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# Ice ages and the Milankovitch theory: A study of interactive climate feedback mechanisms

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ABSTRACT

Several climate feedback mechanisms, which are not conventionally incorporated within climate models, are investigated to illustrate their potential role in enhancing the sensitivity of the earth's climate to changes in orbital parameters; i.e., for application to the astronomical or Milankovitch theory of ice ages. For illustrative purposes changes only in obliquity angle are considered. Specifically the feedback mechanisms which have been incorporated are:

(1) Zenith-angle feedback, which constitutes a latitudinal change in the earth's zonal albedo due to the alteration in latitudinal distribution of insolation, and thus solar zenith angle, with changes in obliquity angle.
(2) Bio-albedo feedback, comprising a climate-related change in surface albedo as a consequence of altered precipitation patterns modifying the vegetation of land surfaces.
(3) Latent-heat feedback, which involves climate-induced changes in the poleward transport of latent heat.

Employing crude parameterizations for these three feedback mechanisms within a simple climate model, it is suggested that collectively these feedback mechanisms could, by several factors, amplify climate change associated with orbital parameter variability.

## 1. Introduction

There recently has been renewed interest in the Milankovitch (1941) theory, which suggests that glacial/interglacial transitions are the result of periodic variations in the earth's orbital elements. These orbital variations comprise the longitude of perihelion (22,000 year period), the earth's obliquity (40,000 year period), and variations in orbital eccentricity (100,000 year period). This renewed interest in the astronomical theory of ice ages stems from analyses of paleoclimatic time series by Hayes et al. (1976), who found a significant correlation between the paleoclimatic record and orbital element variations.

Except for a small change in the annually averaged insolation due to eccentricity variability, the Milankovitch effect essentially comprises a latitudinal redistribution of insolation. A reduction in obliquity angle results, on an annual average, in reduced insolation at high latitudes which is compensated by an increase at low latitudes. There is, moreover, a strong seasonal effect, with increased rather than decreased insolation, for a reduced obliquity angle, occurring at high latitudes during the winter. Variability in the longitude of perihelion influences insolation only through an interaction with eccentricity variations. But as pointed out by Suarez and Held (1978), changes in longitude of perihelion can alter the absorbed solar radiation through a coupling with seasonal albedo variability.

The purpose of the present study is to investigate the interactive role, with respect to orbital element variations, of several climate feedback mechanisms which are not conventionally included within climate models that incorporate the Milankovitch mechanism. Specifically these involve the three following feedback mechanisms:

(1) Zenith-angle feedback
(2) Bio-albedo feedback
(3) Latent-heat feedback



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Zenith-angle feedback refers to albedo change associated with a latitudinal redistribution of insolation, which in turn alters the solar zenith angle and thus the albedo. For example, a reduction in obliquity angle will, on an annual average, increase the zenith angle at high latitudes while decreasing it at low latitudes. Bio-albedo feedback is associated with modifications in the earth's surface albedo due to climate-induced changes in the vegetation of land surfaces and, as discussed by Cess (1978), this constitutes a potential long-term climate feedback mechanism. Recently Coakley (1978) incorporated both of these feedback mechanisms within an annually-averaged energy-balance climate model, but he did not consider the explicit role of zenith-angle feedback.

By latent-heat feedback, we refer to changes in the poleward advective latent-heat transport which cannot, for example, be modeled by a simple diffusion expression employing a constant diffusion coefficient. The study of this feedback was motivated by the general circulation model (GCM) results of Wetherald and Manabe (1975), who found that for a reduction in solar constant there was no net increase in poleward heat transport, despite an increase in pole-to-equator temperature difference. The reason for this is that the increase in sensible heat transport is compensated by a decrease in latent-heat transport, this decrease resulting from reduced evaporation for a cooler planet.

For the present purpose of illustrating the potential effect of these three feedback mechanisms, we restrict ourselves solely to changes in obliquity angle, $\delta$, which constitutes the most significant orbital element change over about the past 50,000 years. Furthermore, we make no attempt to actually predict glacial/interglacial climatic change. Our sole intent is to investigate the potential role of the three above-mentioned feedback mechanisms, and for this purpose we consider their influence upon the sensitivity of the climate, to changes in obliquity angle $\delta$, by introducing the obliquity sensitivity parameter

$$\beta_\delta = \delta_0 \frac{d\bar{T}_s}{d\delta} \tag{1}$$

for the Northern Hemisphere, where $\bar{T}_s$ is the hemispheric mean temperature and $\delta_0 = 23.45°$ the present obliquity angle. Eq. (1) simply constitutes a Milankovitch analog to the sensitivity parameter

$$\beta_s = S_0 \frac{d\bar{T}_s}{dS} \tag{2}$$

introduced by Schneider and Mass (1975) for a solar constant change, where $S$ is the solar constant and $S_0$ its present value.

## 2. Sensitivity to obliquity change

### 2.1. *The climate model*

Suarez and Held (1978) have pointed out the need for employing a seasonal climate model for the purpose of evaluating Milankovitch perturbations. In our present study of the interactive role of feedback mechanisms by investigating the sensitivity of the climate to obliquity change, we adopt a less conventional but perhaps more accurate definition of an annual mean model. As discussed shortly, this incorporates certain seasonal information. From a zonal annual energy balance,

$$Q_{abs} - F = D, \tag{3}$$

where $Q_{abs}$ is the absorbed solar radiation, $F$ the outgoing infrared flux, and $D$ the divergence of the poleward advective flux. Perturbing about the present climate, ignoring possible changes in cloud amount and assuming that $Q_{abs} = Q_{abs}(T_s, \delta)$ and $F = F(T_s)$, where $T_s$ is zonal surface temperature, then

$$\left(\frac{dF}{dT_s} - \frac{\partial Q_{abs}}{\partial T_s}\right)\frac{dT_s}{d\delta} = \frac{\partial Q_{abs}}{\partial \delta} - \frac{dD}{d\delta} \tag{4}$$

The dependence of $Q_{abs}$ upon $\delta$ simply reflects the change in latitudinal insolation distribution with obliquity angle, while the dependence upon $T_s$ incorporates temperature-albedo coupling, such as ice-albedo feedback. Since

$$Q_{abs} = (S/4)\,P(x)(1-\alpha) \tag{5}$$

with $x = \sin(\text{latitude})$, $\alpha$ the zonal albedo, and $P(x)$ the distribution function associated with latitudinal variations in insolation, then eq. (4) becomes

$$\left[\frac{dF}{dT_s} + \left(\frac{S}{4}\right) P \frac{\partial \alpha}{\partial T_s}\right] \frac{dT_s}{d\delta} = \frac{\partial Q_{abs}}{\partial \delta} - \frac{dD}{d\delta} \tag{6}$$

Once $dT_s/d\delta$ is evaluated from this expression, it then follows that the obliquity sensitivity parameter is given by

$$\beta_\delta = \delta_0 \frac{d\bar{T}_s}{d\delta} = \delta_0 \int_0^1 \frac{dT_s}{d\delta}\, dx \qquad (7)$$

But before $dT_s/d\delta$ can be determined, it is necessary to obtain input information for $\partial Q_{abs}/\partial\delta$, $dD/d\delta$ and $\partial\alpha/\partial T_s$.

### 2.2. *Results for* $\partial Q_{abs}/\partial\delta$

From eq. (5)

$$\frac{\partial Q_{abs}}{\partial\delta} = (S/4)(1-\alpha)\frac{dP}{d\delta} - (S/4)\frac{\partial\alpha}{\partial\mu}\frac{d\mu}{d\delta} \qquad (8)$$

where $\mu = \cos$ (zenith angle). The first term on the right side of eq. (8) denotes the basic climate forcing due to obliquity change, while the second term comprises zenith-angle feedback. Although eq. (6) stems from an annual climate model, we at least partially incorporate seasonal effects by employing monthly values for $\alpha$ and $dP/d\delta$, and then performing an average to determine the first term on the right side of eq. (8). The monthly values for $\alpha$ are from Ellis Vonder Haar (1976), while monthly $dP/d\delta$ results were obtained from an orbital calculation, changing $\delta$ from 23.45° to 22.45°. The evaluation of $\partial\alpha/\partial\mu$ is discussed by Lian and Cess (1977), and the relevant information is summarized in Table 1, where $c_z = \partial\alpha/\partial\mu$.

At this juncture it is worth noting that in the absence of any other interactive processes (i.e., $\partial\alpha/\partial T_s = dD/d\delta = 0$), then from eqs. (6) and (7), with $dF/dT_s = 1.6$ W m$^{-2}$ (°C)$^{-1}$ (Cess, 1976),

$$\beta_\delta = \frac{\delta_0}{dF/d\bar{T}_s}\int_0^1 (\partial Q_{abs}/\partial\delta)\, dx = -1.1 \text{ °C}$$

whereas the Milankovitch theory requires that $\beta_\delta$ be positive. The point is that the insolation redistribution, acting solely by itself, gives net global warming for a reduction of obliquity angle, since reduced high-latitude solar absorption is more than compensated by the increased insolation acting at low latitudes where there is a smaller albedo, and this is independent upon whether or not zenith-angle feedback is included (without zenith-angle feedback, $\beta_\delta = -1.5$ °C). This rather fundamental point is generally overlooked.

### 2.3. *Latent-heat feedback*

To incorporate latent-heat feedback, we will simply modify the Budyko (1969) advective parameterization by letting

$$D = \nu(\bar{T}_s)(T_s - \bar{T}_s) \qquad (9)$$

where $\bar{T}_s$ is the hemispheric mean temperature. The modification is that we allow the proportionally constant $\nu$ to be a function of hemispheric mean temperature as a means of at least partially accounting for changes in latent heat transport during climatic change. Although it would be tempting to let $\nu$ depend upon zonal rather than hemispherical temperature, i.e. $\nu = \nu(T_s)$, this would require a latitudinal variation in temperature dependence in order that the condition

$\int_0^1 D(x)\, dx = 0$

be satisfied. Our emphasis is to show gross comparative effects, and within this context eq. (9) serves the purpose.

We now consider means of estimating the dependence of $\nu$ upon $\bar{T}_s$. Letting $\nu_0$ refer to the present climate, then for a perturbed climate

$$\frac{dD}{d\bar{T}_s} = \nu_0\left(\frac{dT_s}{d\bar{T}_s} - 1\right) + \frac{d\nu}{d\bar{T}_s}(T_s - \bar{T}_s) \qquad (10)$$

Table 1. *Model input parameters*

| Latitude (°N) | $(S/4)(1-\alpha)(dP/d\delta)$ W m$^{-2}$ deg$^{-1}$ | $c_z$ | $d\mu/d\delta$ deg$^{-1}$ | $\partial Q_{abs}/\partial\delta$ W m$^{-2}$ deg$^{-1}$ | $c_T$ (°C)$^{-1}$ |
|---|---|---|---|---|---|
| 85 | 2.81 | 0.389 | 0.0102 | 4.16 | 0.0218 |
| 75 | 2.66 | 0.418 | 0.0086 | 3.88 | 0.0120 |
| 65 | 1.73 | 0.446 | 0.0042 | 2.37 | 0.0081 |
| 55 | 0.80 | 0.450 | 0.0016 | 1.04 | 0.0047 |
| 45 | 0.23 | 0.437 | 0.0002 | 0.27 | 0.0009 |
| 35 | −0.27 | 0.382 | −0.0008 | −0.37 | 0 |
| 25 | −0.70 | 0.373 | −0.0015 | −0.89 | 0 |
| 15 | −0.97 | 0.356 | −0.0018 | −1.18 | 0 |
| 5 | −1.07 | 0.358 | −0.0021 | −1.33 | 0 |

To estimate $dv/d\bar{T}_s$, we have previously noted that the GCM study by Wetherald and Manabe (1975) yields $dD/d\bar{T}_s \simeq 0$ for a perturbation in solar constant. Thus

$$\frac{1}{v_0}\frac{dv}{d\bar{T}_s} = -\frac{(dT_s/d\bar{T}_s - 1)}{T_s - \bar{T}_s} \tag{11}$$

and from the GCM results we have determined $dT_s/d\bar{T}_s$, and hence $(1/v_0)(dv/d\bar{T}_s)$, as a function of latitude. Since $dT_s/d\bar{T}_s \simeq 1$ and $T_2 \simeq \bar{T}_s$ at mid latitudes, this procedure is applicable only for low and high latitudes, from which we find that

$$\frac{1}{v_0}\frac{dv}{d\bar{T}_s} \simeq 0.024(^\circ\mathrm{C})^{-1}; \quad \text{low latitudes}$$

$$\frac{1}{v_0}\frac{dv}{d\bar{T}_s} \simeq 0.032(^\circ\mathrm{C})^{-1}; \quad \text{high latitudes}$$

and we choose a hemispherical mean as

$$\frac{1}{v_0}\frac{dv}{d\bar{T}_s} = 0.028(^\circ\mathrm{C})^{-1} \tag{12}$$

A comparable value is obtained, on a hemispherical average, if we assume that 40% of the advective transport is due to latent heat, and that latent-heat transport is proportional to the saturation vapor pressure of water at the planetary surface (Gal-Chen and Schneider, 1976). From this we find that $(1/v_0)(dv/d\bar{T}_s) = 0.026(^\circ\mathrm{C})^{-1}$, in excellent agreement with eq. (12).

Although we have employed $dD/d\bar{T}_s = 0$ for a solar constant change, in order to obtain eq. (12) from the GCM results, this does not imply that $dD/d\bar{T}_s = 0$ for other types of climate forcing. In fact a change in obliquity angle is a considerably different type of climate change mechanism, since here an insolation reduction at high latitudes is accompanied by increased insolation at low latitudes. In the absence of any surface albedo feedback this leads, as previously discussed, to net global warming, whereas within the framework of the Milankovitch theory such an insolation change, corresponding to reduced obliquity, should lead to net global cooling. Moreover, if we associate the last great ice age (18,000 YBP) to an earlier obliquity angle minimum, then in addition to net global cooling, cooling at all latitudes should occur (CLIMAP, 1976; Gates, 1976). At the very minimum, mechanisms which can lead to low-latitude cooling, when there is a low-latitude increase in insolation, comprise a coupling between ice-albedo feedback and advection, such that high-latitude cooling, enhanced by ice-albedo feedback, is transmitted to low latitudes through enhanced poleward advection. If there were no poleward advection enhancement ($dD/d\delta = 0$) associated with a reduction in obliquity, then climatic change associated with each latitude zone would be independent of other zones, and low-latitude heating would occur. On the other hand, excessively strong advection enhancement would tend to "quench" the required ice-albedo feedback at high latitudes.

The preceding arguments illustrate that advective transport could play a more significant role for climate change induced by obliquity angle variability than for that due to a change in solar constant. It is for this reason that we employ eqs. (10) and (12) for purposes of illustration.

To show how our choice of latent-heat feedback influences the sensitivity of the present climate to a change in solar constant, as measured by the sensitivity parameter $\beta_s$ defined in eq. (2), we have incorporated eqs. (10) and (12) within the energy-balance climate model of Lian and Cess (1977), from which

$$\beta_s = 184\,^\circ\mathrm{C}; \quad \frac{1}{v_0}\frac{dv}{d\bar{T}_s} = 0 \tag{13a}$$

$$\beta_s = 207\,^\circ\mathrm{C}; \quad \frac{1}{v_0}\frac{dv}{d\bar{T}_s} = 0.028 \tag{13b}$$

Latent-heat feedback thus constitutes, for this example, a positive feedback mechanism, since it reduces the poleward enhancement in advection for a reduction in solar constant, producing a larger high-latitude temperature decrease and thus enhanced ice-albedo feedback. For the present illustration, however, this positive feedback is relatively insignificant.

### 2.4. *Bio-albedo feedback*

The remaining feedback mechanism which we wish to consider is bio-albedo feedback. As discussed by Cess (1978), this is associated with gross changes in the vegetation of land surfaces due to precipitation changes. Thus, for example, a colder climate leads, on the average, but certainly with regional exceptions, to reduce precipitation with the result that during the last great ice age (18,000 YBP) "desert regions, steppes, grasslands and outwash plains expanded at the expense of forests, yielding a slight increase in the albedo of land areas not covered by ice" (CLIMAP, 1976). This obviously is a positive feedback mechanism due to the increase in surface albedo with decreasing global temperature.

Following the prescription of Cess (1978), which was obtained by comparing the present and 18,000 YBP surface albedos and climates, we incorporate bio-albedo feedback by letting

$$\frac{\partial\alpha}{\partial T_s} = \left(\frac{\partial\alpha}{\partial T_s}\right)_{\text{ice}}; \quad \theta > 50°\,\text{N}$$

$$= \left(\frac{\partial\alpha}{\partial T_s}\right)_{\text{ice}} + \left(\frac{\partial\alpha}{\partial T_s}\right)_{\text{bio}}; \quad \theta = 40° \text{ to } 50°\,\text{N}$$

$$= \left(\frac{\partial\alpha}{\partial T_s}\right)_{\text{bio}}; \quad \theta < 40°\,\text{N}$$

where $\theta$ is latitude, $(\partial\alpha/\partial T_s)_{\text{bio}} = -0.002(°\text{C})^{-1}$ denotes the bio-albedo contribution, and $(\partial\alpha/\partial T_s)_{\text{ice}}$ is the ice-albedo contribution. It is important to note that in order for this crude parameterization to simulate the 18,000 YBP ice age, cooling must occur at all latitudes as suggested by CLIMAP (1976) and the corresponding GCM study of Gates (1976). If a model produces low-latitude heating for a reduction in obliquity, then the above parameterization would, at those latitudes, produce a negative ice-age feedback, since the low-latitude albedo would decrease.

### 2.5. *Ice-albedo feedback*

As previously discussed, ice-albedo feedback constitutes a significant coupling mechanism with regard to achieveing global cooling for a reduced obliquity angle. To appraise the required strength of ice-albedo feedback, we shall *assume* that the 18,000 YBP ice age was caused principally by an earlier obliquity angle minimum and, in accordance with prior discussion, that cooling occurred at all latitudes. We thus require that $dT_s/d\delta > 0$ for all latitudes, and noting the constraint

$\int_0^1 (dD/d\delta)\, dx = 0$

it follows from eq. (6) that

$$\int_0^1 \left(\frac{dF}{dT_s} + (S/4)\,P\frac{\partial\alpha}{\partial T_s}\right)\frac{dT_s}{d\delta}\,dx$$

$$= \int_0^1 \frac{\partial Q_{\text{abs}}}{\partial\delta}\,dx < 0 \tag{14}$$

In that we require $dT_s/d\delta > 0$, the only way in which this expression can be satisfied is that

$$\left(\frac{dF}{dT_s} + (S/4)\,P\frac{\partial\alpha}{\partial T_s}\right) < 0 \tag{15}$$

for at least some latitude zones. Choosing $dF/dT_s = 1.6\ \text{W m}^{-2}(°\text{C})^{-1}$, our present parameterization for bio-albedo feedback does not satisfy eq. (15) for those latitude zones over which we have assumed bio-albedo feedback to operate. The only alternative is that eq. (15) be satisfied at high latitudes, with $\partial\alpha/\partial T_s$ due to ice-albedo feedback.

Recent zonal estimates of $\partial\alpha/\partial T_s$, due to ice-albedo feedback, have been presented by Lian and Cess (1977), from which eq. (15) is found to be satisfied only for the 80° to 90° N latitude zone, which is insufficient to produce $dT_s/d\delta > 0$ at all latitudes. Either the Milankovitch theory, associated solely with obliquity variations as presently modeled, cannot explain the 18,000 YBP ice age, or we require stronger ice-albedo feedback than that suggested by Lian and Cess. A possible case can be made for the latter suggestion. What we are doing is invoking an obliquity perturbation upon the *present* climate. But in order to reproduce at least the qualitative features of the last great ice age, perhaps we should employ ice-albedo feedback appropriate to some average glacial/interglacial climate which would correspond to a lower global temperature than at present. Virtually all climate models show increasing ice-albedo feedback with decreasing global temperature.

In view of the above, and give the uncertainties in estimating ice-albedo feedback, we have arbitrarily increased the zonal ice-albedo values, $(\partial\alpha/\partial T_s)_{\text{ice}}$, of Lian and Cess by a factor of 1.5. Letting $(\partial\alpha/\partial T_s)_{\text{ice}} = -c_T$, the corresponding $c_T$ results are summarized in Table 1. We stress that this is a totally *ad hoc* choice. Without such enhanced ice-albedo feedback, then low-latitude cooling, for reduced obliquity, would not occur, so that any attempt to illustrate the interactive role of bio-albedo feedback would prove meaningless.

Again we emphasize that our goal *is not* to prove or disprove the Milankovitch theory, but rather it is to illustrate the potential role of somewhat nonconventional feedback mechanisms within the context of trying to understand processes that might, in a more detailed treatment, illustrate the viability of the Milankovitch theory.

Before proceeding, we illustrate how our present choice of ice-albedo feedback influences sensitivity to a change in solar constant. Again employing the energy-balance model of Lian and Cess (1977), the 1.5 factor enhancement in the Lian-Cess zonal $(\partial\alpha/\partial T_s)_{\rm ice}$ derivatives yields

$$\beta_s = 238\ {}^\circ\mathrm{C};\quad \frac{1}{v_0}\frac{dv}{d\bar{T}_s} = 0 \tag{16a}$$

$$\beta_s = 357\ {}^\circ\mathrm{C};\quad \frac{1}{v_0}\frac{dv}{d\bar{T}_s} = 0.028 \tag{16b}$$

With reference to eqs. (13a) and (13b), latent-heat feedback now plays a much more significant role, enhancing $\beta_s$ by 50% as opposed to the prior 13% enhancement. This is to be expected, since the importance of advection is increased for stronger ice-albedo feedback due to its role as an interactive mechanism with ice-albedo feedback (Gal-Chen and Schneider, 1976; Lian and Cess, 1977).

### 2.6. *Sensitivity parameter*

To formulate the obliquity sensitivity parameter $\beta_\delta$, as defined by eq. (17), combination of eqs. (6) and (10), with subsequent evaluation of $dT_s/d\delta$, yields

$$\beta_\delta = \frac{\int_0^1 (\partial Q_{\rm abs}/\partial\delta)\, M\, dx}{1 - v_0 \int_0^1 \{1 - [(1/v_0)(dv/d\bar{T}_s)(T_s - \bar{T}_s)\, M]\}\, dx} \tag{17}$$

where

$$M = \left(v_0 + \frac{dF}{dT_s} + (S/4)\, P \frac{\partial\alpha}{\partial T_2}\right)^{-1} \tag{18}$$

In the following we employ as input parameters $S = 1360$ W m$^{-2}$ together with $v_0 = 3.5$ W m$^{-2}$(°C)$^{-1}$ and $dF/dT_s = 1.6$ W m$^{-2}$(°C)$^{-1}$ (Cess, 1976), while $\bar{T}_s = 15$ °C and the zonal $T_s$ values are from Crutcher and Meserve (1970).

It is perhaps well to amplify on our choice for $dF/dT_s$. At the very minimum, the outgoing infrared flux is expressed as a function of two parameters, surface temperature and cloud cover fraction $A_c$, as suggested by Budyko (1969). Thus

$$\frac{dF}{dT_s} = \frac{\partial F}{\partial T_s} + \frac{\partial F}{\partial A_c}\frac{dA_c}{dT_s} \tag{19}$$

If we ignore, as in the present study, climate-induced cloud cover variability, then $dA_c/dT_s = 0$ and, within the confines of this model assumption, $dF/dT_s = \partial F/\partial T_s$. It is the result $\partial F/\partial \bar{T}_s = 1.6$ W m$^{-2}$(°C)$^{-1}$, inferred from zonal annual climatological data (Cess, 1976), which we are thus employing in the present study.

Recently Oerlemans and van den Dool (1978) have suggested, utilizing somewhat different mean surface temperatures than those employed by Cess (1976), that $\partial F/\partial T_s = 2.2$ W m$^{-2}$(°C)$^{-1}$. But Oerlemans and van den Dool have neglected latitudinal variability in cloud cover fraction in arriving at this result. What they have actually obtained is $dF/dT_s = 2.2$ W m$^{-2}$(°C)$^{-1}$, for a situation in which $\Delta A_c \neq 0$, rather than $\partial F/\partial T_s$. To illustrate this difference, we have employed the same zonal annual climatological data as Cess (1976), and find that $dF/dT_s = 2.0$ W m$^{-2}$(°C)$^{-1}$ for the Northern Hemisphere, while $\partial F/\partial T_s = 1.6$ W m$^{-2}$(°C)$^{-1}$.

## 3. Results and Discussion

We have evaluated the obliquity sensitivity parameter, $\beta_\delta$, from eq. (17) for a wide variety of input parameters; these results are summarized in Table 2. The last column indicates whether or not low-latitude cooling is achieved for a decrease in obliquity angle. Model 1 has no albedo-temperature feedbacks and thus poleward advection plays no interactive role. As previously discussed, the negative result for $\beta_\delta$ corresponds to net global warming for a decrease in $\delta$, since high-latitude cooling is more than compensated by low-latitude warming.

In Model 2 we introduce our version of ice-albedo feedback and obtain net global cooling ($\beta >$ 0), although low-latitude warming persists. The same is true for Model 3, in which zenith-angle feedback is additionally included. Note that this feedback nearly doubles sensitivity to obliquity change. Model 4 includes latent-heat feedback with a subsequent increase in sensitivity by the factor

Table 2. *Summary of model results. The quantities $c_z$ and $c_T$ refer to the tabulated values in Table 1*

| Model | $\left(\frac{\partial \alpha}{\partial T_s}\right)_{\text{ice}}$ | $\frac{\partial \alpha}{\partial \mu}$ | $\left(\frac{\partial \alpha}{\partial T_s}\right)_{\text{bio}}$ | $\frac{1}{\nu_0}\frac{d\nu}{d\bar{T}_s}$ | $\nu_0$ | $\beta_\delta$(°C) | Low-latitude cooling |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | — | — | −1.5 | No |
| 2 | $-c_T$ | 0 | 0 | 0 | 3.5 | 4.6 | No |
| 3 | $-c_T$ | $-c_z$ | 0 | 0 | 3.5 | 8.2 | No |
| 4 | $-c_T$ | $-c_z$ | 0 | 0.028 | 3.5 | 12.4 | No |
| 5 | $-c_T$ | $-c_z$ | −0.002 | 0 | 3.5 | 10.3 | Yes |
| 6 | $-c_T$ | $-c_z$ | −0.002 | 0.028 | 3.5 | 19.5 | Yes |
| 7 | $-c_T$ | 0 | −0.002 | 0.028 | 3.5 | 9.3 | No |
| 8 | $-c_T$ | $-c_z$ | −0.002 | 0.028 | 3.0 | 47.5 | Yes |
| 9 | $-1.2c_T$ | 0 | 0 | 0 | 3.5 | 18.6 | Yes |

1.5, essentially the same as for a solar constant change (compare eqs. (16a) and (16b)). Bio-albedo feedback, but not latent-heat feedback, is incorporated within Model 5; low-latitude cooling is now achieved as is required for the incorporation of this feedback mechanism. But the sensitivity enhancement, relative to Model 3, is small, a factor of 1.3, consistent with a similar finding by Coakley (1978). In Model 6 all three feedbacks are present. Comparison with Model 5 shows that, when bio-albedo feedback is included, the enhancement due to latent-heat feedback increased from the previous factor of 1.5 to 1.9, while with reference to Model 4 the enhancement by bio-albedo feedback, when latent-heat feedback has been included, is increased from a factor of 1.3 to 1.6. Clearly there is a mutual amplification by the individual feedback mechanisms, with the collective enhancement, relative to Model 2, being a factor of 4.2.

Zenith-angle feedback is an important ingredient in this mutual amplification process, since if we exclude this feedback while retaining bio-albedo and latent-heat feedbacks (Model 7), the sensitivity is decreased by more than a factor of 2. By itself zenith-angle feedback is of little importance since, for reduced obliquity, the zenith-angle induced high-latitude albedo increase is nearly compensated by a corresponding albedo reduction at low latitudes. But when ice-albedo feedback is included, the zenith-angle increase in high-latitude albedo, which causes reduced high-latitude surface temperatures, amplifies ice-albedo feedback. Thus, like advection, the role of zenith-angle feedback is that of an interactive mechanism with ice-albedo feedback. This, of course, is only a partial explanation, since there is further interaction with the other feedback mechanisms.

In Model 8 we have arbitrarily reduced $\nu_0$ from 3.5 to 3.0 W m$^{-2}$(°C)$^{-1}$ and find that this relatively small change in the Budyko dynamical parameter more than doubles obliquity sensitivity. This serves to further illustrate the very delicate role that advective transport plays regarding climatic response to orbital element change.

Model 9 is included solely for comparison with the seasonal climate model of Suarez and Held (1978). Their model, which does not incorporate any of the three feedback mechanisms of present concern, yields $\beta_s \simeq 400$ °C for a solar constant change, and we achieve the same result through increasing $c_T$, as given in Table 1, by the factor 1.2. With respect to obliquity change, Suarez and Held find that $\beta_\delta = 14.5$ °C, while our model 9 result, $\beta_\delta = 18.6$ °C, is quite comparable.

## 4. Conclusions

The conclusion of the present study is simply that zenith-angle, bio-albedo and latent-heat feedbacks could, collectively, enhance by several factors the sensitivity of the earth's climate to change induced by orbital element variability. We certainly make no claim that the parameterizations which we have employed to model these feedbacks are realistic. Our intent has been to use simple modeling solely for the purpose of illustrating the potential, rather than the quantitative, role of these climate feedback mechanisms. It will take a far more detailed endeavor than that presented herein to either prove or disprove the viability of the

Milankovitch theory. Most likely this will necessitate the incorporation of additional coupling mechanisms associated with changes in all three orbital parameters, while the results of Pollard (1978) suggest the need for coupling climate and glacial models.

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REFERENCES

Budyko, M. I. 1969. The effect of solar radiation variations on the climate of the earth. *Tellus 21*, 611–619.

Cess, R. D. 1976. Climate change: An appraisal of atmospheric feedback mechanisms employing zonal climatology. *J. Atmos. Sci. 33*, 1831–1843.

Cess, R. D. 1978. Biosphere-albedo feedback and climate modeling. *J. Atmos. Sci. 35*, 1765–1768.

CLIMAP Project Members 1976. The surface of the ice-age earth. *Science 191*, 1131–1137.

Coakley, J. A. 1978. A study of climate sensitivity using a simple energy balance climate model. *J. Atmos. Sci.* (in press).

Crutcher, H. L. and Meserve, J. M. 1970. *Selected-level Heights, Temperatures and Dew Point Temperatures for the Northern Hemisphere.* NAVAIR 50-IC-52, Washington, D.C. (available from Chief, Naval Operations).

Ellis, J. and Vonder Haar, T. H. 1976. Zonal average earth radiation budget measurements from satellites for climate studies. Atmos. Sci. Pap. 240, Colorado State University, 50 pp.

Gal-Chen, T. and Schneider, S. H. 1976. Energy balance climate modeling: Comparison of radiative and dynamic feedback mechanisms. *Tellus 28*, 108–121.

Gates, W. L. 1976. A numerical simulation of ice age climate with a global general circulation model. *J. Atmos. Sci. 33*, 1844–1873.

Hayes, J. D., Imbrie, J. and Shackelton, N. J. 1976. Variations of the earth's orbit: Pacemaker of the ice ages. *Science 194*, 1121–1132.

Lian, M. S. and Cess, R. D. 1977. Energy balance climate models: A reappraisal of the ice-albedo feedback. *J. Atmos. Sci. 34*, 1058–1062.

Milankovitch, M. 1941. *Canon of Insolation and the Ice Age Problem.* Royal Serbian Academy, Belgrade, 482 pp; translated by Israel Program for Scientific Translation, Jerusalem, 1969.

Oerlemans, J. and van den Dool, H. M. 1978. Energy balance climate models: Stability experiments with a refined albedo and updated coefficients for infrared emission. *J. Atmos. Sci. 35*, 371–381.

Pollard, D. 1978. An investigation of the astronomical theory of the ice ages using a simple climate-ice sheet model. *Nature 272*, 233–235.

Schneider, S. H. and Mass, 1975. Volcanic dust, sunspots and temperature trends. *Science 190*, 741–746.

Suarez, M. J. and Held, I. M. 1978. The sensitivity of an energy balance climate model to variations in the orbital parameters. *J. Geophys. Res.* (in press).

Wetherald, R. T. and Manabe, S. 1975. The effect of changing the solar constant on the climate of a general circulation model. *J. Atmos. Sci. 32*, 2044–2059.

## ЛЕДНИКОВЫЕ ЭПОХИ И ТЕОРИЯ МИЛАНКОВИЧА: ИЗУЧЕНИЕ ВЗАИМОДЕЙСТВУЮЩИХ КЛИМАТИЧЕСКИХ МЕХАНИЗМОВ ОБРАТНЫХ СВЯЗЕЙ

Исследуются некоторые климатические механизмы обратных связей, которые обычно не включались в модели климата, чтобы показать их потенциальную роль в увеличении чувствительности земного климата к изменениям орбитальных параметров, т.е. для приложения к астрономической, или Миланковича, теории ледниковых эпох. Для иллюстрационных целей рассматриваются только изменения в угле наклонения эклиптики. Конкретно, включаются следующие механизмы обратных связей:

1. Обратная связь по зенитному углу, которая состоит в широтном изменении зонального альбедо Земли из-за изменения в широтном распределении инсоляции и, таким образом, зенитного угла Солнца с изменениями в угле наклонения эклиптики;
2. биоальбедная обратная связь, состоящая в климатическом изменении альбедо поверхности вследствие изменения распределения осадков, видоизменяющих растительность поверхностей суши,
3. обратная связь по скрытому теплу, которая состоит в изменениях с климатом переноса скрытого тепла к полюсу.

С использованием грубых параметризаций для этих трех механизмов обратных связей в простой модели климата предполагается, что в совокупности эти механизмы обратных связей могли бы в несколько раз увеличить изменение климата, связанное с изменчивостью параметров орбиты.