A Global Climatic Model Based on the Energy Balance of the Earth-Atmosphere System

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ABSTRACT

A relatively simple numerical model of the energy balance of the earth-atmosphere is set up and applied. The dependent variable is the average annual sea level temperature in 10° latitude belts. This is expressed basically as a function of the solar constant, the planetary albedo, the transparency of the atmosphere to infrared radiation, and the turbulent exchange coefficients for the atmosphere and the oceans.

The major conclusions of the analysis are that removing the arctic ice cap would increase annual average polar temperatures by no more than 7C, that a decrease of the solar constant by 2–5% might be sufficient to initiate another ice age, and that man's increasing industrial activities may eventually lead to a global climate much warmer than today.

1. Introduction

One of the most intriguing and interesting problems in the atmospheric sciences today is the estimation of the effect of changes in the planetary albedo, the solar constant, or atmospheric turbidity on the large-scale surface temperature field. Most of the work accomplished so far in this area has been done in Russia and is concerned mainly with the removal of the arctic ice sheet. Budyko (1966), for example, concludes that the polar ice decreases the surface temperature in the central arctic by 30–35C in winter and 5C in summer. For his model he used the surface energy balance equation and an empirical relationship between the vertical turbulent heat flux in the arctic and the temperature difference between the equator and 80N. Rakipova (1966a), using a much more elaborate approach, reached essentially the same conclusion, obtaining a surface temperature decrease of 19–26C in winter and 3–4C in summer. Her model utilized the energy balance of an atmospheric column and yielded the vertical temperature distribution up to a height of 20 km between the equator and 90N. Both Budyko and Rakipova apparently neglected heat transfer by ocean currents.

Rakipova (1966b) also considered the zonal distribution of temperature that would result from contamination of the upper atmosphere by dust. Decreasing the solar constant by 10% and assuming no change in the flux of infrared radiation, she obtained a surface temperature drop ranging from 8C at the equator to 14C at 90N. She also cites the conclusion of Veksler (1958) that decreasing the planetary albedo from 0.43 to 0.35 will raise the average temperature of the earth-atmosphere system by 8C.

Eriksson (1968) describes a generalized model of the dynamics of glaciations and presents functional relationships between the amount of ice coverage and the mean surface temperature. He concludes that a 4% decrease in the solar constant might be enough to reduce the global mean temperature by 9C and produce typical ice age conditions. He also mentions the possibility that, once the ice coverage reaches a certain low latitude, any further growth would be explosive and eventually ice might cover the entire earth.

The purpose of this paper is to investigate a different approach than used by either Rakipova or Eriksson. It is based on the concept or conviction that the steady-state average latitudinal distribution of surface temperature, to a first approximation, should depend entirely on the incoming solar energy, the transparency of the atmosphere to terrestrial radiation, the planetary albedo, the ability of the atmosphere to carry heat and water vapor from source to sink, and the heat storage potential of the oceans and land. The latter factor drops out when average annual temperatures are considered. Bernard (1967) has essentially stated the problem in this form.

The model outlined below is a preliminary model with the dependent variable being the average annual sea level temperature in each 10° latitude belt. It is based on the energy balance equation for the earth-atmosphere system, with the boundary conditions that there can be no meridional energy transport across the poles. One of the main purposes of the model is to show that attempts to modify the climate of a small section of the world must ultimately affect the whole globe before a new steady-state regime can be attained. Several empirical and relatively crude relationships are involved. Unfortunately, this is true of all present models and probably will continue to be true in the future. The best one can hope for is that the empirical relationships are realistic and will continue to give valid results when the basic parameters are changed slightly from their current values.

2. The model

Neglecting heat storage in the oceans, land or atmosphere, and hence assuming no long-term climatic trend, the energy balance equation for the earth-atmosphere system may be written

$$R_s = L\Delta c + \Delta C + \Delta F, \tag{1}$$

where R_s is the radiation balance of a given latitude belt, L the latent heat of condensation, assumed to equal 590 cal gm^{-1}, and Δc, ΔC and ΔF are the net fluxes out of the belt of, respectively, water vapor by atmospheric currents, sensible heat by atmospheric currents, and sensible heat by ocean currents.

Eq. (1) may be rewritten in the expanded form

$$-R_s\frac{A_0}{l_1} = Lc_1 + C_1 + F_1 - P_0\frac{l_0}{l_1}, \tag{2}$$

where

$$P_0 + Lc_0 + C_0 + F_0.$$

A_0 is the horizontal area of the latitude belt, and l_0 and l_1 are, respectively, the lengths of its northern and southern latitude boundaries. P represents the total heat transport across the given latitude circle. The units of each term in Eq. (2) are cal cm^{-1} sec^{-1}. With the boundary conditions that c, C and F are all equal to zero at the poles, Eq. (2) reduces to

$$-R_s\frac{A_0}{l_1} = Lc_1 + C_1 + F_1$$

between 80 and 90N and to

$$P_0 = R_s\frac{A_0}{l_0} \tag{3}$$

between 80 and 90S.

Eq. (2) must be expressed in terms of the single unknown ΔT, the sea level temperature difference $T_0 - T_1$ between successive latitude belts. T_0 between 80 and 90N is then specified and adjusted until Eq. (3) is satisfied to the required accuracy. This is an iterative process and ultimately relates the temperature in each latitude belt to the temperature in all other belts.

The components of Eq. (2) can be expressed in the following forms:

$$R_s = Q_s(1-\alpha_s) - I_s, \tag{4}$$

$$\alpha_s = b - 0.009T_g, \qquad T_g < 283.16, \tag{5a}$$

$$\alpha_s = \alpha_d = b - 2.548, \quad T_g > 283.16, \tag{5b}$$

$$I_s = \sigma T_0^4[1 - m \tanh(19T_0^6 \times 10^{-16})], \tag{6}$$

$$c = \left(vq - K_w\frac{\Delta q}{\Delta y}\right)\frac{\Delta p}{g}, \tag{7}$$

$$v = -a(\Delta T + |\overline{\Delta T}|), \quad \text{north of 5N}, \tag{8a}$$

$$v = -a(\Delta T - |\overline{\Delta T}|), \quad \text{south of 5N}, \tag{8b}$$

$$q = \frac{\epsilon e}{p}, \tag{9}$$

$$\Delta q = \frac{\epsilon^2 Le\Delta T}{pR_d T_0^2}, \tag{10}$$

$$e = e_0 - 0.5\frac{\epsilon Le_0\Delta T}{R_d T_0^2}, \tag{11}$$

$$C = \left(vT_0 - K_h\frac{\Delta T}{\Delta y}\right)\frac{c_p}{g}\Delta p, \tag{12}$$

$$F = -K_0\Delta z\frac{l'}{l_1}\frac{\Delta T}{\Delta y}. \tag{13}$$

In these equations the notation is as follows:

a. For each latitude belt

Q_s	incident solar radiation
α_s	planetary albedo
I_s	infrared emission to space
b	empirical coefficient (see Table 1)
T_g	average surface temperature ($= T_0 - 0.0065Z$)
Z	average surface elevation in meters (see Table 1)
σ	Stefan-Boltzmann constant [1.356×10^{-12} ly sec^{-1} (°K)$^{-4}$]
m	atmospheric attenuation coefficient (0.5 for present conditions)
e_0	mean sea level saturation vapor pressure

b. For each latitude circle

v	mean meriodional wind speed (positive northward)
q	mean saturation specific humidity at sea level
K_w	eddy diffusivity for water vapor in air
Δy	1.11×10^8 cm
Δp	pressure depth of the troposphere (see Table 1)
g	gravity (10^3 cm sec^{-2})
a	meridional exchange coefficient
$\lvert\overline{\Delta T}\rvert$	average absolute value of ΔT (weighted with respect to l_1)
ϵ	0.622
e	mean sea level saturation vapor pressure
p	average sea level pressure (1000 mb)
R_d	gas constant [6.8579×10^{-2} cal gm^{-1} (°K)$^{-1}$]
K_h	eddy thermal diffusivity for air
c_p	specific heat at constant pressure [0.24 cal gm^{-1} (°K)$^{-1}$]
K_0	eddy thermal diffusivity for ocean currents
Δz	ocean depth (see Table 1)
l'	length of the ocean-covered portion of l_1

There are a number of approximations involved in Eqs. (4)–(13). Probably the most important is, in Eqs. (7), (12) and (13), that average atmospheric temperatures and specific humidities and ocean temperatures are assumed to be proportional to their respective sea level values. Further, the actual specific humidity is replaced by the saturation specific humidity, thus permitting the use of Eq. (10), the finite difference form of the Clausius-Clapeyron equation, and Eq. (11) to

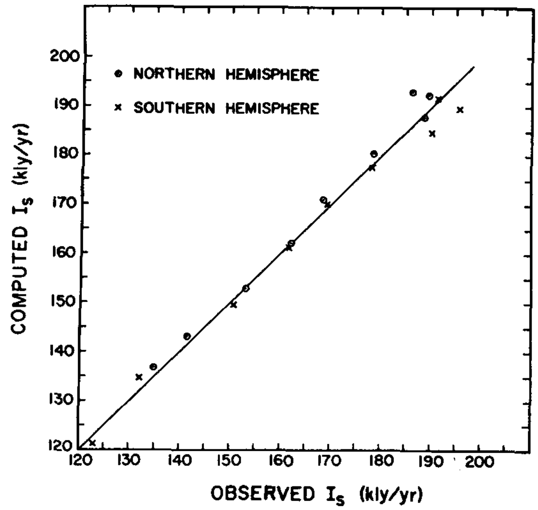

FIG. 1. A plot of the computed and observed values of the annual infrared emission to space in 10° latitude belts. The computed values were obtained from Eq. (6). The observed values are those given by Sellers (1965), modified slightly by recent satellite measurements.

relate temperature and vapor pressure. The constants of proportionality are absorbed into the diffusivities and the meridional exchange coefficient.

In Eq. (5a) the planetary albedo is given as a function of the surface temperature T_g. It is assumed that variations in the albedo are associated mainly with variations in surface snow cover and that the relationship is valid only as long as the surface temperature <10C and the albedo <0.85. For higher temperatures, Eq. (5b) is used to give the planetary albedo α_d in the absence of a snow cover. These latter values are listed in Table 1. If the computed albedo >0.85, a value of 0.85 is used. Actually, Eq. (5a) plays a critical role in the analysis. It indicates that the albedo will increase by 0.009 for every 1C drop in surface temperature. This figure was obtained by comparing present-day albedos and temperatures in the same latitude belts of the two hemispheres. Eriksson (1968), using a maximum snow surface albedo of 0.65, implies a value laying between 0.004 and 0.008. The coefficient b was selected so that the equation would fit the observed data. The effects of variations in cloud cover on the albedo were ignored, mainly because there is no easy way to include them. Eriksson points out that large changes in the mean cloudiness of the planet as a whole should not be expected. However, the meridional distribution of cloud cover can vary significantly.

Eq. (6), relating the infrared radiation loss to space to the sea level temperature, was obtained from present data (see Fig. 1)), where the bracketed quantity can be viewed as an atmospheric transmission factor or, as Bryson (1968) puts it, an effective emissivity, which ranges from about 0.8 at -30C to 0.5 at 30C when $m=0.5$. It represents the effect of water vapor, carbon dioxide, dust and clouds on terrestrial radiation. The attenuation coefficient m should go up or down as the atmospheric infrared turbidity increases or decreases, respectively. Very roughly, an increase or decrease in the atmospheric water vapor content by a factor of 1.4 or in the CO_2 content by a factor of 10 would be needed to change m by 10%.

In Eqs. (7) and (12), the poleward transport of water vapor and sensible heat in the atmosphere is assumed to consist of two parts, one associated with a mean meridional motion and the other with large-scale eddies or cyclones and anticyclones. The inclusion of the mean meridional motion is necessary in order to avoid having to deal with negative diffusivities. The dependence of the north-south velocity component v on the meridional

TABLE 1. Average values of b, Z and α_d for each latitude belt and of Δp and Δz for each latitude circle.

Latitude belt	b	Z (m)	α_d	Latitude circle	Δp (mb)	Δz (km)
80–90N	2.924	137	0.376	80N	709	2
70–80N	2.927	220	0.379	70N	710	1
60–70N	2.878	202	0.330	60N	713	2
50–60N	2.891	296	0.343	50N	750	3
40–50N	2.908	382	0.360	40N	800	4
30–40N	2.870	496	0.322	30N	833	4
20–30N	2.826	366	0.278	20N	880	4
10–20N	2.809	146	0.261	10N	904	4
0–10N	2.808	158	0.260	0	906	4
0–10S	2.801	154	0.253	10S	904	4
10–20S	2.798	121	0.250	20S	880	4
20–30S	2.815	156	0.267	30S	833	4
30–40S	2.865	106	0.317	40S	800	4
40–50S	2.922	5	0.374	50S	750	4
50–60S	2.937	5	0.389	60S	713	4
60–70S	2.989	388	0.441	70S	710	3
70–80S	2.992	1420	0.444	80S	709	0
80–90S	2.900	2272	0.352			

TABLE 2. Average values of Q_s for each latitude belt and of K_h, K_w, K_0 and a for each latitude circle.

Latitude belt	Q_s (kly yr^{-1})	Latitude circle	K_h (10^{10} cm^2 sec^{-1})	K_w (10^9 cm^2 sec^{-1})	K_0 (10^6 cm^2 sec^{-1})	a [cm sec^{-1} (°K)$^{-1}$]
80–90N	135.7	80N	1.9	4.6	0.7	0.5
70–80N	145.1	70N	1.2	2.0	6.6	1.0
60–70N	167.3	60N	1.7	2.5	6.9	1.0
50–60N	202.2	50N	1.5	5.9	7.6	1.0
40–50N	237.7	40N	0.9	5.1	5.3	1.0
30–40N	269.0	30N	1.3	2.9	9.6	2.0
20–30N	293.9	20N	10.3	2.2	13.3	3.0
10–20N	311.1	10N	133.2	34.4	59.9	3.0
0–10N	319.8	0	68.2	16.3	7.0	3.0
0–10S	319.8	10S	30.8	0.6	19.0	3.0
10–20S	311.1	20S	8.5	0.8	9.5	3.0
20–30S	293.9	30S	2.3	4.3	5.1	2.0
30–40S	269.0	40S	2.3	11.9	2.9	1.0
40–50S	237.7	50S	1.9	12.8	1.8	1.0
50–60S	202.2	60S	1.4	8.2	0.5	1.0
60–70S	167.3	70S	1.0	7.4	0.2	0.5
70–80S	145.1	80S	0.5	6.3	0.0	0.5
80–90S	135.7					

temperature gradient was determined empirically. Eqs. (8a) and (8b) are based on the observations, first, that both v and the zonal velocity component in the lower troposphere average close to zero for the earth as a whole, and, second, that the strongest westerlies have a poleward component and the strongest easterlies an equatorward component. The resulting correlation, plus that between the zonal speed and the temperature gradient, yields Eqs. (8a) and (8b).

Eqs. (7) and (12) involve the three unknowns v, K_w and K_h, which, therefore, cannot be determined directly from presently available data. However, since the diffusivities must be greater than zero, upper or lower limits on v can be determined [by setting K_w and K_h equal to zero in Eqs. (7) and (12)]. These, then, can be used as a guide for specifying the coefficient a. When this is done, the values of a, K_w and K_h given in Table 2 result. The magnitude 10^{10}–10^{11} cm^2 sec^{-1} for K_h in middle latitudes is in agreement with values used or suggested by Rakipova (1966b), Adem (1964), Panchev (1968) and Eriksson (1968), among others. The relative magnitudes of K_w, K_h and K_0 seem to be quite reasonable. Because they all apply to horizontal transfer, the large values near the equator are difficult to explain. However, since the temperature and moisture gradients here are small, the resulting poleward transfer is no greater, and often smaller, than that associated with the mean meridional circulation.

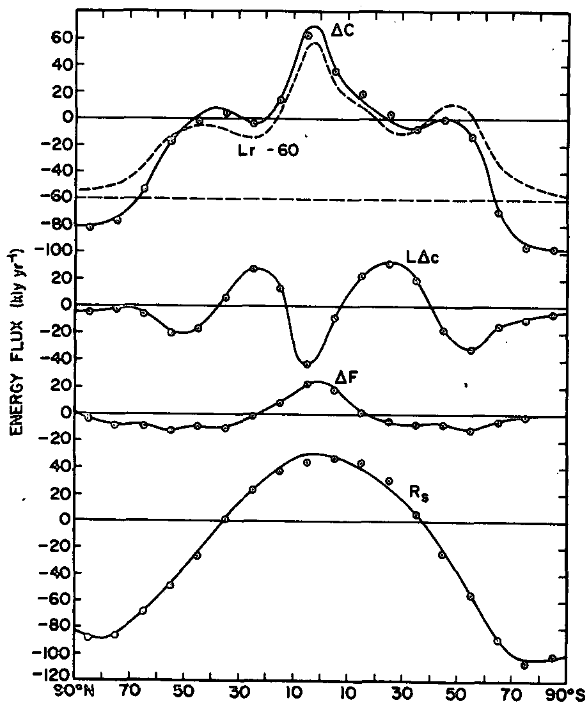

FIG. 2. The observed latitudinal distribution of the net fluxes out of each 10° latitude belt of sensible heat by atmospheric currents, ΔC, latent heat by atmospheric currents, $L\Delta c$, and sensible heat by ocean currents, ΔF. Also shown are the distribution of the energy released by condensation, Lr, and the radiation balance R_s of the earth-atmosphere system. The circled points represent the values computed using the model.

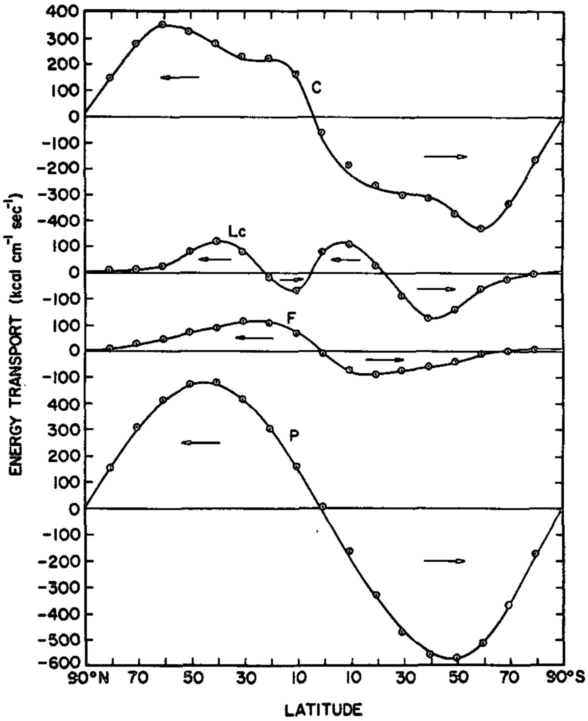

FIG. 3. The observed latitudinal distribution of the annual meridional sensible heat (atmosphere) transport C, latent heat transport Lc, sensible heat (ocean) transport F, and the total transport P. The circled points represent the values computed using the model. The arrows indicate the direction of the transport.

In Eq. (13) average ocean depths given by Dietrich (1963) were used for Δz. If it is believed more satisfactory to use instead the depth of the mixed layer, which averages about 60 m, the values of K_0 should be multiplied by approximately 10^2.

Substituting Eqs. (4)–(13) into Eq. (2) results in a second-order equation in ΔT, with only the negative root (giving ΔT negative in the Northern Hemisphere and positive in the Southern Hemisphere) yielding realistic temperatures. It is interesting to speculate that a more complex model might give a higher order equation with several realistic roots and, hence, several plausible equilibrium temperature distributions for a given set of input variables. Lorenz (1968) touches on this subject.

In this model, the primary variables that determine the equilibrium latitudinal distribution of sea level temperature are the incoming solar radiation, the eddy diffusivities, the meridional exchange coefficient, and the atmospheric attenuation coefficient. Current average values of Q_s, a, K_h, K_w and K_0 are given in Table 2 for each latitude zone or circle. As mentioned earlier, the attenuation coefficient $m=0.5$. With these data, the model was first used to reconstruct the present state of

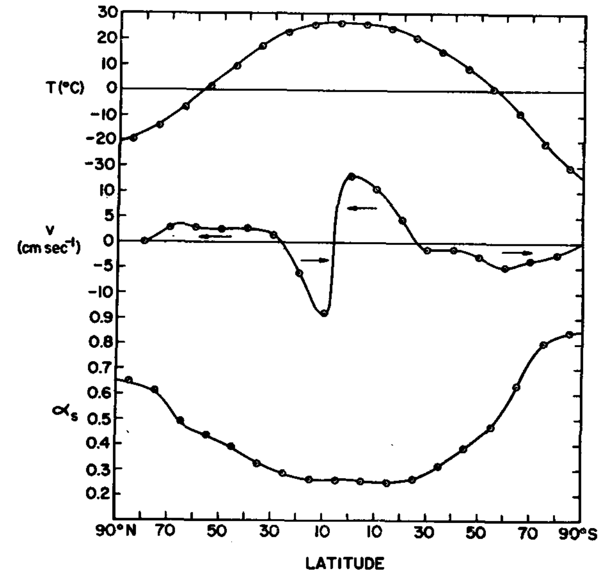

FIG. 4. The observed latitudinal distribution of the mean annual sea level temperature T, meridional wind speed v, and planetary albedo α_s. The circled points represent the values computed using the model.

the earth-atmosphere system. The results are shown in Figs. 2, 3 and 4. The observed data are essentially those given by Sellers (1965), with minor changes instigated by recent satellite measurements of both the short- and longwave radiative fluxes at the top of the atmosphere (Vonder Haar, 1968; Raschke *et al.*, 1967; Arking and Levine, 1967).

Since the eddy diffusivities were determined from the data, the observed and computed values should coincide, which, in general, they do. The latitudinal distributions of ΔC, $L\Delta c$, ΔF and R_s are shown in Fig. 2. Superimposed on the ΔC curve is that for Lr, the energy released by condensation. There are obvious similarities between the two, suggesting that the condensation process provides most of the energy transferred poleward in the atmosphere as sensible heat. It is felt, however, that the relationship is not close enough to incorporate into the model and, thus, to allow estimates of global precipitation. The major source region for both atmospheric and oceanic sensible heat lies in the tropics between 20N and 20S. Latent heat, on the other hand, originates primarily in the subtropics (15–35N, 15–35S) where annual evaporation far exceeds annual precipitation.

In Fig. 3 are shown the latitudinal distributions of the meridional transport terms, C, Lc, F and P. In general, the transport is poleward in both hemispheres. The one exception is the latent heat or water vapor flux, which, as a result of a strong Hadley circulation, is directed equatorward between 20N and 20S. The bulk of the required transport occurs in the atmosphere in the form of sensible heat.

The latitudinal distributions of the sea level temperature, the meridional wind speed, and the planetary albedo are shown in Fig. 4. Because of the presence of the Antarctic continent, sea level temperatures are lower and albedos higher at the south pole than at the north pole. This asymmetry should assure some degree of interaction between the two hemispheres. The meridional wind component is small everywhere except between 20N and 20S where the trade wind systems of the two hemispheres produce considerable equatorward mass transfer in the lower troposphere. Mintz (1968) gives similar results. Because of the assumptions involved in the model, the values given for v should be considered only proportional to those which actually exist. They appear to be low by a factor of about 10.

The model obviously specifies present conditions very well. This, however, does not assure its reliability when applied to situations where one or more of the variables in Table 2 are different than currently observed. Therefore, the following applications should be taken only as an indication of what might happen. As further improvements are made in the functional relationships among the variables involved and the model is extended to the individual months, the picture might change considerably. Also, recall that steady-state conditions are specified, and these may take many years to attain, considering the great heat storage capacity of the world's oceans. Eriksson (1968), for example, gives a lag time of the order of 1000 years.

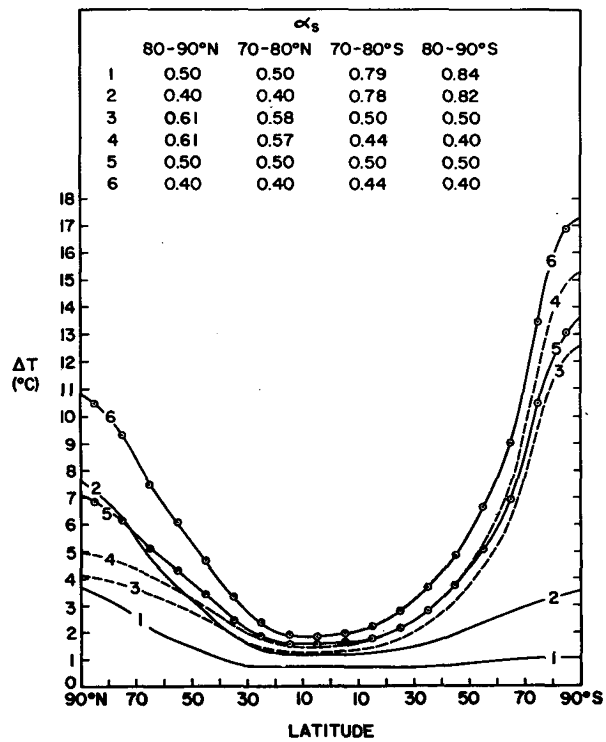

FIG. 5. Predicted latitudinal distribution of the mean annual temperature rise associated with albedo manipulation at one or both poles.

3. Applications

a. Modification of the polar ice caps

As mentioned earlier, Budyko (1966) and Rakipova (1966a) estimate that the surface temperature in the arctic would rise 15–20C if the ice sheet were either melted or covered with a black powder. However, both authors dealt mainly with the local energy balance and neglected possible interactions with other regions at lower latitudes.

The basic parameter, and the only one that need be changed in the model, is the planetary albedo at high latitudes. Rakipova (1966b) uses an average value of 0.619 with the ice in, 0.484 with the ice out. The corresponding values used by Fletcher (1966) are 0.51 and 0.34, both of which seem to be low, judging from available satellite data. In the present analysis, a number of different combinations were used, with albedos at one or both poles (70–90°) being set equal to and held fixed at either 0.50 or 0.40 (with the exception of 70–80S, where, in line with Table 1, a minimum value of 0.44 was used). Before proceeding to a discussion of the results, it should be emphasized again that the present state of the earth-atmosphere system is assumed in the model to be the only possible equilibrium state as long as the variables in Table 2 are not changed.

The results, shown in Fig. 5, bring out a number of interesting points. First, removing the north polar ice would increase the temperature poleward of 70N by, at most, ~7C. At the same time, temperatures would rise by about 1C in the tropics and 1–3C near the south pole. A similar treatment in the antarctic would produce a temperature increase there of 12–15C, with a concomitant rise of about 4C in the arctic. Treating both polar regions would yield a temperature increase of 7–10C in the arctic and 13–17C in the antarctic. Warming in the tropics would never exceed 2C.

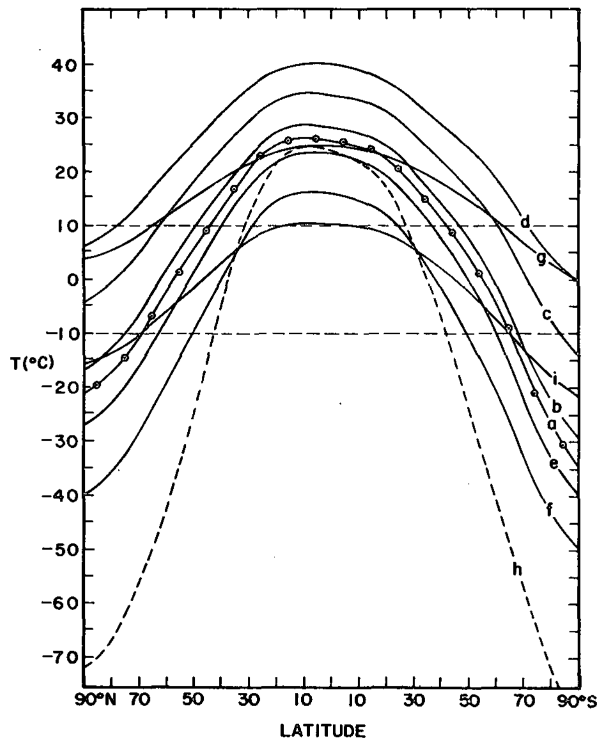

FIG. 7. The predicted latitudinal distribution of the mean annual sea level temperature when the solar constant is increased by 0%, a, (present conditions), 1%, b, 5%, c, and 10%, d, or reduced by 1%, e, 2%, f. Curve i shows the distribution resulting from a 3% decrease of the solar constant and a 100% increase in the exchange coefficient and eddy diffusivities. In curves g and h the solar constant is kept fixed at its present value of 2.00 ly min^{-1} and the exchange coefficients and eddy diffusivities are increased by 100% and decreased by 50%, respectively. In all cases the planetary albedo is given by Eqs. (5a) and (5b).

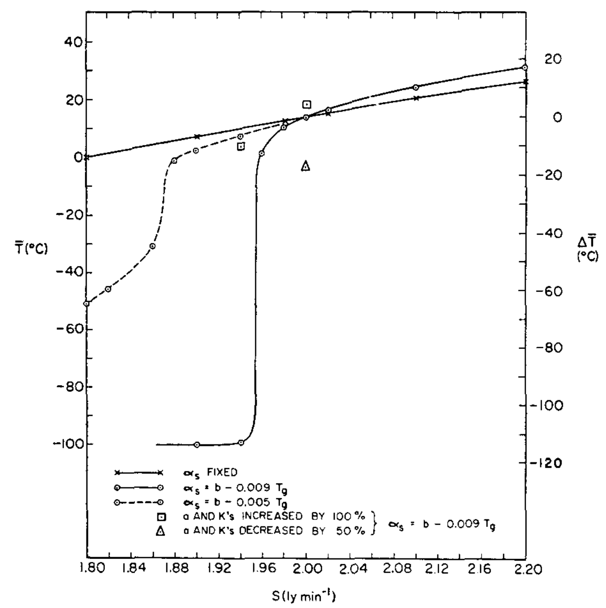

FIG. 6. The mean global sea level temperature $\bar{T}$ as a function of the solar constant S for different responses of the planetary albedo α_s, and different values of the meridional exchange coefficient and the eddy diffusivities, K_h, K_w and K_0.

Thus, albedo manipulation at either pole would have worldwide repercussions. As an extreme illustration, reducing the albedo south of 70S to 0.50 would apparently produce a larger temperature rise in the arctic than would a reduction of the albedo north of 70N to 0.50 (compare curves 1 and 3 in Fig. 5). The greater effects of treatment in the antarctic than in the arctic are simply the result of its higher initial albedo (see Fig. 4). Along this line, Fletcher (1968) has recently concluded that the extent of sea ice in the Southern Hemisphere has a much more potent effect on the global circulation than the extent of sea ice in the Northern Hemisphere.

b. Variations in the solar constant

One of the favorite theories of climatic change during the last million years attributes the ice ages to variations in the intensity of solar radiation or, equivalently, to variations in the contamination of the upper atmosphere by dust of volcanic or cosmic origin. The general feeling seems to be that a slight reduction in the solar constant (or increase in global dust contamination) would be sufficient to initiate another ice age. This appears to be borne out by the calculations made in this study and summarized in Figs. 6 and 7. In Fig. 6 the global mean sea level temperature $\bar{T}$ is plotted as a function of the solar constant S, currently assumed to equal 2.00 ly min^{-1}. The present value of $\bar{T}$ is about 14.0C. Three analyses were carried out, two with the planetary albedo allowed to vary, according to $\alpha_s = b - 0.009T_g$ and $\alpha_s = b - 0.005T_g$, respectively, and the other with the albedo held fixed at its current values (Fig. 4). The latter case corresponds to that reported by Rakipova (1966b), who, as mentioned earlier, obtained temperature decreases ranging from 8C at the equator to 14C at 90N when the solar constant was decreased by 10%. In the present study the magnitudes of the computed drops were the same, but the range was from 14.3C between latitudes of 0° and 20° and 50–60° to 13.0C between 80 and 90°. With a 10% increase in the solar constant, the global mean temperature should rise about 12C if the albedos are held fixed. These results are in good agreement with those of Manabe and Wetherald (1967) and Eriksson (1968).

When the albedos are more realistically permitted to vary with temperature according to Eq. (5), the picture changes considerably. If all other variables are held constant, a decrease in the solar constant by about 2% would be sufficient to create another ice age, with the ice caps extending equatorward to 50° ($T = -10$C) and mountain glaciers and heavy winter snow to 30° ($T = 10$C) as shown in Fig. 7. Any further drop in the solar constant is, as a result of Eq. (5), accompanied in the model by a rapid transition to an ice-covered earth with an albedo of 0.85 and an equilibrium temperature of −100C. Since the model is based more on functional data fitting techniques than on physical laws, extrapolation to such extreme conditions is hazardous. Generally speaking, valid results should be expected only as long as the response to small changes in the basic parameters is itself small. However, Eriksson (1968) mentions that an explosive development of the ice caps might take place once the ice coverage extended beyond a certain latitude, which he indicates to be about 50°.

Although not in line with observed data, the preceding analysis was repeated using a constant of 0.005 instead of 0.009 in Eq. (5), the values of b being adjusted accordingly. With this weaker dependence of the planetary albedo on surface temperature and ice cover, a severe ice age would not occur until the solar constant decreased by 5–6%.

On the positive side, an increase in the solar constant of ~3% would probably be sufficient to melt the ice sheets. An increase of something more than 10% would be needed, however, to eliminate completely snowfall anywhere on the earth.

Up to this point, the only variable in Table 2 allowed to change was the solar intensity Q_s. Suppose now that this is held fixed at its current values and the eddy diffusivities and meridional exchange coefficients are arbitrarily either increased by 100% or decreased by 50%. As shown in Figs. 6 and 7, the higher values would raise the global mean temperature by about 5C, greatly reduce the equator to pole temperature difference (from 48C to 28C in the Northern Hemisphere), and melt the ice sheets. The lower values would initiate an ice age probably worse than any that has ever been experienced; average temperatures would drop below −70C at the poles and below −10C at 45N and 45S. However, there would be little change in temperatures near the equator.

If the values of Q_s are reduced by 3% and those of a, K_h, K_w and K_0 are increased by 100%, there would still be a worldwide temperature drop, but not by nearly as much as when only Q_s was reduced. The enhanced meridional heat exchange would decrease the pole to equator temperature difference to 26C in the Northern Hemisphere. The ice caps would remain near their present positions, but seasonal snowfall would occur almost to the equator, where the temperature would be about 16C lower than it is today.

Thus, a relatively small change in the ability of the atmosphere and oceans to transfer heat poleward could conceivably offset any increase or decrease in the intensity of solar radiation. Hence, it might be quite risky to change one variable without accounting for possible changes in the others. Nevertheless, the model seems to indicate quite conclusively that a decrease in the solar constant of less than 5% would be sufficient to start another ice age.

c. Variations in the infrared transmissivity of the atmosphere

The global mean temperature responds to changes in the atmospheric attenuation coefficient m in Eq. (6) in much the same way as it does to changes in the solar constant. A 3% decrease in m should be sufficient to put the globe on the brink of an ice age. Fortunately, because of the increasing carbon dioxide content of the atmosphere, m is more likely to increase than decrease. Hence, the global mean temperature should slowly rise due to this factor.

d. Increased use of stored energy by man

Budyko *et al.* (1966) point out that the quantity of energy used by man and converted into heat, presently about 0.02 kly yr^{-1} averaged over all continental areas, is increasing by 4% each year. Should this rate of increase continue, in less than 200 years the heat produced will reach 50 kly yr^{-1}, or approximately the

TABLE 3. Annual sea level temperature rise ΔT_1 due solely to an increase in the energy consumption by man from 0.02–50 kly yr^{-1} averaged over all continental areas and the temperature rise ΔT_2 taking into account the reduction in incoming solar radiation ΔQ_s, due to increased air pollution.

Latitude belt	H* (kly yr^{-1})	ΔT_1 (°C)	ΔQ_s* (kly yr^{-1})	ΔT_2 (°C)
80–90N	0.0	27.0	0.0	25.2
70–80N	1.4	25.9	0.1	24.2
60–70N	23.0	24.2	1.6	22.6
50–60N	50.5	22.0	4.2	20.5
40–50N	114.8	19.0	11.3	17.6
30–40N	96.4	15.1	10.7	13.9
20–30N	76.2	12.6	9.2	11.5
10–20N	41.3	11.4	5.3	10.5
0–10N	23.0	11.3	3.0	10.3
0–10S	23.9	11.3	3.2	10.4
10–20S	34.4	11.4	4.4	10.5
20–30S	46.9	11.9	5.7	10.9
30–40S	24.8	12.8	2.8	11.7
40–50S	6.9	14.2	0.7	13.7
50–60S	0.5	16.5	0.0	15.3
60–70S	2.3	19.1	0.2	17.7
70–80S	3.7	22.2	0.2	20.5
80–90S	0.0	24.4	0.0	22.5

* Values are expressed per cm² of land.

value of the radiation balance of the continents. Hence, from that time on, "solar energy will no longer be the main climate forming factor, and the climate will become primarily a result of the activity of man."

The latter statement is probably a slight exaggeration, since 50 kly yr^{-1} averaged over all continental areas is equivalent to about 15 kly yr^{-1} averaged over the entire earth surface or little more than 5% of the solar radiation intercepted by the globe annually. Nevertheless, the effects could be considerable, especially in middle and high latitudes of the Northern Hemisphere where the energy used would presumably be greatest.

The latitudinal sea level temperature distribution that might result from the added heating was obtained from the model by spreading the heating H, rather arbitrarily, among the various latitude belts, as shown in Table 3. The only guide used here was the latitudinal distribution of large cities, the main source of combustion. It was assumed that this distribution will not change significantly during the next 200 years.

The results given in Table 3 show that the temperature rise ΔT should average about 15C, ranging from 11C near the equator to 27C at the North pole. This should be enough to eliminate all permanent ice fields, leaving only a few high mountain glaciers on Antarctica and perhaps Greenland. These conclusions ignore any possible decrease, ΔQ_s, in the intensity of solar radiation because of the increased air pollution. When this is taken into account, the temperature rise decreases only slightly (by 1–2C). The values of ΔQ_s in Table 3 are based partly on information given by Bornstein (1968). His data imply a value of about 90 kly yr^{-1} for H at New York City. Radiation data, on the other hand, indicate that the incoming solar radiation at the surface is decreased there by 9.4 kly yr^{-1} or about 3.7% of the extraterrestrial radiation. In general, ΔQ_s appears to equal about 10% of H.

Thus, man's activity, if it continues unabated, should eventually lead to the elimination of the ice caps and to a climate much warmer than today. Annual mean temperatures of 26C, now characteristic of the tropics, would exist as far poleward as 40°. Considering the thermal inertia of the world's oceans, it is impossible to state how long it will take for this warming to occur—possibly as little as 100 years or as long as 1000 years. During this time, it is not inconceivable that the solar constant will change. A decrease of slightly more than 7% in its value would yield a global mean temperature equal to that existing today. Since such a large drop in the solar constant over any extended period is on the fringe of being highly unlikely, if one believes the earlier results of this paper, it follows that Budyko *et al.* (1966) may be correct after all in stating that eventually man may inadvertently generate his own climate.

4. Conclusions

In this paper an attempt has been made to develop a consistent, yet simple, climatic model based on the global conservation of energy. The major conclusions—that removing the arctic ice cap would have less effect on climate than previously suggested, that a decrease of the solar constant by 2–5% would be sufficient to initiate another ice age, and that man's increasing industrial activities may eventually lead to the elimination of the ice caps and to a climate about 14C warmer than today—should all be viewed in the light of the assumptions made in the model. Although these were specified so as to be physically realistic, the possibility still remains that neglected higher order or nonlinear effects could alter the picture considerably.

While the assumptions made must limit the accuracy of the model, it is believed that the use of only mean annual values of the parameters involved is even more restrictive. The logical solution here is to go to mean monthly values. This would, of course, entail a great deal more work, not only because of the much greater volume of data involved, but also because energy storage in the atmosphere and oceans would have to be taken into account. The distribution of land and water would become an important factor. The end result, however, would be a much more flexible model than presented here, and one that could be used to study a broad spectrum of possible climatic effects.

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