Reports

Carbon Dioxide and Climate: The Importance of Realistic Geography in Estimating the Transient Temperature Response

Abstract. *Results obtained from a detailed air-sea-ice climate model for an instantaneous increase in the atmospheric carbon dioxide content are used to estimate the transient surface temperature response for several time-dependent carbon dioxide increase scenarios. The inclusion of realistic variations of land fraction and ocean mixing with latitude is found to limit the applicability of steady-state simulations as approximate guides to the actual time-dependent temperature response, particularly when the regional response is considered.*

Traditionally, studies of the climatic effects of increased atmospheric CO_2 based on the use of large dynamical climate models have concentrated on the statistical steady-state response to a fixed CO_2 increase (*1*, *2*). This approach has been taken because simulating the detailed time evolution of climate for a time-dependent CO_2 increase necessitates use of coupled air-sea-ice models, and this procedure is at present very expensive for century-long integrations. Schneider and Thompson have pointed out (*3*) that, because of geographical variation in heat capacity (from land-sea contrast and variable oceanic mixing), the actual meridional surface temperature gradient during a plausible CO_2 increase could evolve in time quite differently from that determined from a sequence of equilibrium calculations. This difference could have profound implications for estimating any regional climatic changes associated with increasing CO_2. However, these conclusions rested in part on the results of a relatively simple climate model. Schneider and Thompson therefore called for additional simulations with more physically comprehensive, higher resolution models to test the seriousness of any errors arising from the neglect of transients.

Bryan *et al.* (*4*) have recently provided one such test. Although confirming our result (*3*) that different latitudes respond differently in time to an impulsive increase in CO_2, they concluded (*4*, p. 58) that "barring an unforeseen drastic acceleration of the rate of CO_2 increase in the atmosphere, sensitivity studies of climate equilibrium can be used as an approximate guide for predicting the latitudinal pattern of sea surface temperature trends." Bryan *et al.* are referring to zonal averages based on the results of their model, in which highly idealized geography and a step-function CO_2 increase were used. Thus their statement may not apply for all plausible CO_2 increase scenarios, nor is it necessarily likely to apply for regional temperature responses to a CO_2 increase, particularly when realistic geography is considered. Therefore, we wish to discuss here the validity and limitations of the use of equilibrium calculations or step-function transient responses in order to estimate actual time-evolving CO_2-induced climatic changes. We do this by building on the results of Bryan *et al.* to estimate the sea surface temperature response at several latitudes to three time-dependent scenarios of atmospheric CO_2 increase.

One may visualize the response of the climate system to a continuous CO_2 increase as the sum of responses to many small step-function increases. To infer the response to a time-dependent CO_2 scenario, on needs (i) the time-dependent climatic response to a unit step-function CO_2 increase, (ii) the time derivative of the CO_2 heating (derived from a scenario of CO_2 concentration increase), and (iii) a climatic system whose response to CO_2 increases is quasi-linear in the range of interest (*5*). It is difficult to gauge the degree of conformity of the actual climatic system to the last requirement, but, barring large changes in surface ice cover, models have not shown the zonally averaged climate to have a highly nonlinear response to large-scale external forcing like CO_2 increases (*1*).

By combining data in figures 2 and 3 of Bryan *et al.*, we construct functions for the temperature response at latitudes 0° and 60° to a step-function CO_2 doubling (*6*). These functions may be approximated by one or two exponential functions of time to sufficient accuracy for illustrative purposes here. Thus,

$$f(t-\gamma) = A\{1-C[\exp(-\frac{t-\gamma}{a_1})+\exp(-\frac{t-\gamma}{a_2})]\}$$

where f is the response to a step-function CO_2 increase, t is time (in years), γ is the time of the step CO_2 increase (in years), A is a scaling constant, and a_1 and a_2 are time constants (in years). For latitude 60°, a single exponential with a time constant of 30 years fits the results of Bryan *et al.* well ($a_1 = 30$, $a_2 = 0$, $C = 1$). For latitude 0°, time constants of 4 and 50 years are used in a two-exponential fit ($a_1 = 4$, $a_2 = 50$, $C = 0.5$).

For mathematical convenience we express the CO_2 heating of the surface-troposphere system as $B(e^{\beta t-1})$, where B and β are constants chosen to match the CO_2 concentration in 1975 and an arbitrary year in which CO_2 doubles [600 parts per million by volume (ppmv)] (*7*). Year 0 (300 ppmv) is taken to be A.D. 1925. To illustrate the sensitivity of the results to various CO_2 increase rates, three CO_2 scenarios are chosen corresponding to a doubling at A.D. 2020, 2050, and 2100. These will be referred to as fast, medium, and slow, respectively (*8*).

With the above assumptions we solve (*5*) for temperature versus time at 0° and 60° latitude, assuming warmings of 1.5 K and 3.2 K, respectively, caused by the steady-state CO_2 doublings. Given in Fig. 1A are curves of the change in the sea surface temperature difference between 0° and 60° latitude (δ) for three assumptions of time constants: (i) instant equilibrium, (ii) globally uniform time constant ($a_1 = 20$, $a_2 = 0$, $C = 1$), and (iii) latitude-dependent time constants (from the step-function responses derived from Bryan *et al.*). The globally uniform time constant is chosen to give the transient calculation a global mean temperature which lags behind that of the instant equilibrium solution by about 20 years, which is in the range of present estimates (*3*). We have chosen δ as a measure of the meridional surface temperature gradient, a quantity thought to have an important effect on the meridional distribution of heat transport and therefore regional climate (*9*).

The value of δ for both globally uniform and latitude-dependent time response behavior (see Fig. 1A) is smaller in magnitude than that for instant equilibrium, reflecting the lag effect of the thermal inertia. The relative difference between δ for instant equilibrium and

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latitude-dependent response becomes smaller for slower CO_2 increases (*3*, *4*).

From Fig. 1A it is apparent that an appropriate choice of globally uniform time constant might allow one to mimic reasonably the effect of latitude-dependent time constants on δ. However, it is difficult to know a priori what value of global time constant to choose. There are many important climatological variables, for example, lapse rate and cloud cover, each of which would probably require a different effective time constant. Yet, from Fig. 1A it does appear, in agreement with the conclusion of Bryan *et al.*, that, unless the CO_2 increase is very rapid, an equilibrium calculation with an appropriate global lag would come close to the actual δ. This result suggests that a series of equilibrium calculations would be reasonable approximations of the actual transient response, a much less expensive way to estimate transient climatic changes than an explicit, time-dependent, synchronously coupled air-sea-ice model simulation. Nevertheless, the applicability of the above conclusion is limited by the highly idealized geography of the model of Bryan *et al.*, some effects of which we now examine.

Both the Northern Hemisphere and the Southern Hemisphere have less land (39 and 19 percent, respectively) than is assumed in the idealized hemisphere in the model of Bryan *et al.*, which has 50 percent land at all latitudes. Moreover, the ratio of the fraction of a zone occupied by land at 60° latitude to that at the equator is greater than unity for the Northern Hemisphere but nearly zero for the Southern Hemisphere. These large differences in the meridional distribution of the land fraction can contribute to substantial nonuniformity in the meridional distribution of effective heat capacity [see (*3*), figures 6 and 7].

In the absence of a Southern Hemisphere simulation by Bryan *et al.*, we can estimate an approximate step-function response of their model for Southern Hemisphere geography by making additional assumptions (*10*). From these we estimate the time constant for realistic geography at 60°S (100 percent ocean) to be 60 years, about twice as large as that for 60° latitude in the model of Bryan *et al.*

Figure 1B shows δ for the three CO_2 increase scenarios with these new assumptions. For a time constant of 60 years at 60°S, δ diverges from (and even is of opposite sign to) the values for the instant equilibrium and globally uniform time constant curves. These results agree qualitatively with our model calculations for the Southern Hemisphere (*3*, figure 7). No effective uniform value of the time constant would adequately mimic the δ for a nonuniform time constant. No simple tricks to use instant equilibrium solutions with some tuned lag coefficient are readily apparent to us. Only a more detailed transient air-sea-ice model can be trusted to produce a reasonable simulation for the evaluation of δ or to show the extent to which less detailed or equilibrium model results may be reliable.

This Southern Hemisphere result demonstrates the importance of variations in zonal effective heat capacity for making estimates of the transient climatic response, since any regional climatic or general circulation features that are sensitive to δ may evolve quite differently from those inferred from a sequence of instant equilibrium or even lagged equilibrium studies. Of course, climatic response to increasing CO_2 includes more than just the change of zonal mean temperatures. The effect of actual geographic variations in thermal lag are likely to be even more important for the evolution of regional climatic changes than for zonal changes—even in the Northern Hemisphere, where mid-continent and mid-oceanic temperature responses to CO_2 increases could be quite different, even in the same zone.

Bryan *et al.* have begun the process of using coupled dynamical climate models of the atmosphere and oceans to analyze the importance of the CO_2 transient problem. Although we strongly applaud this important early step, we believe it is

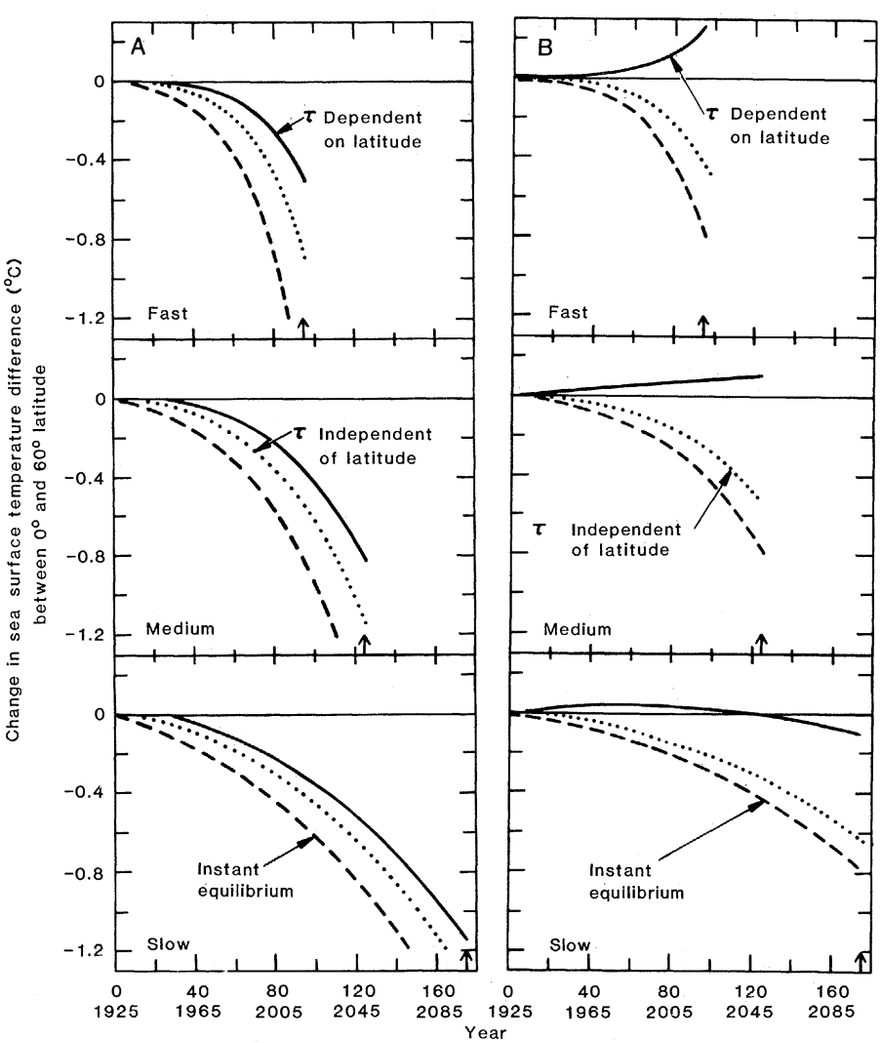

Fig. 1. (A) Change in the sea surface temperature difference between 0° and 60° latitude for three time-dependent CO_2 scenarios (fast, doubling in 2020; medium, doubling in 2050; and slow, doubling in 2100). Dashed lines refer to solutions in equilibrium with time-evolving CO_2 concentration. Dotted lines are solutions based on a globally uniform response to step-function forcing where the response function has a time constant of 20 years. Solid lines are based on the step-function response derived from (*4*) (see text). The arrow denotes the year of CO_2 doubling for each scenario. (B). Same as (A) except that the solid lines are based on a step-function response for 60° latitude that is modified to have a time constant of 60 years to simulate the response of 60°S.

premature to conclude that sensitivity studies based on climate equilibrium simulations can be reliably used to predict regional patterns of climatic changes. Such studies must be approached with great caution, even "as an approximate guide for predicting the latitudinal pattern of sea surface temperature trends," particularly in the Southern Hemisphere. However, to further narrow uncertainties and to test relationships between transient and equilibrium simulations, we believe that the use of the following hierarchical approach would be helpful. (i) The response to actual time-dependent CO_2 increase scenarios must be simulated (as opposed to inferred) and compared to instant equilibrium or lagged equilibrium estimates. (ii) Simulations with idealized geography (like the sector model of Bryan *et al.*) should be extended to include the actual fractions of land and ocean at different latitudes. (iii) Simulations with interactive deep oceans should eventually use realistic global geography in both latitude and longitude, as in (*2*). Without further simulations we cannot know the extent to which the neglect of explicit transient calculations will prove a serious omission in estimating regional climatic response to increasing CO_2.

STARLEY L. THOMPSON*
Department of Atmospheric Sciences, University of Washington, Seattle 98195

STEPHEN H. SCHNEIDER
Advanced Study Program, National Center for Atmospheric Research, Boulder, Colorado 80307

References and Notes

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5. We require this information in order to apply Duhamel's equation, which translates the step-function response into a transient climatic response [see C. R. Wylie, Jr., *Advanced Engineering Mathematics* (McGraw-Hill, New York, 1960), p. 338].
6. Figures 2 and 3 of (*4*) give the normalized step-function responses and necessary scale factors, respectively. The equilibrium doubling response is taken as one-half the quadrupling response.
7. See (*3*) for an explanation of a very similar approach.
8. Even slower scenarios are considered plausible by A. Lovins, H. Lovins, F. Krause, and W. Bach [*Least Cost Energy* (Brick House, Andover, Mass., 1981), p. 161].
9. E. N. Lorenz, *J. Atmos. Sci.* **36**, 1367 (1979); I. M. Held, *ibid.* **35**, 572 (1978).
10. We estimate the step-function response by assuming that the *e*-folding response time τ of temperature to a perturbation can be approximated by $\tau = R/\lambda$, where R is the thermal inertia and λ is the thermal damping coefficient (*3*). We estimate these parameters from (*4*) and then use them to construct a response function for 60°S. For estimating the zonal mean thermal inertia, we use an arithmetic average of land and ocean values. [This is the "infinite wind" limit derived by S. L. Thompson and S. H. Schneider, *J. Geophys. Res.* **84**, 2401 (1979)]. The ocean thermal inertia is estimated by integrating the temperature perturbation at 60° over depth [see (*4*), figure 3] to get an equivalent mixed layer depth of 625 m. [The technique for determining an equivalent mixed layer depth is described in (*2*).] For the model of Bryan *et al.*, λ falls in the range of 1 to 2 W m^{-2} K^{-1}, typical of climate models (*3*). We make a global estimate for λ in the model of Bryan *et al.* of about 1.3 W m^{-2} K^{-1} by dividing their given ocean surface heating increase of 6.5 W m^{-2} by their global temperature increase of about 4.9 K for a CO_2 quadrupling. By this process, we assume that λ for 60° is probably about the same as the global value. This assumption appears reasonable since the albedo-temperature feedback in the model of Bryan *et al.* is weakened as a result of "excessive warming at high latitudes" in their control case [(*4*), p. 57]. With R estimated from the effective mixed layer depth and an assumption of a 50 percent land fraction, we get a time constant of 32 years for latitude 60° in the model of Bryan *et al.* This independent estimate of the time constant is close to what we estimated visually from figure 2 of Bryan *et al.* With this encouragement, we estimate the time constant for a realistic land/sea fraction at 60°S to be 60 years. Finally, to scale the step-function response for 60°S, we assume an equilibrium temperature change for CO_2 doubling of 2.3 K (*2*).

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* Present address: Advanced Study Program, National Center for Atmospheric Research, Boulder, Colo. 80307.

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Atom Pair Distribution Functions of Liquid Water at 25°C from Neutron Diffraction

Abstract. *The structure of liquid water is described by three atom pair distribution functions* $g_{OO}(r)$, $g_{OH}(r)$, *and* $g_{HH}(r)$. *These functions have now been derived from neutron diffraction data on four mixtures of light and heavy water. They will provide a crucial and sensitive test for proposed models of liquid water.*

Enormous effort has been invested in experimental determinations of the properties of liquid water, in attempts to interpret these properties in terms of molecular interactions, and in the development of models with which known properties can be correlated and unknown properties predicted. Despite the effort, our factual knowledge is meager and our understanding rudimentary. An example is the structure of liquid water, described by the three atom pair distribution functions $g_{OO}(r)$, $g_{OH}(r)$, and $g_{HH}(r)$. Only the function $g_{OO}(r)$ is known (*1*) with sufficient accuracy to test proposed models of liquid water.

Neutron diffraction is a unique tool for probing the structure of water, because the hydrogen atoms cannot be "seen" with adequate precision by other techniques (such as x-ray or electron diffraction). This was recognized in the pioneering work of Wollan and Shull (*2*), who, in 1946, measured the first neutron diffraction patterns of liquid water at the X-Pile in Oak Ridge. The existence of two stable hydrogen isotopes with different coherent scattering lengths suggests that one could perform the standard isotopic substitution experiments (*3*) on water and obtain the three partial structure functions. In practice, however, the very large incoherent cross section of light hydrogen obscures the structural information contained within the coherent scattering. This means that in order to

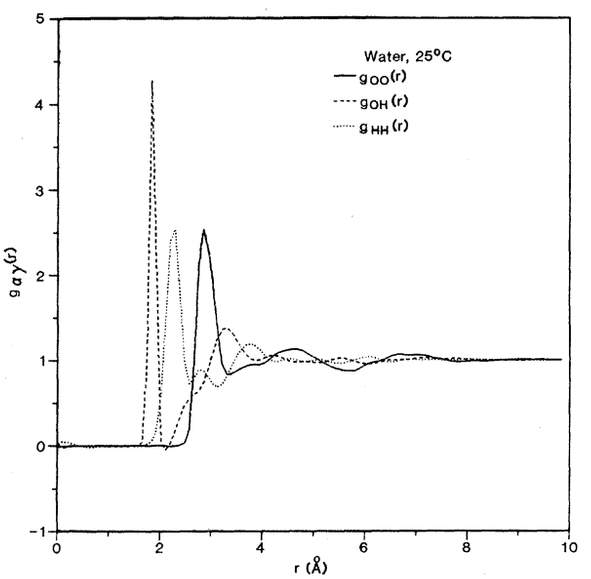

Fig. 1. Intermolecular atom pair distribution functions for liquid water at 25°C.

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