ENERGY BALANCE MODELS INCORPORATING EVAPORATIVE BUFFERING OF EQUATORIAL THERMAL RESPONSE

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Abstract. We describe two non-standard energy balance models which include effects of latent heat on climate sensitivity, and apply them to study sensitivity to uniform variations in insolation and changes in the concentration of atmospheric CO_2. The Tropical Equatorial Constraint (TEC) model incorporates the proposal of Newell and Dopplick (1979) that evaporative losses from tropical sea surface strongly limit thermal response. The two phase model includes an approximate treatment of energy transfer both as sensible heat and as latent heat of water vapor.

We compare the mathematical and physical assumptions underlying each model, and contrast their solutions with results from a standard model in which the diffusion coefficient remains constant with forcing. Both the TEC and two phase model produce stronger thermal response in polar regions than does the standard model. The TEC model shows that the implication of Newell and Dopplick (1979), that equatorial buffering will limit climate response to increasing CO_2, is not justified when its global consequences are considered. The two phase model closely reproduces results for temperature change with latitude found by Manabe and Wetherald (1980) using a general circulation model. Polar amplification found in the two phase model is attributable to the behavior of a temperature dependent effective diffusion coefficient that increases with warming.

1. Introduction

In previous papers we developed two types of energy balance models, (EBMs): the TEC (for Tropical Equatorial Constraint), and two phase model, that incorporate different aspects of the possible influence of latent heat on climate sensitivity. The TEC model developed in Hoffert et al. (1982, hereafter referred to as Paper I) explores the consequences of the proposal of Newell and Dopplick (1979, hereafter ND) that evaporative losses from sea surface strongly limit thermal response in the tropics. That idea was incorporated as an explicit boundary condition on equatorial temperature as a function of solar constant. Here we extend the TEC model to the case of forcing by changes in the concentration of atmospheric CO_2. Flannery (1982, hereafter referred to as Paper II) developed a two phase EBM that includes the effect of energy transport in the form of latent energy of water vapor and the thermal energy of air.

Here, in section 2, we describe the physical basis and mathematical form of a standard EBM (see North et al., 1981) and of the TEC and two phase models, and in section 3 we systematically compare the behavior of these models for sensitivity to solar and CO_2 forcing. In section 4, we compare a few special cases with corresponding cases calculated using a general circulation model (GCM) (Manabe and Wetherald 1980, hereafter referred to as MW). We will especially focus on the question of the latitudinal distribution of temperature change with forcing. We discuss and summarize our results in section 5.

2. Energy Balance Models

The Standard EMB

We consider annual mean, steady state, latitudinally resolved, symmetric, EBMs which prescribe the distribution of surface temperature $T(x)$ as a function of latitude $\Theta = \sin^{-1}(x)$. The standard model equation, as discussed in North et al. (1981), describes conservation of energy on a sphere subject to solar heating $S(x)$ attenuated by

TABLE 1. Standard EBM Coefficients, Tuned to Current Climate

INSOLATION	$Q_o = 334\ W\ m^{-2}$	$s_o = 1.246$	$s_2 = 0.738$
IR RADIATION	$A = 205\ W\ m^{-2}$	$B = 2.23\ W\ m^{-2}\ °C^{-1}$	
ABSORPTION		$a_o = 0.785$	$a_2 = 0.263$
		$b_o = 0.380$	$T_s = -10°C$

fractional absorption $a(x,T)$, longwave infrared cooling $I[T,F(CO_2)]$, and diffusive energy transport characterized by diffusion coefficient D

$$-D \frac{d}{dx} (1-x^2) \frac{dT}{dx} = a(x,x_s)\ S(x) - I[T,F(CO_2)] . \quad (1)$$

For a symmetric model, boundary conditions are: at the pole

$$x=1: \frac{dT}{dx} = \frac{a(x,x_s)\ S(x) - I[T,F(CO_2)]}{2D} , \quad (2a)$$

at the equator

$$x = 0: \frac{dT}{dx} = 0 . \quad (2b)$$

Functionally, insolation includes a scale factor Q, which is 1/4 the solar constant, and geometrical projection factors

$$S(x) = Q(s_o - s_2x^2) . \quad (3)$$

To study sensitivity to solar forcing, we vary Q from its present value Q_o. We represent longwave radiation as a linear function of surface temperature, plus a term dependent on the atmospheric concentration of CO_2,

$$I[T,F(CO_2)] = A + BT + C \ln[F(CO_2)] , \quad (4)$$

where $F(CO_2)$ is the concentration of atmospheric CO_2 relative to its current value. The temperature dependence has been discussed by Warren and Schneider (1979). Satellite observations constrain A and B in order of magnitude, but they require tuning to match a prescribed temperature distribution. Following Hoffert et al. (1980), we include a logarithmic dependence on the atmospheric concentration of CO_2 relative to its present value, and we adjust C to agree with consensus values for global mean temperature rise from CO_2 doubling, $\Delta \langle T\rangle \approx 2.5$ K. Our representation of albedo comes from Hartmann and Short (1979); it includes the important non-linear effect of ice-albedo feedback when temperature falls below a critical value T_s for the formation of ice or snow cover

$$a(x,T) = a_o - a_2x^2, \text{ for } T > T_s , \quad (5)$$

$$a(x,T) = b_o, \text{ for } T < T_s . \quad (5b)$$

Table 1 lists values for the coefficients adopted here. They have been adjusted to match a current climate with T(eq) = 29°C, and an ice line at $x_s = 0.947$ ($\Theta = 71°$) which also results in T(pole) = -15°C, and a global mean temperature $\langle T\rangle = 14.33°C$. These parameterizations and coefficient values are in close agreement with values found and discussed in North et al. (1981). We refer to the model defined by these equations as the standard model. In contrast to the TEC and two phase models, the principal distinguishing features of the standard model are that (1) transport is simply proportional to the temperature gradient and (2) the diffusion coefficient D does not vary when Q or $F(CO_2)$ change.

Fortunately, the standard model can be analyzed exactly by representing the temperature and net source term as expansions in Legendre polynomials

$$a(x,x_s)S(x) = \sum_{L=0}^{\infty} \xi_L P_L(x), \quad T(x) = \sum_{L=0}^{\infty} T_L P_L(x). \quad (6)$$

The coefficients of the source term depend only on the location of the ice-line

$$\xi_L(x_s) = \int_{-1}^{1} a(x,x_s)S(x)P_L(x)dx . \quad (7)$$

The coefficients T_L are given by

$$T_o = (\xi_o - A)/B; \; T_L = \xi_L/[L(L + 1)D + B], \quad (8)$$

for $L \geq 1$.

As discussed in North et al. (1980) a consistent solution for T(x) and Q can be found by iterating until $T(x_s) = T_s$. Note that the coefficient T_o is also the global mean temperature $\langle T\rangle$. Because the radiative loss term is linear with T, and diffusion only redistributes energy, losses at the mean temperature exactly compensate mean net insolation ξ_o. This is simply a restatement of global energy balance.

The TEC EBM

ND proposed that an evaporative constraint on heating of tropical seas would limit global warming by increases in atmospheric CO_2 to values an order of magnitude lower than previously accepted model predictions, i.e., 0.25 K compared with 2-3 K. They based their idea on seasonal and historical observations, and on quantitative analysis of surface energy balance between sea and air, identifying the strong cooling effect of evaporative losses as the controlling feature. Their proposal became the subject of several subsequent studies since it contradicted consensus ideas for global warming from CO_2. GCMs, such as those of Manabe and Wetherald (1975), do include the supposed limiting evaporative effects of ND, but do not find such constrained temperature rise: so other effects must operate that overcome the evaporative limit. The discrepancy between ND and GCM results is hardly surprising because the ND analysis neglects important contributing effects in the highly coupled climate system that are included in the GCM.

The discrepancy has been resolved by attributing the GCM rise to additional feedback from water vapor emission, calculated fully self-consistently in the numerical models (see Ramanathan, 1981; Newell and Dopplick, 1981; Kandel, 1981). However, some aspects of the problem remain controversial: ND point out that the tropical temperature and concentration of water vapor in the Manabe and Wetherald (1975) model for current climate significantly exceed observed values; Kandell notes that analyses differ substantially in the magnitude of terms in the surface energy balance; and results of line-by-line radiative transfer calculations by Wiscombe quoted in Paper I indicate that water vapor feedback is less pronounced under equatorial conditions than in mid-latitudes characteristic of global analyses--this is because water vapor bands are nearly saturated under conditions of high absolute humidity in the tropics (see also Kiehl and Ramanathan, 1982). Limited response of tropical sea surface temperature also receives support from studies of paleoclimate, e.g. Frakes (1979, page 178); Schopf (1980, page 142).

The TEC model developed in Paper I explicitly examines the consequences of the effect proposed by ND. We fixed the response of the equatorial temperature to changes in solar insolation, Q/Q_o, by imposing a boundary condition

$$T_{eq}\ (°C) = 29 + 17.3\ \ln(Q/Q_o) \quad . \qquad (9)$$

This form is based on analysis of surface energy balance closely resembling that of ND. Since the standard model described by Eqs. (1-5) cannot satisfy Eq. (9), except for $Q/Q_o = 1$, an additional degree of freedom was provided by allowing D to vary with Q -- mathematically D(Q) becomes an adjustable parameter. (We continued to keep D independent of latitude). However, physically plausible solutions do not exist for arbitrary values of Q. In Paper I, we showed that D becomes negative outside the limits $0.80 \leq Q/Q_o \leq 1.15$. To maintain equatorial temperatures higher than in the standard model as Q decreases so must D, until when D = 0 the model reaches local radiative equilibrium at $Q/Q_o = 0.80$. Similarly, as Q rises so does D to maintain temperatures lower than in the standard model. Ultimately, D approaches infinity, and the model becomes isothermal at $Q/Q_o = 1.15$. Thus, ND's hypothesis can only be incorporated into a standard EBM by forcing the meridional transport, as parameterized by the diffusion coefficient D, to be a function of tropical conditions.

Paper I compared the TEC and standard EBM results for changes produced by varying insolation. Relative to the standard model, the TEC constraint buffers equatorial temperature change, but it amplifies response in polar regions. The result is readily explained by global energy balance, using the analytic results in Eqs. (6-8). With increasing Q, T must rise, but the rise at the pole will be enhanced if the equatorial temperature is constrained. Consequently, imposing such a limit strongly alters the latitudinal distribution of temperature change.

Here we also apply the TEC model to variations in the concentration of atmospheric CO_2. A straight forward extension of the simplified surface energy balance analysis of Paper I to include CO_2 radiative effects does not change Eq. (9), i.e., the equatorial temperature does not change at all with rising CO_2. This occurs because we neglect variations in IR feedback under the assumption that water vapor feedback dominates, but is small, since the water vapor bands are already near saturation under tropical conditions. Clearly, such strong anchoring overestimates the buffering effect, but not materially. If mean global warming of 2 K occurs, then, for the rest of the model, it hardly matters whether equatorial temperature changes by 0 K or 0.2 K. For the same reasons as for solar forcing, the TEC model shows strong amplification of thermal response at the poles for CO_2 forcing.

The Two Phase Model

In Paper II we described an EBM formulation that includes both sensible heat of air and latent energy of water vapor as agents of diffusive energy transfer. In the two phase model, the fundamental equation

$$-D'\frac{d}{dx}(1-x^2)\frac{d(1+\Psi_L)T}{dx} = a(x,x_s)S(x) - I[T,F(CO_2)], \qquad (10)$$

closely resembles the standard equation, but includes the energy associated with water vapor through the term Ψ_L, which is the ratio of latent to sensible energy,

$$\Psi_L = \frac{r_a q_{sat}(T) L(T)}{c_p T} \quad , \qquad (11)$$

where L(t) is the latent energy of water vapor, r_a is the relative humidity, $q_{sat}(T)$ is the saturation vapor pressure and c_p is the specific heat of air at constant pressure. This expression can be obtained from physical arguments that identify the diffusive flux as arising from the exchange of parcels of air between adjacent latitudinal segments of the atmosphere with different temperature and humidity, as described in Paper II. The principal physical dependence introduced by adding latent heat to the model is the exponential variation of saturation vapor pressure with temperature given by the Clausius-Clapeyron equation

$$\ln(q_{sat}) = \text{const} - L/(RT) \qquad (12)$$

where R is the gas constant of water vapor. $L/R \approx 5300$ K at 300 K.

The two phase model requires a prognostic equation for the distribution of water vapor. Paper II adopted a simple but reasonably accurate assumption for relative humidity that has the advantage of allowing one to define a useful diagnostic concept, the effective diffusion coefficient $D_{eff}(T)$. With reasonable accuracy, the mean distribution of water vapor in the atmosphere can be represented by assuming constant humidity $r_a = 0.8$, independent of latitude, and results, such as those in MW, suggest that relative humidity tends to remain constant during climate change. In that case, Ψ_L is only a function of temperature, and the latitudinal gradient of Ψ_L can be converted into an expression proportional to the temperature gradient. This results in an expression that can be interpreted as an effective diffusion coefficient $D_{eff}(T)$ characterizing the diffusive energy flux

$$F \propto -D' \frac{d(1+\Psi_L)T}{dr} = -D' \left[1+\Psi_L \frac{L}{RT}\right] \frac{dT}{dr} \qquad (13a)$$

$$D_{eff} = D' \left[1+\Psi_L \frac{L}{RT}\right] \qquad (13b)$$

In Paper II, the two phase model was tuned to reproduce T(eq) = 29°C, $x_s = 0.947$, as in the standard and TEC models discussed above. This required adjustment of both D', from 0.623 to 0.317 W m^{-2} K^{-1}, and the radiative loss coefficient B, from 2.23 to 1.95 W m^{-2} (deg C)$^{-1}$, because the models are slightly different in the distribution T(x). The fiducial two phase model gives a mean temperature $\langle T \rangle$ = 16.55°C, and polar temperature -17.55°C, compared with 14.33°C and -14.69°C, respectively, in the standard and TEC models.

In the sensitivity studies of Paper II, D' is held constant, as is D in the standard model, but the effective diffusion coefficient varies strongly with latitude and forcing, through its dependence on temperature. In the fiducial model of current climate obtained with the two phase model, $D_{eff}(T)$ varies from D/2 at the pole to 2D at the equator. Also, as forcing produces a warmer climate $D_{eff}(T)$ rises at all latitudes, but most rapidly in the tropics. This behavior causes temperature changes to be relatively larger at the pole than at the equator. The actual latitudinal distribution of warming with latitude agrees very well with the GCM calculations of MW for Q/Q_o = (1.02, 1.04), and $F(CO_2)$ = (2,4).

3. Results for Solar and CO_2 Forcing

We investigated sensitivity to solar and CO_2 forcing for the standard, TEC, and two phase EBMs using numerical solutions to the model equations for values of scaled insolation in the range $0.87 \le Q/Q_o \le 1.15$, and $0.5 \le F(CO_2) \le 4.0$. For all models, we used identical numerical techniques employing relaxation on a finite difference grid to solve the two point boundary value problem. This method works readily for the highly non-linear two phase model, and allows us to incorporate the adjustment of the diffusion coefficient in the TEC model in a direct fashion. In Table 2, we list the explicit differences associated with the tuned models, parameterizations, and boundary conditions in the three EBMs.

Figure 1 illustrates the major differences in sensitivity to solar forcing. We only examine those solutions closely related to the "current climate" solution, and we do not show results appropriate to the well-known alternate branches of the standard EBM formulation: the ice-covered earth branch, or the unstable branch for which $dx_s/dQ < 0$ (Held and Suarez 1974). If sensitivity is measured by the retreat of ice with increasing insolation, then the TEC model is most sensitive, with $dx_s/dQ(\text{TEC}) = 4dx_s/dQ$ (standard), and the two phase model intermediate, but much closer in response to the standard model. Figure 1(b) shows the monotonic increase of the diffusion coefficient with insolation in the TEC model. While the global mean temperature change with insolation is nearly identical in all the models, the response with latitude varies considerably, as shown in Figures 1(c) and 1(d). The TEC model constraint produces a small equatorial variation, but, since the mean temperature rise is not greatly altered, this forces large polar amplification. Again, the two phase model exhibits polar amplification and equatorial buffering intermediate between the standard and TEC models.

Polar amplification can readily be understood in terms of global energy balance and the analysis of results using Legendre expansions, as in Eqs. (6-8). Radiative losses at the global mean temperature exactly compensate for net warming at the global mean insolation rate, which only depends on the location of the ice-line. When the

TABLE 2. Comparison Between Standard, TEC and Two Phase Models

Fiducial Model	x_S	T(eq)	T(pole)	<T>
Standard	0.947	29.00 °C	-14.69 °C	14.33 °C
TEC	0.947	29.00 °C	-14.69 °C	14.33 °C
Two Phase	0.947	29.00 °C	-17.55 °C	16.54 °C

Fiducial Parameters	Diffusion	B(in I = A + BT)
Standard	0.623 W m^{-2} K^{-1}	2.23 W m^{-2} $°C^{-1}$
TEC	0.623	2.23
Two Phase	0.317	1.95

Forcing Constraints	T(eq)	Diffusion
Standard	Free	Fixed
TEC	Prescribed	Adjusts
Two Phase	Free	Fixed

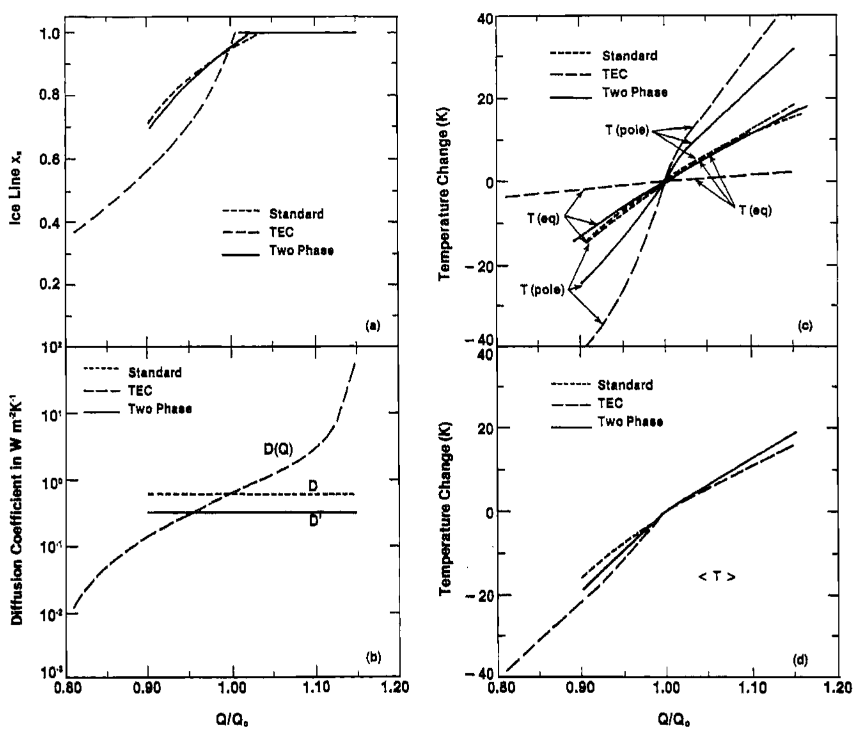

Fig. 1. Comparison of changes induced by scaled changes in insolation Q/Q_0 derived from three types of EBM: (a) location of the ice-line, (b) diffusion coefficient, (c) change in equatorial and polar temperature, and (d) global mean temperature.

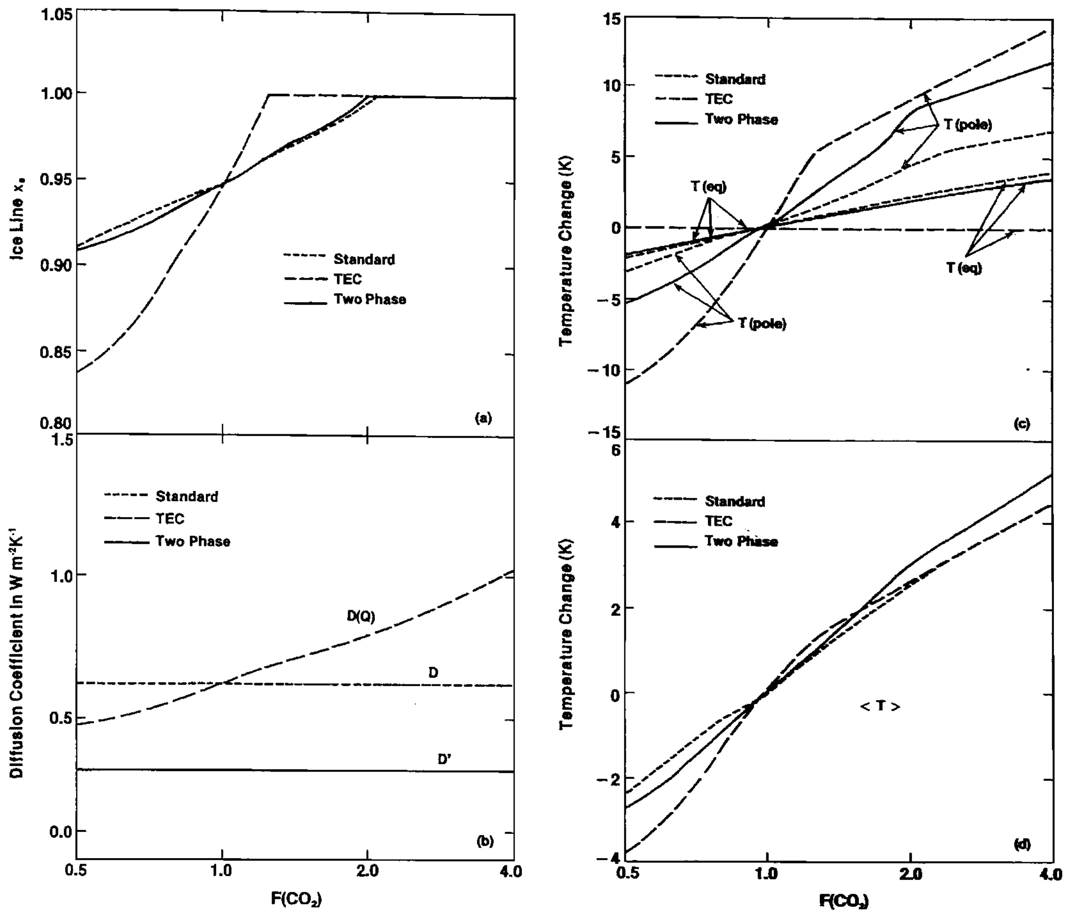

Fig. 2. Comparison of changes induced by variations in the concentration of atmospheric CO_2, relative to its current value, derived from three types of EBM: (a) location of the ice-line, (b) diffusion coefficient, (c) change in equatorial and polar temperature, and (d) global mean temperature.

ice-line coincides for any two models, then A + B <T> must agree. In particular, this happens for all models once the ice-line disappears, for $Q/Q_0 > 1.03$. This accounts for the common value of $\Delta\langle T\rangle$ between the TEC and Standard models for large Q, and explains the slightly larger value of $\Delta\langle T\rangle$ in the two phase model. Since B (two phase)/B (Standard) = 1.14, $\Delta\langle T\rangle$ (two phase) = $1.14\Delta\langle T\rangle$ (Standard). Obviously, the TEC model must exhibit polar amplification, since the mean temperature rise must agree but the equatorial response is constrained. Mathematically, that rise occurs because D(Q) grows, so that more energy can be transported poleward in spite of the reduced temperature gradient. In the two phase model a similar change occurs, associated with a rise in the effective diffusion coefficient, $D_{eff}(T)$, as defined in Eq. (13b).

In fact, Figure 1(c) shows that polar amplification in the standard model only occurs because ice-albedo feedback operates. Once ice disappears in the standard model, it is easy to show analytically, using Eqs. (6-8), that $\Delta T(x) \propto T(x)$, i.e. the equator warms more than the poles in the Standard model. This explains the crossover in Figure 1(c), where equatorial warming exceeds polar warming for large Q. The TEC and two phase models continue to exhibit polar amplification even after ice vanishes.

Figure 2 illustrates the sensitivity of the EBMs to variation in the concentration of atmospheric CO_2. Behavior with increasing CO_2 is similar to that found for increasing insolation. Both models that include effects related to latent heat show polar amplification, with the strongest effects in the TEC model, and the two phase model showing intermediate amplification. Note that, for CO_2 doubling, all models produce a rise in global mean temperature of about 2.5 K, as tuned by the choice of C in the parameterization of CO_2 effects, Eq. (4). The slight differences between the models result from slightly different positions for the ice-line with doubled CO_2, and the different value of B in the two phase model.

4. Comparison with Results from GCM Simulations

In their simulations of the effects of atmospheric CO_2 increases on climate, MW calculated a set of models that compared the effects of increasing insolation with increasing CO_2. Their GCM considered idealized, sector geography with swamp oceans, i.e. no heat capacity, and only evaluated annual mean forcing without seasonal effects. Thus, their model is in many respects comparable to the simple EBMs of this study. Some of our results can be directly compared with the GCM simulations; we have intentionally drawn our Figures 3 and 4 to nearly the same scale as corresponding Figures 19 and 3 in MW.

MW found that insolation and CO_2 forcing produced quite similar response, i.e. 2 (and 4) X CO_2 concentration and +2% (and 4%) changes in Q/Q_0 produce nearly identical patterns of temperature change with latitude, and they showed that poleward energy transport of latent heat was comparable with transport of sensible heat. A principal result from their study was the pronounced amplification of temperature rise at the poles: $\Delta T(\text{pole}) \approx 4\Delta T(\text{eq})$.

Figure 3 shows the temperature variation with latitude $\Delta T(x)$ found in the three EBM simulations for $F(CO_2) = (2,4)$ and $Q/Q_0 = (+2\%, +4\%)$. The standard model produces a relatively flat distribution of temperature rise, with only slight polar amplification, while the TEC model produces strong amplification. Results for $\Delta T(x)$ from the two phase model agree nearly exactly with the GCM result (see Figure 19 of MW).

In Figure 4, we show the net poleward flux of energy for each of the three models for the cases $F(CO_2) = (1,2,4)$. The pattern of response in poleward flux is completely different in the three cases. In the standard model, the flux falls nearly everywhere with rising CO_2 while in the TEC model flux rises at nearly all latitudes. The more complex response in the two phase model agrees very well with the pattern of change in poleward flux with latitude found in the GCM study (see Figure 3 of MW).

However, the agreement of the two phase model with the GCM results cannot be carried through in complete detail, physically. The two phase EBM formulation prescribes a functional form for transport of latent heat in which flux is proportional to a temperature gradient, Eq. 13(a), and the model equations actually impose constraints only on the divergence of flux. In Figure 3 of MW, the poleward flux is separately shown for the sensible and latent heat components. While the net flux in the GCM agrees quite well with the two phase flux, the latent heat flux in tropical regions in the GCM, and in real climate, actually pumps energy against the gradient of temperature and absolute himidity. This occurs by correlations in the three dimensional motion and energy content that can be resolved in the GCM but cannot be accounted for in the simple diffusion model of this paper. Nonetheless, the divergence of latent heat flux in the GCM behaves as in the two phase model, and the variation in total flux with forcing agrees remarkably well between the GCM and two phase models.

Finally, Figure 5 shows the absolute humidity and effective diffusion coefficient, Eq. (13b), of

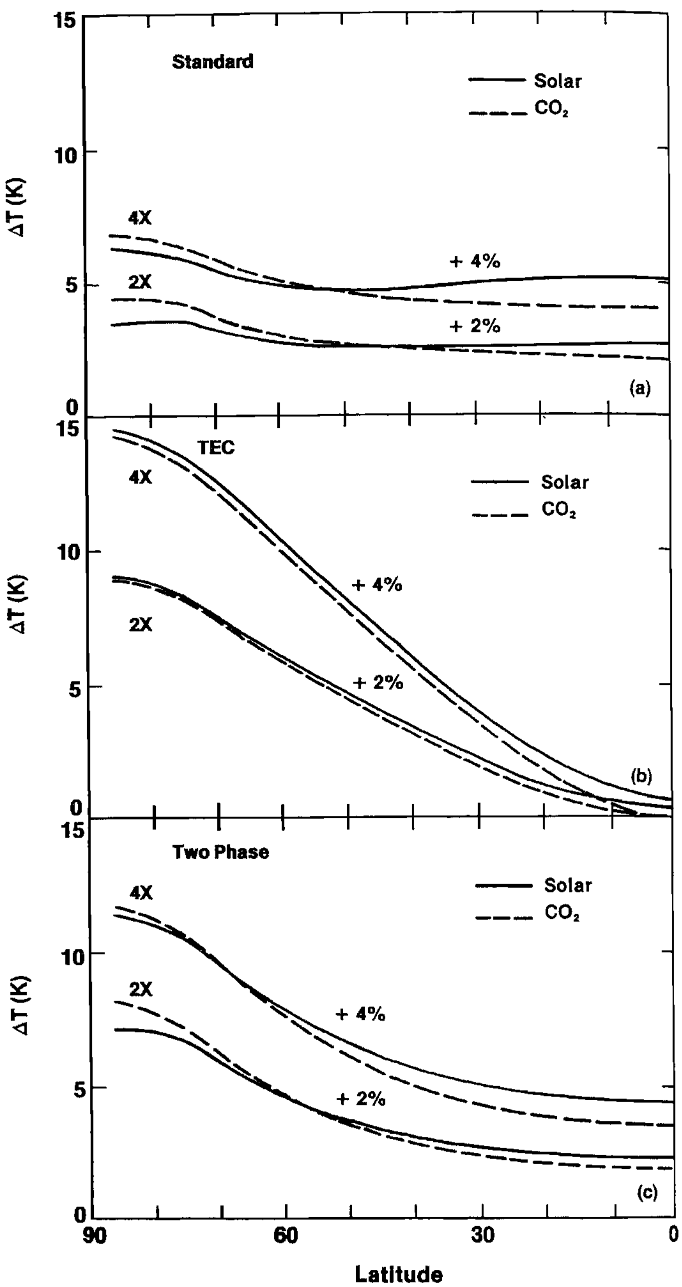

Fig. 3. The latitudinal distribution of temperature change produced by 2% and 4% increases in the solar constant, and increases in atmospheric concentration of CO_2 by factors of 2 and 4, as calculated from the standard (a), TEC (b), and two phase (c), EBM.

the two phase model as a function of latitude for the cases with CO_2 forcing. The distribution of humidity agrees quite well with that found in MW. This produces a variation in $D_{eff}(T)$ such that the mean value roughly agrees with D in the standard model, but the variation from equator to pole is substantial, with $D_{eff}(\text{eq}) = 3\ D_{eff}(\text{pole})$. Because of its exponential temperature dependence, $D_{eff}(T)$ rises at all latitudes with

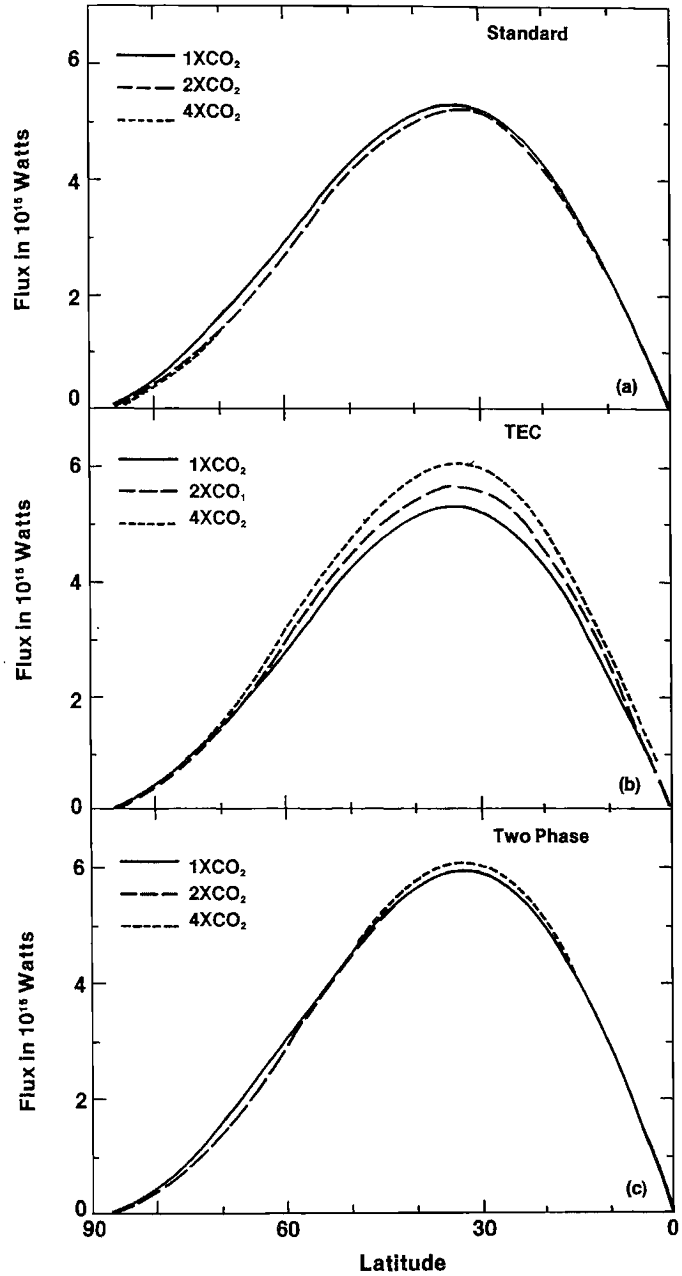

Fig. 4. The latitudinal distribution of poleward flux of energy produced by 2% and 4% increases in the solar constant, and increases in atmospheric concentration of CO_2 by factors of 2 and 4 as calculated from the standard (a), TEC (b), and two phase (c), EBM.

warming, but most rapidly at the equator. Thus, warmer climate becomes more nearly isothermal in the two phase model. With rising temperature, the ability of the system to transport energy rises because the latent heat content rises exponentially.

5. Conclusions

From these models, it is clear that effects of water vapor strongly influence climate sensitivity of EBMs. In particular, they strongly enhance polar amplification of thermal response to both solar and CO_2 forcing beyond that produced solely by ice-albedo feedback and geometrical effects. In this respect, the two phase model agrees far better with the GCM results of MW than does the standard model.

The behavior of the effective diffusion coefficient, $D_{eff}(T)$, characterizing the two phase model explains polar amplification. Since $D_{eff}(T)$ rises exponentially with temperature, the temperature distribution becomes more isothermal with warming. Of course, such an analysis applies to the behavior of the model, but extension to real climate is plausible. In a warmer climate the latent heat content of the atmosphere rises exponentially, so any form of dynamical motion is more effective at transporting energy.

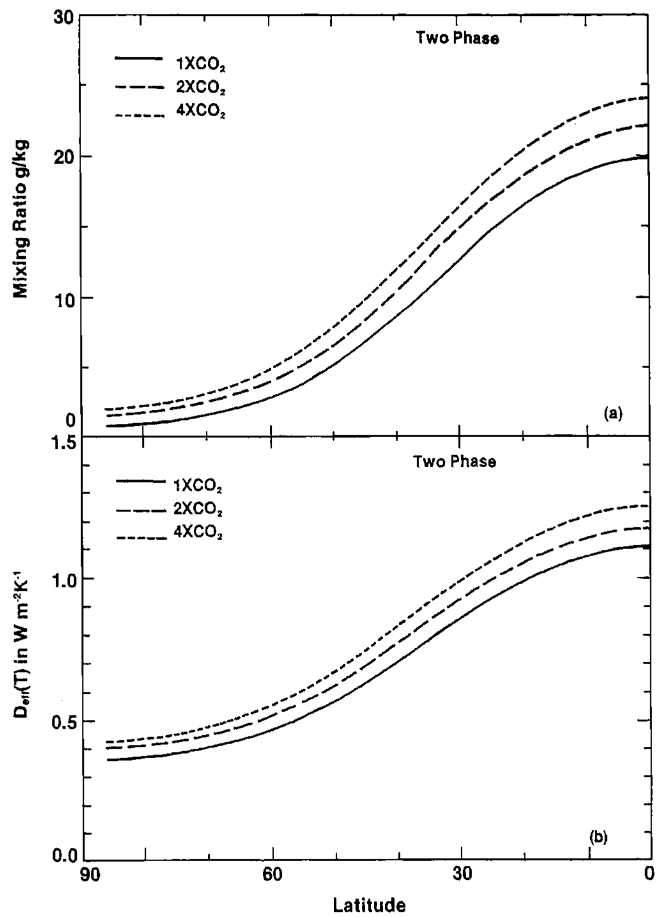

Fig. 5. The latitudinal distribution of (a) water vapor mixing ratio and (b) effective diffusion coefficient, Eq. (13b), as calculated in the two phase EBM for atmospheric concentrations of CO_2 (1, 2 and 4) times its present value.

Of course these simple physical models serve only to highlight specific effects to the extent that they can be analyzed in an EBM; their consequences for true climate require a far more complex analysis in a more fundamental and complete model, such as a GCM. Nonetheless, they have value as understandable examples of analyzable mechanisms. Physically, such behavior produces a tendency to global isothermality with warming.

Results of the TEC model show that limiting equatorial response by evaporative buffering, as proposed by ND, does not limit global response: rather, such buffering strongly amplifies polar response. This result arises from considerations of global energy balance.

6. Comparison with the MLEBM results of Peng, Chou, and Arking

Since presentation of this paper at the Ewing Symposium, our attention has been directed to the recent work of Peng, Chou, and Arking (1982) and Chou, Peng, and Arking (1982) who have developed a Multi-layer EBM which they used to examine climate response to solar and CO_2 forcing. Their model includes highly resolved, vertical radiative transport, and parameterized dynamical energy transfer involving both horizontal and vertical transport. Their results are far more detailed in content, since they have the ability to analyze vertical components of response, and to treat the dependence of CO_2 and water vapor radiative effects as a function of changing vertical distributions with latitude. Their model treats horizontal transport in a far more non-linear fashion than ours, even in the absence of water vapor transport, since they explicitly include parameterizations modeling dependences of baroclinic instability on the solution. Also, they use an albedo prescription that is less sensitive than that used by us.

The most common grounds for comparison between Chou et al. (1982) and this work are their Figure 8, for poleward flux, with our Figure 4, and their Figure 10, for change in surface temperature, with our Figure 3. Qualitatively, the responses are very similar: both models show pronounced polar amplification. However, the magnitude of high latitude temperature change for doubled atmospheric CO_2 found by Chou et al. is about 60% that found here with the two phase model or in the GCM simulation of MW. Although it is difficult to be certain of attribution in such different models, probably the major source of discrepancy arises from the less sensitive albedo response used by them.

Overall, they find that, by comparing models with fixed and variable poleward transport by latent heat effects, only about 20% of the enhanced polar temperature response can be attributed to enhanced transport by water vapor. This is unlike earlier GCM results of MW, or our results, which suggest that enhanced poleward transport by water vapor is of comparable magnitude with ice-albedo feedback. In our models with large variation from current conditions, polar ice disappears but polar amplification persists. Again, part of that discrepancy arises from the smaller overall response found by Chou, et al. than found by us or MW, and which, probably, can be attributed to different specifications for ice-albedo variation. Nonetheless, all of these models highlight the crucial role of water's influence on climate sensitivity through its effect on ice-albedo change, radiative transfer, and meridional energy transport.

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