Reports

Transient Climate Response to Increasing Atmospheric Carbon Dioxide

Abstract. *The ocean's role in the delayed response of climate to increasing atmospheric carbon dioxide has been studied by means of a detailed three-dimensional climate model. A near-equilibrium state is perturbed by a fourfold, step-function increase in atmospheric carbon dioxide. The rise in the sea surface temperature was initially much more rapid in the tropics than at high latitudes. However, the fractional response, as normalized on the basis of the total difference between the high carbon dioxide and normal carbon dioxide climates, becomes almost uniform at all latitudes after 25 years. Because of the influence of a more rapid response over continents, the normalized response of the zonally averaged surface air temperature is faster and becomes nearly uniform with respect to latitude after only 10 years.*

Long-term measurements (*1*) at several stations provide firm evidence that the atmospheric concentration of CO_2 is increasing on a global scale. The increase is usually ascribed to the burning of fossil fuels, but changes in the carbon content of the biosphere may also contribute. Studies of the impact of increasing atmospheric CO_2 on climate have tended to focus on the global equilibrium climate for different atmospheric CO_2 concentrations. The results from mathematical models of climate (*2*) indicate that a doubling of the present CO_2 concentration may cause the globally averaged sea surface temperature to increase by 1.5° to 4.5°C. Precise results differ from one model to another depending on the details of the albedo feedback effects of snow, ice, and cloudiness. Recently (*2–4*), attention has been drawn to the nonequilibrium climate problem. In other words, if an increase in the globally averaged temperature will eventually take place for a specified increase in the atmospheric CO_2 concentration, how rapidly will the change actually occur? The moderating effect of the ocean plays a key role. In a recent report of the National Academy of Sciences (*2*), it is estimated that a climatic response to increasing atmospheric CO_2 will have a delay of the order of decades because of the thermal inertia of the ocean. In this study, we attempt to investigate this transient response problem by examining the results from numerical experiments with a coupled ocean-atmosphere model.

The climate model used in this study has been developed over a period of years. The oceanic and atmospheric components have been tested separately in independent studies. This was the first time that the model has been used to study the time-dependent behavior of the climate system, and it required a completely synchronous integration with respect to time of the ocean and atmosphere. Our numerical experiment consisted of a "switch on" case in which an equilibrium climate solution is perturbed by a step function increase of atmospheric CO_2. A "switch on" experiment provides information on the response for a wide range of time scales, which can be applied to more realistic scenarios of atmospheric CO_2 buildup. Unfortunately, our climate model calculation required many hours of calculations on a large-capacity computer, limiting consideration to only a few cases. It is important that the search for simpler models that are consistent with both tracer data (*5*) and more detailed climate models continue.

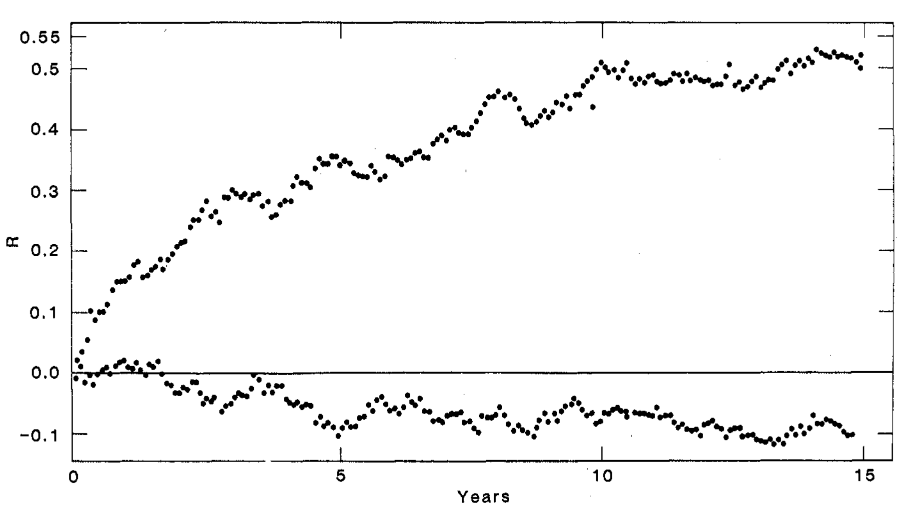

Fig. 1. The normalized response of the globally averaged sea surface temperature plotted at 30-day intervals (upper curve); the response for a calibration experiment (lower curve).

The coupled three-dimensional climate model used in this study is slightly less complex than that of some earlier studies (*6, 7*). The seasonal variation in solar insolation was not included, and the geometry of land and sea was highly idealized. To minimize the amount of calculation, the model atmosphere and ocean was constrained to be triply periodic in a zonal direction with mirror symmetry across the equator. Land and ocean occupy adjacent 60° sectors of longitude, extending from the equator to one of the poles. The atmospheric model used finite differences in the vertical plane, and variables were represented by spherical harmonics in the horizontal plane. The radiation balance, the hydrologic cycle, and the transport effects of atmospheric cyclones and anticyclones were included explicitly. The ocean model did not have sufficient resolution to resolve mesoscale eddies, which are the dynamic counterparts of cyclones and anticyclones in the atmosphere. The resolution was sufficient, however, to permit the inclusion of the main features of the observed wind-driven and thermohaline circulation. Twelve levels in the vertical specified as in (*7*) provided a detailed representation of the ocean thermocline. A simple model of sea ice and land snow cover allowed an important albedo feedback mechanism. Because of the great difficulty of accurately determining parameters with which to represent the cloud distribution, zonally uniform cloudiness is fixed to the observed climatology at each latitude.

Since we are interested in the response

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of the coupled model as it makes the transition from one equilibrium state to another, the first requirement was to calculate equilibrium climates corresponding to normal and high atmospheric CO_2. The increase in CO_2 (four times normal) was deliberately chosen to be large relative to any foreseeable actual change in the composition of the earth's atmosphere in order to discriminate between CO_2-induced change and background temporal fluctuations of the model climate. The economical method used to obtain climate equilibrium has been described in (*6*). Briefly, a nonsynchronous method is used to couple the atmosphere, upper ocean, and deep ocean to allow for the extremely disparate time scales of the climate system. The deep ocean has a time scale of millennia. The atmosphere has a time scale of about 1 month, whereas time scales of the upper ocean lie in an intermediate range. Nonsynchronous coupling may be thought of as a relaxation procedure to hasten the convergence to equilibrium. In this study, 1 year in the atmospheric model was taken to correspond to 110 years in the upper ocean. One year in the upper ocean, in turn, was taken to be equivalent to 25 years in the deepest levels of the ocean.

Convergence to a climatic equilibrium for the normal and high CO_2 cases was obtained after an integration of the numerical models over the equivalent of 6 years in the atmosphere, 650 years in the upper ocean, and 16,000 years for the deep ocean. Zonally averaged surface air temperatures for the equilibrium states are shown in Table 1. The model climate for normal CO_2 compares quite well with observations (*8*) except in high latitudes where warming by the active ocean in the model led to a less extensive snow and sea ice cover than observed. The excessive warming at high latitudes occurred because the ocean in the climate model extended directly to the pole. Table 1 also shows that the difference between the zonally averaged surface air temperatures for the normal CO_2 and high CO_2 climates increased with latitude. The pattern of sensitivity was similar to that found in earlier studies (*9*), but the amplitude was somewhat less in middle and high latitudes. This reduced sensitivity occurs because the present model climate for normal CO_2 was warmer and had less snow and ice at high latitudes than models without an active ocean.

The determination of two climatic equilibrium states provides the basis for a "switch on" experiment in which the normal CO_2 equilibrium climate is perturbed by a sudden quadrupling of the atmospheric CO_2. The atmosphere and ocean models are numerically integrated in a synchronous mode as opposed to the nonsynchronous, economical method used to obtain climate equilibrium. The normalized response of the globally averaged sea surface temperature is shown as a function of time in Fig. 1 (upper curve). The normalized response, R, may be defined as

$$R = \frac{T - T_0}{T_\infty - T_0}$$

where T is the globally averaged sea surface temperature, T_0 is its initial equilibrium value, and T_∞ is its final equilibrium value for a fourfold increase in atmospheric CO_2. The response consists of a quick rise in temperature over the first 3 years to nearly 30 percent of the total difference between equilibrium states. This rapid rise is associated with the heating of the mixed layer and is followed by a much slower rise as the effect of vertical transfer of heat to lower levels is felt. The bottom curve of Fig. 1 shows the response of a calibration experiment in which the initial conditions are the same as those of the climate response experiment but without the increase in atmospheric CO_2. The calibration experiment shows a downward trend in R that is equivalent to 0.5°C over 15 years. An analysis of the ocean model solution, however, shows that the temperature trend is confined to the near surface. Although the climate of the model is not in perfect equilibrium, the departure is relatively small. Evidence for this is found in the net heating rate of the ocean, which is equivalent to a heat flux of -0.06 W/m^2 at the ocean surface averaged over 15 years as compared to $+6.5$ W/m^2 for the "switch on" experiment.

The results of an earlier study (*3*), in which a Budyko-Sellers climate model and a passive ocean with a heat capacity varying with latitude were used, suggested the possibility of a more rapid response at low latitudes. The zonally averaged normalized response as a function of time and latitude (Fig. 2a) supports this idea in the early stage of the experiment. After 20 years, however, a systematic difference in the normalized

Table 1. Zonally averaged surface air temperature of the ocean-atmosphere climate model.

Latitude (deg)	Observed temperature (°C)	Temperature for the normal CO_2 climate (°C)	Temperature difference (high − normal CO_2 climate) (°C)
80°	−15.8°	− 6.2°	10.7°
60°	− 1.0°	3.7°	6.4°
40°	12.7°	12.9°	5.2°
20°	25.0°	23.9°	4.4°
0°	26.2°	25.4°	3.5°

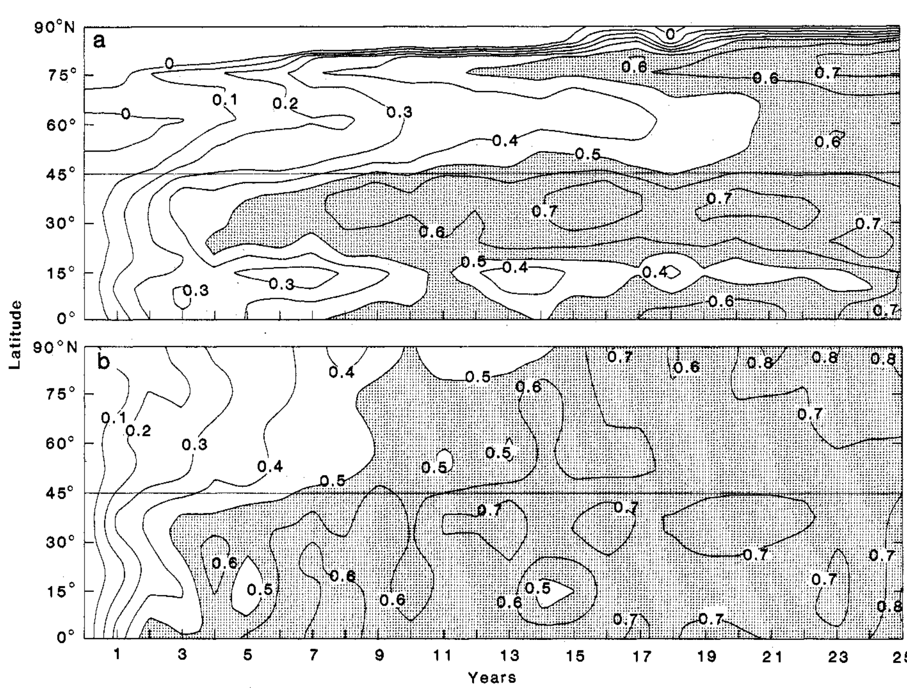

Fig. 2. Time-latitude variation of the zonally averaged normalized response of (a) sea surface temperature and (b) surface air temperature averaged over continent and ocean. The normalized response, R, is calculated from Eq. 1 with the use of zonally averaged temperatures.

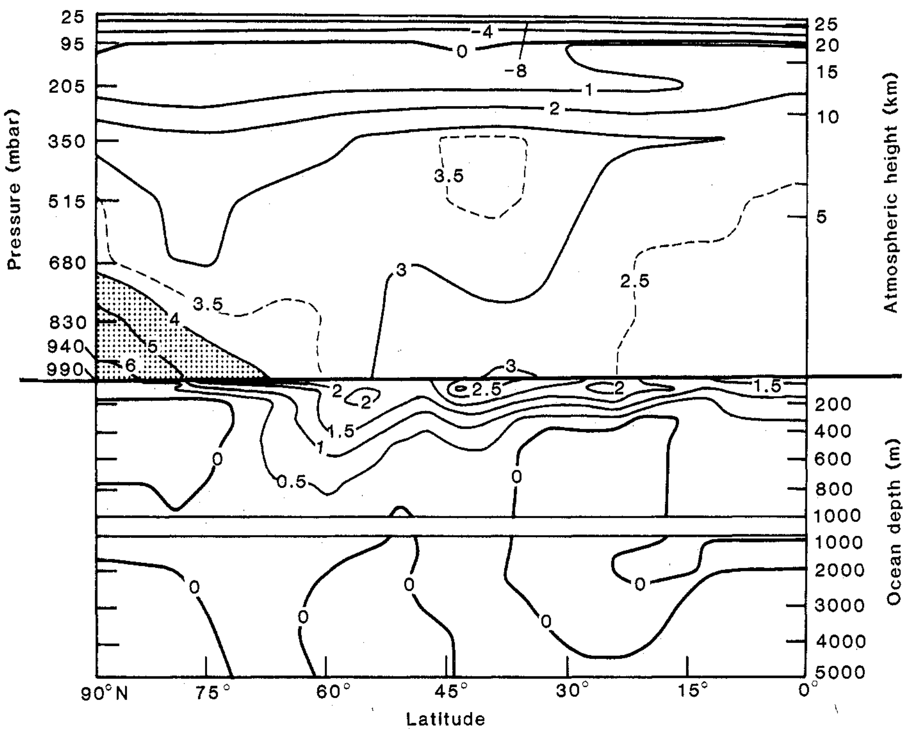

Fig. 3. Latitude-height distribution of the zonally averaged temperature at 10 years minus the initial temperature, showing the response to a step-function increase in atmospheric CO_2. Units are degrees Celsius.

response between low and high latitudes is no longer obvious. Since R is the temperature increase normalized in terms of the total difference between high CO_2 and normal CO_2 climates at each latitude, Fig. 2a implies that normalized sea surface temperature increases will have almost the same latitudinal distribution for time scales in excess of 25 years. According to Fig. 2b which illustrates the normalized response of zonal mean surface air temperature, R becomes almost uniform after only 10 years, influenced by the faster response over the continent. If this finding is supported by further numerical studies with even more detailed ocean models, it is a significant result. The conclusion would be 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.

In Fig. 3 the zonally averaged response at 10 years is shown for all levels in the atmosphere and the ocean. In the polar region when sea ice exists at the air-sea interface, the atmosphere exhibits the largest response at the earth's surface whereas the temperature of the underlying seawater remains at the freezing point. Near the sea ice margin located at about 75° latitude, the CO_2-induced warming of sea surface temperature is limited to the thin surface layer because of the stable stratification. At about 60° latitude where the ocean has a weak stratification, the heat anomaly finds pathways for relatively deep penetration. The greater stratification of the tropical ocean prevents much vertical heat exchange at low latitudes.

Our calculations represent a first attempt to predict the transient response of climate to increasing atmospheric CO_2 with a model that includes an active ocean. The aim of our study has not been to provide reliable calibration for simpler models, since the precise results obtained depend on the particular geometry and other assumptions inherent in the model. The importance of our study lies in the greater insight that a more detailed model can provide, which in turn can suggest how simpler models should be designed and how the available data can best be used to test them.

An important finding in our calculation is that the initial response to a sudden "switch on" of atmospheric CO_2 is a rapid rise of sea surface temperature in the tropics. After 10 years, however, sea surface temperature rises decrease in the tropics but persist at higher latitudes. The normalized sea surface temperature response becomes almost uniform with latitude after 25 years. However, the normalized response of zonal mean surface air temperature is even faster and becomes nearly uniform with respect to latitude after only 10 years, because of the influence of a faster response over the continents. The results of an earlier study (*3*) with a much simpler ocean-atmosphere model raised the possibility that the ocean could cause a transient response very different from that indicated by sensitivity studies of normal CO_2 and high CO_2 equilibrium climates. Our conclusion, based on Fig. 2, is that R would be essentially uniform with latitude except in the unlikely event of very rapid increases of CO_2, much more rapid than those indicated in present measurements. Of course, the existence of ocean currents does change the sensitivity of the present model, compared to earlier studies in which a full ocean was not included (*10*).

Our test calculation shows that the uptake of heat by the ocean causes a sizable delay in the response of climate to a sudden increase in atmospheric CO_2. Quantitative results of our calculations must be considered tentative, since this is a process study rather than an exhaustive examination of all model parameters. With this reservation, we conclude that the oceans can delay but by no means eliminate a strong climatic response to increasing atmospheric CO_2.

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10. A detailed analysis for this effect will be presented elsewhere (K. Bryan, F. G. Komro, S. Manabe, M. J. Spelman, in preparation).
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