature, the warming of the ocean temperature is largely independent of model sensitivity. There is a modest dependence on ocean diffusivity with models' behavior characteristic of large diffusivity while observations are more characteristic of low diffusivity. However, the distinctions appear to lie within observational uncertainty. There is little reason to assume that more realistic models will behave very differently in this regard. Therefore, we conclude that the behavior of deep ocean temperatures is not a test of model sensitivity, but rather a consequence of having the correct global mean surface temperature time history. *INDEX TERMS:* 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 1635 Global Change: Oceans (4203); 1699 Global Change: General or miscellaneous; 1620 Global Change: Climate dynamics (3309)

1. Introduction

[2] In recent papers [*Levitus et al.*, 2001; *Barnett et al.*, 2001] data has been used to show warming of the deep oceans over the past 50 years. The fact that models forced by increasing CO_2 and tuned by nominal inclusion of aerosol effects to simulate the global mean temperature record for the past century roughly matched the observed deep ocean record was taken as evidence of the correctness of the models and of the anthropogenic origin of the deep ocean warming. The ocean and model behavior are shown in Figure 1. The purpose of the present note is simply to ascertain whether the degree of agreement noted in Figure 1 depends primarily on the fact that the surface temperature record was essentially correct, or whether it depends on the models' climate sensitivity and/or the models' ocean heat takeup rate as well. Note that the models tend to show greater ocean warming than is observed. Although there are differences between the Atlantic and Pacific, roughly, the models show about 0.3C warming in the thermocline region while observations show 0.2C. However, *Barnett et al.* [2001] suggest that this is within observational uncertainty.

[3] In the present note, we are not concerned with the accurate and detailed behavior of the ocean. Rather we will examine the simplest situation wherein we can still address our question. We assume that the results of [*Levitus et al.*, 2001] and [*Barnett et al.*, 2001] are not regional phenomena but are, instead generally characteristic of the oceans as a whole. For our ocean model, we take a simple box-diffusion model which allows us to vary the rate of ocean heat uptake by varying a diffusion coefficient. Our point is simply that if in such a transparently simple example, the behavior of the model ocean's temperature at depth does not distinguish between different climate model sensitivities, then it is hard to imagine how in the real ocean, which can have temperature changes for a variety of reasons, the case could be made that the temperature record does indeed confirm the climate model's sensitivity.

2. Model

[4] To ascertain what is important for the agreement of models and observations of temperature change at depths of about 500 m, we use a simple energy balance model with a box-diffusion ocean of the sort described in detail in [*Lindzen and Giannitsis*, 1998] which we will subsequently refer to as LG. LG showed, moreover, that such a model with a finite thermocline behaved essentially like the box-diffusion-upwelling models of [*Hoffert et al.*, 1980] and [*Harvey and Schneider*, 1995]. The model accounts for land and sea surfaces as well as transport between land and sea regions. It also allows the specification of radiative forcing, climate sensitivity, and vertical exchange in the ocean below the mixed layer.

[5] The equations for this model are simply

$$C_{land}\frac{\partial \Delta T_{land}(t)}{\partial t} - \frac{\nu}{A_{land}}(\Delta T_{ml}(t) - \Delta T_{land}(t)) + \frac{B}{gain}\Delta T_{land}(t) = \Delta Q(t), \tag{1}$$

$$C_{ml}\frac{\partial \Delta T_{ml}(t)}{\partial t} - \frac{\nu}{A_{sea}}(\Delta T_{land}(t) - \Delta T_{ml}(t)) + \frac{B}{gain}\Delta T_{ml}(t) + \left(-\lambda \frac{\partial \Delta T_{therm}}{\partial z}\bigg|_{z=0}\right) = \Delta Q(t), \tag{2}$$

$$\frac{\partial \Delta T_{therm}}{\partial t} = \kappa \frac{\partial^2 \Delta T_{therm}}{\partial z^2}, \tag{3}$$

with boundary conditions

$$\Delta T_{therm}|_{z=0} = \Delta T_{ml}, \tag{4}$$

$$\frac{\partial \Delta T_{therm}}{\partial z}\bigg|_{z=H_{therm}} = 0, \tag{5}$$

where variables are as defined in LG. As noted in LG, the quantities C_{land}, C_{ml} (and relatedly the thickness of the mixed layer, H_{ml}), and ν, are tuned to replicate the observed seasonal cycle. We take B = 4 Wm^{-2} deg^{-1} which corresponds approximately to the

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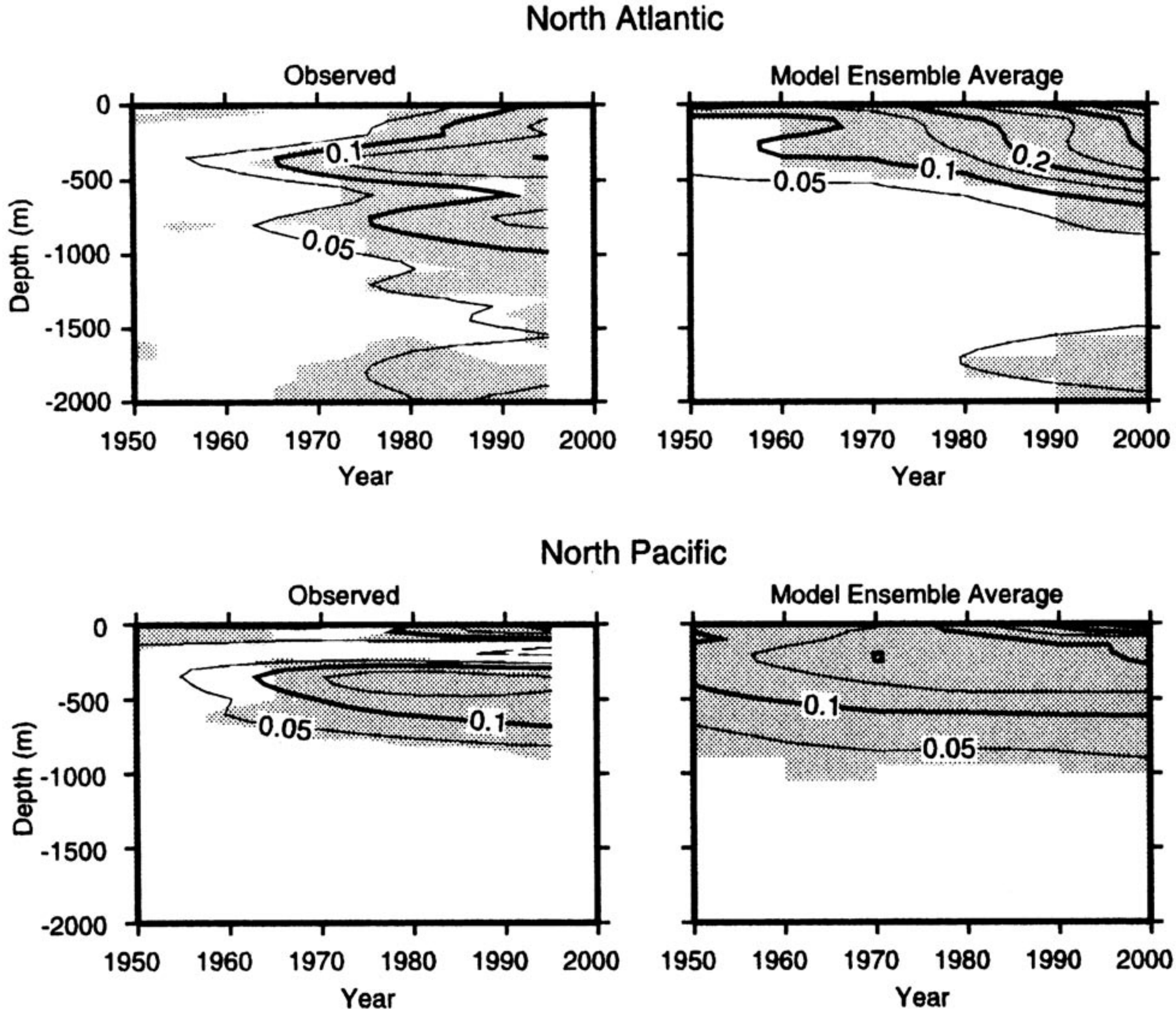

Figure 1. Modeled and observed temporal and vertical changes in the temperature in the upper 2000 m of the data-rich North Pacific and North Atlantic Oceans. Near the surface, where interannual and decadal changes and external forcings strongly affect the thermal structure, any agreement is largely due to chance. Gray-shaded regions denote areas where changes are statistically different from zero. The model broadly reproduces the the main features of the vertical structure and its temporal evolution over the last 40 years. The contour interval is 0.05°C. From *Barnett et al.* [2001].

equilibrium sensitivity of current models in the absence of feedbacks. Since climate models generally are characterized by sensitivities greater than this (due to the presence of positive feedbacks in the models), we include the gain parameter which allows for feedbacks in the climate system. κ is uncertain, and a range of values will be considered (0.2 $cm^2\,sec^{-1}$ to 1.5 $cm^2\,sec^{-1}$; the smaller value has been suggested by [*Danabasoglu et al.*, 1994], while the larger value is consistent with tracer distributions). ΔQ will be taken to consist in two parts. The first is the forcing due to increasing anthropogenic greenhouse gases. If greenhouse gases increase exponentially with time, then radiative forcing will increase approximately linearly with time. While, the assumption is not strictly correct, it suffices for the present study. We will take the greenhouse forcing to begin in 1880 reaching 2.55 Wm^{-2} by 2000 (following [*IPCC*, 2001]). This forcing then reaches 4 Wm^{-2} in 2088 which corresponds to a doubling of equivalent CO_2. This is compatible with common scenarios employed by the IPCC. The second part of the forcing is taken to be $-\beta\Delta Q$, where $\alpha = 1 - \beta$ is chosen so as to bring ΔT in 2000 to the observed value of 0.6 C. Thus,

$$\Delta Q = \alpha \frac{2.55\,Wm^{-2}}{120\,years}(t - 1880).$$

This essentially corresponds to the invocation of aero-sols to bring observed and calculated temperature records into agreement. Because we will be considering gains of less than one, α can be greater than one (and β negative) (presumably associated with black carbon). Before proceeding, it should be noted that both [*Levitus et al.*, 2001] and [*Barnett et al.*, 2001] emphasized the heat content of the ocean. As we can see from the above equations, the heat content of the oceans has no influence on the equilibrated temperature of the surface; it only affects the ocean delay. This, it must be emphasized, is not the

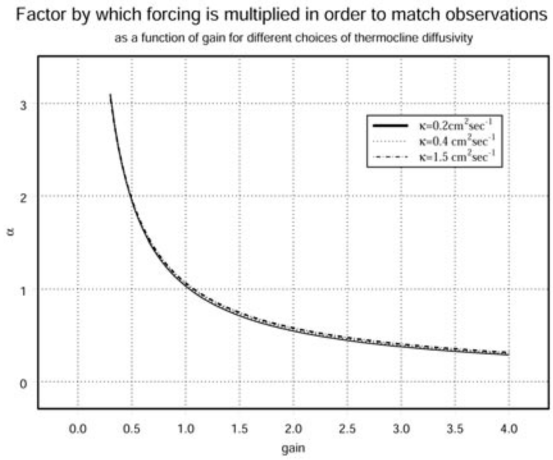

Figure 2. The compensating factor, α, as a function of model gain (climate sensitivity) for various choices of thermocline diffusivity.

same as the ocean heat uptake time; the longer the uptake time, the shorter the delay.

3. Procedure

[6] The question we wish to deal with is whether agreement between models and observations results from the fact that one has adjusted models so that surface temperature corresponds to observations or whether the agreement usefully depends on model climate sensitivity in which case the agreement reflects on the predictive capacity of the models. Our procedure is to look at a range of gains for a range of thermocline diffusivities, κ. For each choice, we determine the value of α which brings ΔT at 2000 to 0.6 C. For this choice of α, we then determine the increase in temperature at the bottom of the thermocline (corresponding to a depth of 475 m) between 1950 and 2000. The results are shown in Figures 2 and 3 which show how α and the temperature increase from 1950 to 2000 at a depth of 475 m vary as a function of gain for different choices of κ. Note that this temperature increase in general represents earlier surface forcing because it takes time for the effect of such forcing to reach this depth. It should be noted, as well, that in adopting the common procedure of invoking ill-known additional forcing to bring model results into line with observed temperature change, we are hardly endorsing this procedure. Observed changes could readily be due to natural internal variability, and as noted by [*Lindzen et al.*, 2001], internal variability in global mean temperature is by no means incompatible with relative insensitivity to global forcing.

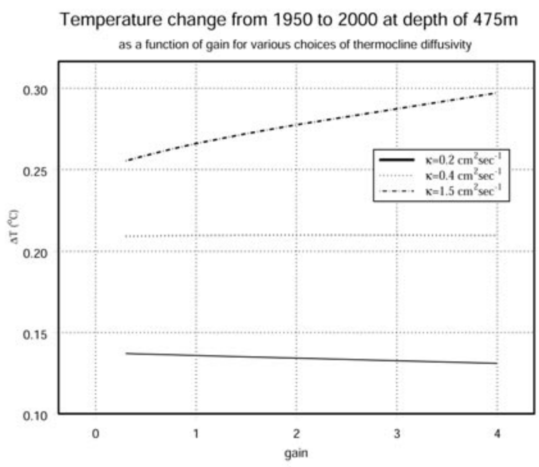

Figure 3. Calculated ocean temperature change between 1950 and 2000 at a depth of 475 m as a function of gain (climate sensitivity) for various choices of thermocline diffusivity.

4. Discussion

[7] Interestingly, the choice of a depends only slightly on choice of κ. Basically, the larger the gain of climate model, the more one has to compensate greenhouse forcing. At the same time, the temperature change at 475 m is almost independent of gain (climate sensitivity), though there is a distinct dependence on κ. Such variation as exists, is primarily for larger values of κ, and here agreement with observations improves as gain decreases. The choice of κ = 1.5 cm^2 sec^{-1} best replicates model behavior, while κ = 0.4 cm^2 sec^{-1} best replicates observations. It would appear from the present simple model (which is similar to what the IPCC uses to evaluate scenarios) that the ocean temperature change largely reflects only the fact that surface temperature change is made to correspond to observations, and says almost nothing about model climate sensitivity. Hence, such agreement provides little evidence of the predictive capacity of models. It is, of course, possible that more complex models could alter these conclusions, but the present calculations demonstrate clearly that oceanic temperature variations can reflect surface temperature without this result depending significantly on climate sensitivity. Stated differently, the ocean temperature increases present some support for the surface temperature record, but they do not provide support for the climate models themselves. It must be added that we are dealing with observed surface warming that has been going on for over a century. The oceanic temperature change over the period 1950–2000 reflects earlier temperature changes at the surface. How early depends on the rate at which surface signals penetrate the ocean. In the present simple ocean model, this is determined by our choice of κ, but in the real ocean undoubtedly other processes can be involved.

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R. S. Lindzen, Program in Atmospheres, Oceans, and Climate, Massachusetts Institute of Technology, Cambridge, MA, 02139 USA. (rlindzen@mit.edu)