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INCORPORATION OF SURFACE ALBEDO-TEMPERATURE FEEDBACK IN A ONE-DIMENSIONAL RADIATIVE-CONVECTIVE CLIMATE MODEL

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ABSTRACT

The feedback between ice-snow albedo and temperature is included in a one-dimensional radiative-convective climate model. The effect of this feedback on sensitivity to changes in solar constant is studied for the current values of the solar constant and cloud characteristics. The ice-snow albedo feedback amplifies global climate sensitivity by 33% and 50%, respectively, for assumptions of constant cloud altitude and constant cloud temperature.

Introduction. One-dimensional radiative-convective models which determine the thermal structure of the atmosphere as a result of the balance between the radiative flux and a parameterized convective flux are useful tools for climate studies. Such models, which can include realistic vertical distributions of radiatively-important atmospheric constituents, can be used to examine the role that these constituents play in determining the global mean temperature structure. One major drawback of these models is their lack of the ice-snow albedo-temperature feedback which is of great importance because of the large difference in albedo between ice and ice-free areas. The present work describes a simple method of incorporating the albedo-temperature feedback in a one-dimensional radiative-convective climate model. In addition the effect of this feedback on the sensitivity of the climate to changes in solar constant is studied and compared with the sensitivity found in other models.

Analysis. The one-dimensional radiative-convective model described in Wang and Lacis (1979) is used in the present study. In order to incorporate the ice-snow albedo-temperature feedback in a global model, it is necessary to know the response of the global mean surface albedo to changes in the ice-snow line as a result of changes in global mean surface temperature.

We assume first the zonal mean surface albedo α_s has a simple form

$$\alpha_s = \begin{cases} a & 0 \le x < x_s \\ b & x_s \le x \le 1 \end{cases} \qquad (1)$$

where a and b are constants characterizing the ice-free and ice-covered surface albedos, respectively, and x_s is the sine of the latitude of the edge of the ice sheet. For the ice-sheet edge, the prescription by Budyko (1969) is adopted, i.e., if the zonal mean surface temperature T_s is less than -10° C, ice will be present. We will further use the simple formulation of the latitudinal temperature structure used by North (1975). In this formulation the temperature structure is approximated by the first two Legendre polynomials in a series expansion, i.e.,

$$T_s(x) = \overline{T}_s + T_2 P_2(x) \tag{2}$$

where $P_2(x) = (3x^2-1)/2$. The first term $\overline{T}_s$ is the global mean surface temperature since the second term vanishes upon integration from 0 to 1. This two-mode approximation with $T_2 = -28.40$ C yields a reasonably good temperature distribution compared with observations.

In the atmosphere T_2 varies with the tropospheric lapse rate because of the effect of large scale eddies (Stone, 1978). Since the tropospheric lapse rate is essentially constant in the radiative-convective model, we can adopt the simple parameterization suggested by Stone (1978) for taking into account the effect of the eddies on temperature structure in climate calculations, i.e., T_2 = constant = -28.4 C. Then setting $x = x_s$, $T = T_s = -10^\circ$ C in Equation (2) we obtain

$$x_s = (0.5681 + 0.02347\, \overline{T}_s)^{\frac{1}{2}} . \tag{3}$$

This equation describes how the extent of the polar ice cap changes as the global mean surface temperature changes.

Next, we wish to determine the relationship between the global mean surface albedo $\overline{\alpha}_s$ and x_s. Employing Equation (1), we obtain

$$\overline{\alpha}_s = \int_0^1 S_s(x,x_s)\, \alpha_s(x,x_s) dx \Big/ \int_0^1 S_s(x,x_s) dx \tag{4}$$

where S_s is the zonal mean solar radiation received at the surface. S_s is a complicated function, which depends on solar zenith angle and atmospheric transmissivity. As an initial calculation, to test the method, we assume that S_s has the same latitudinal distribution as the solar insolation at the top of the atmosphere, S_o. This approximation will be relaxed ultimately. Also we will use North's (1975) two mode approximation for S_o, i.e., we choose

$$S_s(x,x_s) = [\, 1+ S_2 P_2(x) \,]\, \overline{S} \tag{5}$$

where $\overline{S}$ is the mean value of S_s and $S_2 = -0.482$. Substituting Equations (1) and (5) into (4), we obtain the following expression

$$\overline{\alpha}_s = [b(1-x_s) + a x_s] + S_2(b-a)(x_s - x_s^3)/2 \tag{6}$$

where the first term is the geometrical albedo. Equations (3) and (6) when coupled give a highly non-linear relation describing the feedback between ice-snow albedo and temperature.

Results and discussion. First we examine the sensitivity of the present radiative-convective model with and without the surface albedo-temperature feedback. A convenient measure of the sensitivity of the

Table 1. Comparison of the model sensitivity parameter β_0 and the ice-snow albedo amplification parameter γ for several climate models. C_T is the dependence of zonal surface-atmosphere albedo upon zonal mean surface temperature (cf., Sellers, 1969).

MODEL	β_0 (°C)	γ
A. Energy balance models		
Budyko (1967)	155	1.58
Lian and Cess (1977)	147	
$C_T = C_T(x)$		0.25
$C_T = 0.009$		1.68
$C_T = 0.004$		0.27
Sellers (1969)	150	
$C_T = 0.009$		1.17
Gal-chen and Schneider (1976)	134	
$C_T = 0.009$		0.98
$C_T = 0.004$		0.22
B. Radiative-convective models		
Wetherald and Manabe (1975)		
I	128	
II*	114	
Present model		
FCA†	112	0.33
FCT†	140	0.49

*Uses the radiation scheme of Rodgers and Walshaw (1966).
† FCA denotes fixed cloud altitude, FCT denotes fixed cloud temperature.

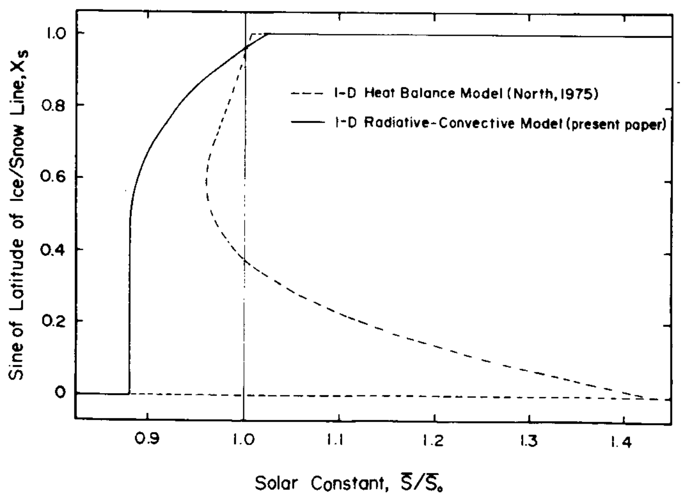

Fig. 1. Position of the edge of the polar ice cap as a function of the solar constant, as determined by the present model (solid curve) and by North (dashed curve).

global climate model is the parameter defined as

$$\beta = \bar{S}\frac{d\bar{T}_s}{d\bar{S}} \quad . \tag{7}$$

The enhancement in global sensitivity due to surface albedo-temperature feedback can be described by the amplification parameter,

$$\gamma = \frac{\beta - \beta_o}{\beta_o}, \tag{8}$$

where β_o is the model sensitivity in the absence of the surface albedo-temperature feedback. Values of β_o and γ for the present model and several other climate models are given in Table 1. In the calculations the present value of the solar constant S was chosen to be 1365 W m^{-2} and values of a and b were chosen to be 0.09 and 0.6, respectively. The characteristics of the model corresponding to the present climate are: $\bar{\alpha}_s = 0.1$, $x_s = 0.964$, $\bar{T}_s = 15.37°$ C and global mean planetary albedo 0.306.

In general, radiative-convective models yield smaller values of β_o than energy balance models, since the former do not include the α_s - T_s positive feedback. The most accurate values of β and γ are those given by Lian and Cess (1977) for $C_T = C_T(x)$, whose calculations included the most realistic parameterizations of this feedback. The results of our model with this feedback included are also listed in Table 1. The enhancement of the model's sensitivity is in good agreement with Lian and Cess' results, although the magnitude of the enhancement is subject to modification when a more accurate representation of S_s is used.

We also calculated the variation of the ice line with solar constant in the radiative-convective model. The solution is illustrated in Fig. 1. The qualitative behavior is similar to that in the 1-D heat balance models. As the solar constant is decreased, a point is reached at which the ice cap is unstable and will grow spontaneously until it covers the whole earth. For the approximation to S_s we have used, this occurs when the solar constant has decreased by 12%.

We conclude that the surface albedo-temperature feedback can be included in a one-dimensional radiative-convective climate model in a qualitatively realistic way. This addition represents a significant improvement in the ability of such models to simulate the effects of radiative perturbations on climate in a realistic way.

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