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The Effect of Ocean Heat Capacity Upon Global Warming Due to Increasing Atmospheric Carbon Dioxide

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Time-dependent global warming due to increasing levels of atmospheric carbon dioxide has been estimated by employing an ocean-land global climate model. Ocean heat capacity is incorporated by means of a global ocean model having a 70 m deep mixed layer, with heat being transported from the mixed layer to deeper waters by eddy diffusion. The time-dependent increase in atmospheric CO_2, from 1860 to 2025, is taken from carbon-cycle models. The model results suggest that ocean heat capacity will produce a lag in CO_2-induced global warming of about 2 decades. For example, without inclusion of ocean heat capacity the model predicts that an increase in global surface temperature of 1°C, relative to 1860, will occur by 1988. But when ocean heat capacity is included, the 1°C warming is delayed until 2006–2012, this range of times corresponding to no land-ocean advective coupling (2006) and complete land-ocean coupling (2012). By 2025, when the assumed atmospheric CO_2 content is twice the 1860 value, the model predicts global warming of 1.5°–1.8°C, in contrast to 3.1°C when ocean heat capacity is neglected.

INTRODUCTION

A number of published model studies have examined the climatic effects of increased atmospheric carbon dioxide resulting from fossil fuel burning [e.g., *Manabe and Wetherald,* 1967; *Sellers,* 1974; *Schneider,* 1975; *Manabe and Wetherald,* 1975; *Augustsson and Ramanathan,* 1977; *Lee and Snell,* 1977; *Ohring and Adler,* 1978; *Ramanathan et al.,* 1979]. All such studies show that increased atmospheric CO_2 would produce an increase in surface and tropospheric temperatures.

These modeling endeavors, however, simply increase atmospheric CO_2 by a fixed amount, usually doubling the present CO_2 concentration, so that they are comparing one equilibrium climatic state to another. In reality, of course, the CO_2 increase is a time-dependent process, and one would anticipate, as a consequence of the heat capacity of the oceans, that CO_2-induced global warming might exhibit a significant time delay. *Thompson and Schneider* [1979] suggest that a time delay of a few years to a decade or so is possible. Recently, *Hunt and Wells* [1979] have coupled a seasonal thermocline model with a time-dependent climate model and conclude that such a time delay would not be appreciable. But as they point out, their model does not allow for heat transport to the deeper ocean, and thus their model might underestimate the time delay.

To appraise crudely whether or not heat transport to the deeper ocean could significantly influence time-dependent global warming due to increasing atmospheric CO_2, a global ocean model has been employed which is similar to that used by *Oeschger et al.* [1975] in studying the carbon cycle. This ocean model is coupled to a global ocean-land energy-balance climate model, and global mean surface temperature is then estimated as a function of time for the period 1860–2025. The increase in atmospheric CO_2 with time is taken from current carbon-cycle models.

OCEAN MODEL

Figure 1 illustrates the presently employed global ocean model, which is equivalent to the box-diffusion model utilized by *Oeschger et al.* [1975] in studying the carbon cycle. This consists of a mixed layer having the heat capacity $R_m = 3 \times 10^8$ W s^{-1} m^{-2} C^{-1}, which corresponds to a layer 70 m deep. By definition $R_m = \rho c_p \Delta z$, where ρ is the density of sea water, c_p is its specific heat, and $\Delta z = 70$ m.

Below the mixed layer heat is transported by turbulent diffusion, with κ representing a global eddy diffusion coefficient. In addition, although as discussed shortly it is a transport mechanism which may for present purposes be neglected, there exists vertical advection due to bottom water production by sinking in the polar latitudes. Upon letting $T_0(z, t)$ denote the ocean temperature within the lower layer as a function of depth and time, then the equation governing $T_0(z, t)$ is

$$\frac{\partial T_0}{\partial t} = \kappa \frac{\partial^2 T_0}{\partial z^2} - w \frac{\partial T_0}{\partial z} \quad (1)$$

where w is the vertical advection velocity measured in the positive z direction. The steady state form of (1) produces an exponential variation of $T_0(z)$ with depth, for which the scale height is $\kappa/(-w)$ [e.g., *Munk,* 1966].

Employing observed steady state temperature, salinity, and radiocarbon profiles, *Munk* [1966] suggests that $\kappa = 1.3$ cm^2 s^{-1} and $w = -1.4 \times 10^{-5}$ cm s^{-1}. Comparable values have been obtained by others, such as *Craig*'s [1969] $\kappa = 2$ cm^2 s^{-1} and $w = -2 \times 10^{-5}$ cm s^{-1} results. Recently, *Oeschger et al* [1975] have shown that this transport model, with $\kappa = 1.3$ cm^2 s^{-1} and $w = 0$, is compatible with observed uptake by the oceans of radiocarbon which was produced during the period of nuclear weapons testing. The neglect by *Oeschger et al.* [1975] of vertical advection in dealing with a short-term time-dependent process (i.e., bomb-produced radiocarbon) suggests that this simplification might also be applicable to other time-dependent processes, such as the present problem involving time-dependent CO_2 heating.

To illustrate the applicability of this assumption, let

$$\theta_0(z, t) = T_0(z, t) - T_0(z, 1860)$$

represent the temperature change relative to the 1860 steady state profile, such that (1) becomes

$$\frac{\partial \theta_0}{\partial t} = \kappa \frac{\partial^2 \theta_0}{\partial z^2} - w \frac{\partial \theta_0}{\partial z} \quad (2)$$

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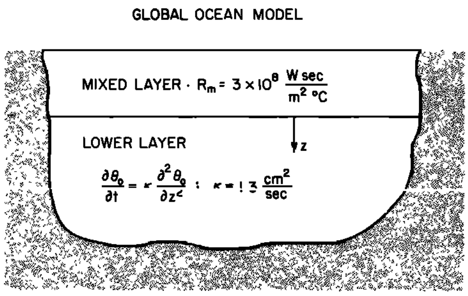

Fig. 1. Schematic illustration of the global ocean model.

For the sole purpose of estimating the relative importance of vertical advection, we may replace $\partial\theta_0/\partial t$ by θ_0/τ_c, where τ_c is the appropriate time scale for the CO_2 heating process; in the following section this is taken to be 33 years. With this replacement within (2), it readily follows that

$$\theta_0(z, t) = \theta_0(0, t)e^{-z/H} \tag{3}$$

where

$$\frac{1}{H} = \frac{(-w)}{2\kappa} + \frac{1}{2}\left[\frac{(-w)^2}{\kappa^2} + \frac{4}{\kappa\tau_c}\right]^{1/2} \tag{4}$$

Interestingly enough, the variation of $\theta_0(z, t)$ with z, as described by (3), is in virtually precise agreement with the complete solution presented later (see Figure 5). For $\tau_c \to \infty$, (4) reduces to the steady state scale height $H = \kappa/(-w)$, as should be expected. On the other hand, with $\tau_c = 33$ years for the CO_2 heating problem, and employing *Munk*'s [1966] values of $\kappa = 1.3$ cm^2 s^{-1} and $w = -1.4 \times 10^{-5}$ cm s^{-1}, then $H = 0.82 \sqrt{\kappa\tau_c}$, where $\sqrt{\kappa\tau_c}$ denotes H for $w = 0$. In view of the uncertainties in estimating κ and w, we regard this difference in H between $w = -1.4 \times 10^{-5}$ cm s^{-1} and $w = 0$ to be insignificant, so that for the present time-dependent model we shall ignore vertical advection and replace (2) by

$$\frac{\partial\theta_0}{\partial t} = \kappa \frac{\partial^2\theta_0}{\partial z^2} \tag{5}$$

with $\kappa = 1.3$ cm^2 s^{-1}, as depicted within Figure 1. In this context, our model is consistent with the diffusive-advective model of *Munk* [1966] as well as with the strictly diffusive model of *Oescher et al.* [1975].

On the other hand, (5) may alternatively be interpreted as including vertical advection, providing κ is replaced by an effective diffusion coefficient κ', which accounts for both diffusive and advective transport. From (2) and (3) it readily follows that

$$\kappa' = \kappa + wH$$

with $\kappa' = 0$ for steady state conditions since H (steady state) $= \kappa/(-w)$. Employing *Craig*'s [1966] values of $\kappa = 2$ cm^2 s^{-1} and $w = -2 \times 10^{-5}$ cm s^{-1}, together with $\tau_c = 33$ years, we find that $\kappa' = 1.4$ cm^2 s^{-1}. Thus within this context, our transport model, with $\kappa' = 1.3$ cm^2 s^{-1}, is consistent with Craig's transport quantities.

Heat transport within the lower ocean is now described by the boundary-value problem comprising (5) together with the boundary conditions

$$\theta_0(z, 0) = 0 \qquad \left(\frac{\partial\theta_0}{\partial z}\right)_{z=0} = -\frac{F_0(t)}{\kappa\rho c_p} \tag{6}$$

where $F_0(t)$ is the heat flux from the atmosphere and mixed layer system to the lower ocean layer. Thus, for a prescribed $F_0(t)$, the solution of this boundary-value problem yields $\theta_0(0, t)$ which, due to continuity of temperature, also denotes the global mixed-layer (and thus sea-surface) temperature. For present purposes it will be sufficient to assume that the ocean is infinitely deep since, for the time periods considered herein, time-dependent heat transport is restricted to roughly the upper 1 km of the oceans, such that there is no practical distinction between an infinitely deep ocean and one of finite depth.

The heat flux $F_0(t)$ is caused by CO_2-induced heating of the surface-troposphere system, with subsequent modification due to processes occuring within the atmosphere and mixed layer. Thus the specification of $F_0(t)$ requires a coupled climate model, and this model is described in the following section.

CLIMATE MODEL

Let $\theta_{0s}(t)$ denote the global sea-surface temperature increase relative to 1860, a quantity which will additionally represent the temperature increase throughout the mixed layer, while $\theta_{Ls}(t)$ is the corresponding quantity for the global land surface. The heat flux into the lower ocean layer, $F_0(t)$, may thus be expressed as

$$F_0(t) = \Delta F(t) - B\theta_{0s} + (\nu/f_0)(\theta_{Ls} - \theta_{0s}) - R_m(d\theta_{0s}/dt) \tag{7}$$

The term $\Delta F(t)$ represents heating of the surface-troposphere system due to increasing atmospheric CO_2. However, this heating will be modified through the additional terms appearing within (7). The second term represents modification of the surface-atmosphere radiation budget resulting from increased sea-surface temperature, where

$$B = \frac{dF}{dT_s} + Q\frac{d\alpha}{dT_s}$$

with dF/dT_s representing the change in outgoing infrared flux with surface temperature, Q is the global insolation, and $d\alpha/dT_s$ is the change in albedo due to ice-albedo feedback. The next term in (7) represents heat transport from land to ocean surfaces, with ν denoting a land-ocean coupling coefficient,

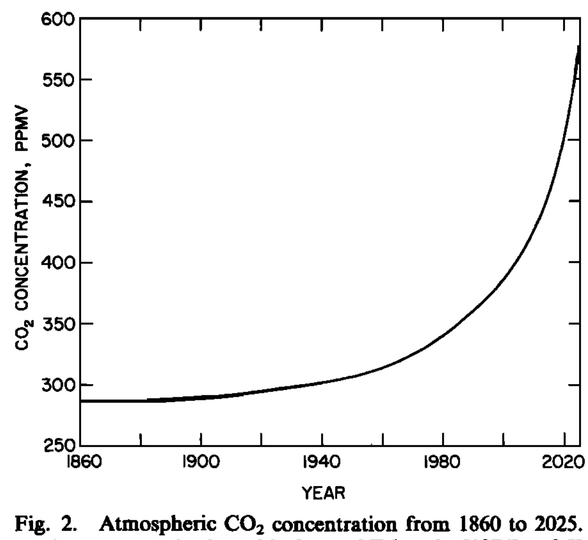

Fig. 2. Atmospheric CO_2 concentration from 1860 to 2025. This comprises a composite from *Machta and Telegadas* [1974] and *Keeling* [1976].

while $f_0 = 0.71$ is the global ocean fraction. The final term represents heat storage by the mixed layer.

A comparable expression applies to the land surface, such that

$$0 = \Delta F - B\theta_{Ls} - (\nu/f_L)(\theta_{Ls} - \theta_{0s}) \quad (8)$$

for which heat storage by the land is assumed to be negligible compared with that by the ocean. The primary difficulty associated with (7) and (8) concerns specification of the coupling coefficient ν. But for present purposes it will suffice to consider only the extremes of complete land-ocean coupling ($\nu = \infty$) and no land-ocean coupling ($\nu = 0$). In the former ($\nu = \infty$)

$$F_0 = \Delta F/f_0 - B\theta_{0s}/f_0 - R_m(d\theta_{0s}/dt) \quad (9)$$

with $\theta_{Ls} = \theta_{0s}$, while for the latter ($\nu = 0$)

$$F_0 = \Delta F - B\theta_{0s} - R_m(d\theta_{0s}/dt) \quad (10)$$

with $\theta_{Ls} = \Delta F/B$, and the global temperature increase is the area average of θ_{0s} and θ_{Ls}.

The quantity B governs the sensitivity of the climate model. For example, considering a change in solar constant, it follows that [*Cess,* 1976]

$$\beta = S_0 \frac{dT_s}{dS} = \frac{F}{B}$$

where S is the solar constant, S_0 is the present solar constant, T_s is the global mean surface temperature, and F(= 234 W m^{-2}) is the global outgoing infrared flux. Several climate models suggest that $\beta \simeq$ 185°C [*Wetherald and Manabe,* 1975; *Lian and Cess,* 1977] giving $B = 1.26$ W m^{-2} C^{-1}, a value which we employ within the present study for both ocean and land surfaces.

The final quantity which remains to be specified is $\Delta F(t)$. Recall that $\Delta F(t)$ represents infrared heating of the surface-troposphere system due to increasing levels of carbon dioxide. This first necessitates knowledge of the variation in atmospheric CO_2 with time, which has been taken from the carbon-cycle models of *Machta and Telegadas* [1974] and *Keeling* [1976]. The time-dependence of CO_2 concentration, which is a composite of these two models, is shown in Figure 2, with the preindustrial (1860) concentration of 287 ppmv doubling to 584 ppmv by 2025.

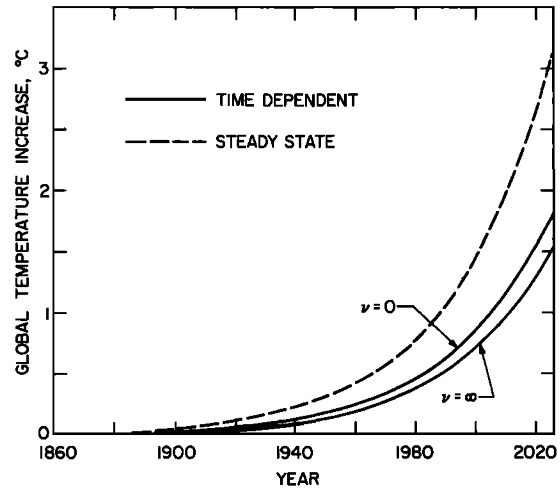

Fig. 4. Model results for the increase in global surface temperature from 1860 to 2025.

The corresponding CO_2 radiative heating, $\Delta F(t)$, was obtained by logarithmically extrapolating and interpolating the 320, 426, 534, and 640 ppmv results, relative to 320 ppmv, presented by *Ramanathan et al.* [1979]. The resulting $\Delta F(t)$ is illustrated in Figure 3, and this may be approximated by the expression

$$\Delta F(\text{W m}^{-2}) = 0.0277(e^{t/\tau_c} - 1) \quad (11)$$

where $\tau_c = 33.3$ years. Equations (9) and (10) in turn yield

$$F_0 = A(e^{t/\tau_c} - 1) - B'\theta_{0s} - R_m(d\theta_{0s}/dt) \quad (12)$$

where $A = 0.0277$ W m^{-2} and $B' = B$ for $\nu = 0$, while $A = 0.0390$ W m^{-2} and $B' = B/f_0$ for $\nu = \infty$.

The time-dependence of sea-surface temperature, $\theta_{0s}(t)$, is thus determined from the solution of (5), (6), and (12). The resulting boundary-value problem has been solved by an analytic-iterative procedure.

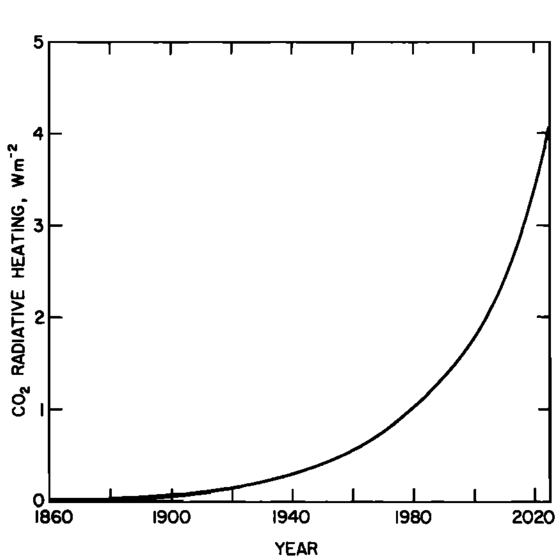

Fig. 3. The CO_2 radiative heating function, $\Delta F(t)$, from 1860 to 2025.

RESULTS AND DISCUSSION

We first consider model estimates of the global temperature increase in 2025 relative to 1860; Table 1 summarizes several results which have been obtained from the present model. The steady state value of 3.10°C simply refers to a comparison of equilibrium climatic states for a doubling of atmospheric CO_2 from 287 ppmv (1860) to 584 ppmv (2025). This result agrees well with more detailed model studies, such as the 2.93°C global warming for 2 × CO_2 predicted by *Manabe and Wetherald* [1975] employing a general circulation model.

Table 1 also illustrates results of the time-dependent model

TABLE 1. Global Temperature Increase From 1860 to 2025

R_m, W s^{-1} m^{-2}	Temperature Increase, °C		
	$\nu = 0$	$\nu = \infty$	Steady State
0	1.89	1.67	3.10
3×10^8	1.80	1.53	3.10
6×10^8	1.72	1.42	3.10

TABLE 2. Global Time Delay for 2 × CO_2 and $\nu = 0$

$CO_2(t)$	dF/dT_s, W m^{-2} C^{-1}	Time Delay, years
Carbon-cycle models	1.26	18
Carbon-cycle models	2.20	12
Exponential, (10)	1.26	28
Exponential, (10)	2.20	20

for the two limiting cases of land-ocean coupling, $\nu = 0$ and $\nu = \infty$, as well as for several values of the mixed layer heat capacity R_m. Clearly, the heat capacity of the mixed layer does not exert a strong influence upon the model's time-dependent behavior. Instead, the reduction in the time-dependent values, relative to the steady state increase of 3.10°C, is primarily the result of heat transport by diffusion below the mixed layer.

The land-ocean coupling coefficient ν also exerts a small influence upon the global mean temperature increase. The coupling coefficient does, of course, influence the separate land and ocean temperature increases. For complete land-ocean coupling ($\nu = \infty$), there is no distinction between land and ocean surface temperature, whereas for no land-ocean coupling ($\nu = 0$), the sole influence of ocean heat capacity is to delay the increase in ocean temperature. Thus, for example, in 2025 with $\nu = 0$, the land temperature increase is 3.10°C while that for the ocean surface is 1.27°C.

The primary point concerning Table 1 is the reduction in global warming due to ocean heat capacity, with the time-dependent model predicting global warming of 1.5°C ($\nu = \infty$) to 1.8°C ($\nu = 0$) by 2025, in contrast to 3.1°C when ocean heat capacity is neglected. This should not, however, be interpreted as a reduction in CO_2-induced warming. Rather, it is simply a time delay.

This time delay is illustrated in Figure 4, which shows the 1860 to 2025 time history for both the steady state and time-dependent cases, from which the time delay is roughly 2 decades. To give an example of this, without inclusion of ocean heat capacity the model predicts 1°C global warming by 1988. But when ocean heat capacity is included, there is an 18–24 year delay in this warming to 2006 ($\nu = 0$) and 2012 ($\nu = \infty$).

It should be emphasized that the time delay is not uniquely dependent upon the ocean model. Rather, it is process dependent such that it is also influenced by the time variation of $F_0(t)$, which in turn is a function of both the assumed carbon-cycle model and the sensitivity of the coupled climate model. To illustrate this, model predicted time delays, for $\nu = 0$ and corresponding to the time at which CO_2 is doubled, are shown in Table 2 for changes in both the time dependence of CO_2 concentration and the sensitivity of the climate model.

The heading $CO_2(t)$ in Table 2 refers to the assumed time increase in CO_2, with the 'carbon-cycle models' designation refering to $CO_2(t)$ as given in Figure 2. Recall that the quantity B governs the sensitivity of the climate model, and the increase in B from 1.26 to 2.20 W m^{-2} C^{-1} corresponds to a decrease in model sensitivity. For example, with $B = 2.20$ W m^{-2} C^{-1}, the steady state global temperature increase, for 2 × CO_2, is reduced from 3.1°–1.8°C, this latter value being consistent with the climate model employed by *Hunt and Wells* [1979]. From Table 1, the decreased climate sensitivity, for the carbon-cycle models $CO_2(t)$, reduces the time delay from 18 to 12 years.

To illustrate the effect of employing a different $CO_2(t)$, we have chosen

$$CO_2(t) = (300 \text{ ppmv})\, e^{t/\tau_0} \quad (13)$$

where $\tau_0 = 104$ years. This coincides with one of the scenarios employed by *Hunt and Wells* [1979], and it leads to a doubling of CO_2 in 72 years. Clearly from Table 2 the assumed $CO_2(t)$ function can significantly influence the time delay.

Hunt and Wells [1979] have employed (13) together with a climate model whose sensitivity coincides with our choice of $B = 2.20$ W m^{-2} C^{-1}, a seasonal mixed layer model, and no coupling between land and ocean surfaces. They find an ocean time delay of only 8 years, which corresponds to a global (land plus ocean) time delay of about 6 years, substantially less than the 20 year value given in Table 2. A possible reason for this difference is that the seasonal thermocline model employed by Hunt and Wells does not allow heat transport to the deeper ocean; within their model there is no heat transport to ocean waters below about 200 m. Figure 5 illustrates the increase in ocean temperature as a function of depth, as predicted by the present model, for 2025 relative to 1860, with $R_m = 3 \times 10^8$ W s^{-1} m^{-2} C^{-1} and $\nu = 0$. Clearly, at least within the confines of this model, time-dependent heat transport exists to significant depths.

CONCLUSIONS

The primary conclusion of the present study is simply that, due to ocean heat capacity, global warming resulting from increasing atmospheric CO_2 could be delayed by roughly two decades. This estimate obviously stems from a highly simplistic ocean model, and a more detailed treatment of the oceans is certainly necessary in future time-dependent modeling endeavors. What the present study further illustrates is the uncertainty in the estimated time delay arising from both the assumed CO_2 concentration as a function of time and the sensitivity of the climate model. This should be borne in mind in subsequent modeling efforts, since it could significantly influence model comparisons.

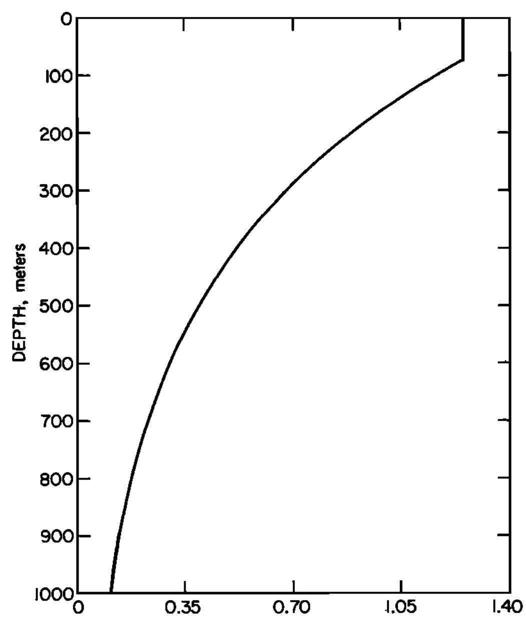

Fig. 5. Ocean temperature increase from 1860 to 2025, as a function of depth, for $\nu = 0$.

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