ENERGY BALANCE MODELS OF CLIMATE—A REVIEW

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ABSTRACT

Energy balance models which came in the field during 1968–69 have since become very popular in the scientific world chiefly because they yield realistic results without use of too much computer time which is required by GC models. Important results achieved by these models are briefly reviewed.

HISTORICAL BACKGROUND

STUDY of climate attracted many scientists after the first general circulation experiment of Philips with quasi-geostrophic model in 1956. Computers grew in speed and capacity while general circulation models increased in complexity. The first primitive equation (PE) model of the general circulation (GC) came in 1962. Subsequently, Smagorinsky and his collaborators performed a series of GC experiments with PE, model and successfully simulated the large scale features of the present climate of the earth. One difficulty about these models has been the enormous amount of computer time required to perform these experiments. In late 1960's came very simple models of climate classed as Energy Balance Models (EBM's)[1-3]. These did not contain the detailed physics of PE models of general circulation but did contain some truths of climate which seemed to churn out the essence of some physical processes operating in the earth-atmosphere climate system. These models required no large computers and hence were very economical in experimentation. Further, past and future climates could be speculated upon with as much ease as the present one. One of the speculations of these models was that if the solar constant were to decrease by even 2 %, the earth's climate would change drastically giving ice sheets over the whole earth from north pole to south pole including the tropics. Around that time, the scientists also became more conversant with the fact that CO_2 in the atmosphere had been increasing continuously since the time of industrial revolution and that this could significantly affect the climate, although in the opposite direction, causing general warming of the earth's surface air layers. The disastrous failure of rains over many parts of the world during 1972 created an alarm that man's interference with the earth's atmosphere was about to exceed tolerable limits. Public interest and scientists' interest in climate studies has since been growing fast. These simple EBM's of climate have been the centre of much research from the early 1970's.

BASIC PHILOSOPHY OF EBM's

In these models *earth-atmosphere climate* is usually represented by *earth's surface or sea level temperature* averaged zonally for a *latitudinal strip*, generally 10° *wide.* Energy balance is expressed in terms of incoming solar radiation, outgoing radiation and meridional exchanges of latent and sensible heat as schematically shown in figure 1.

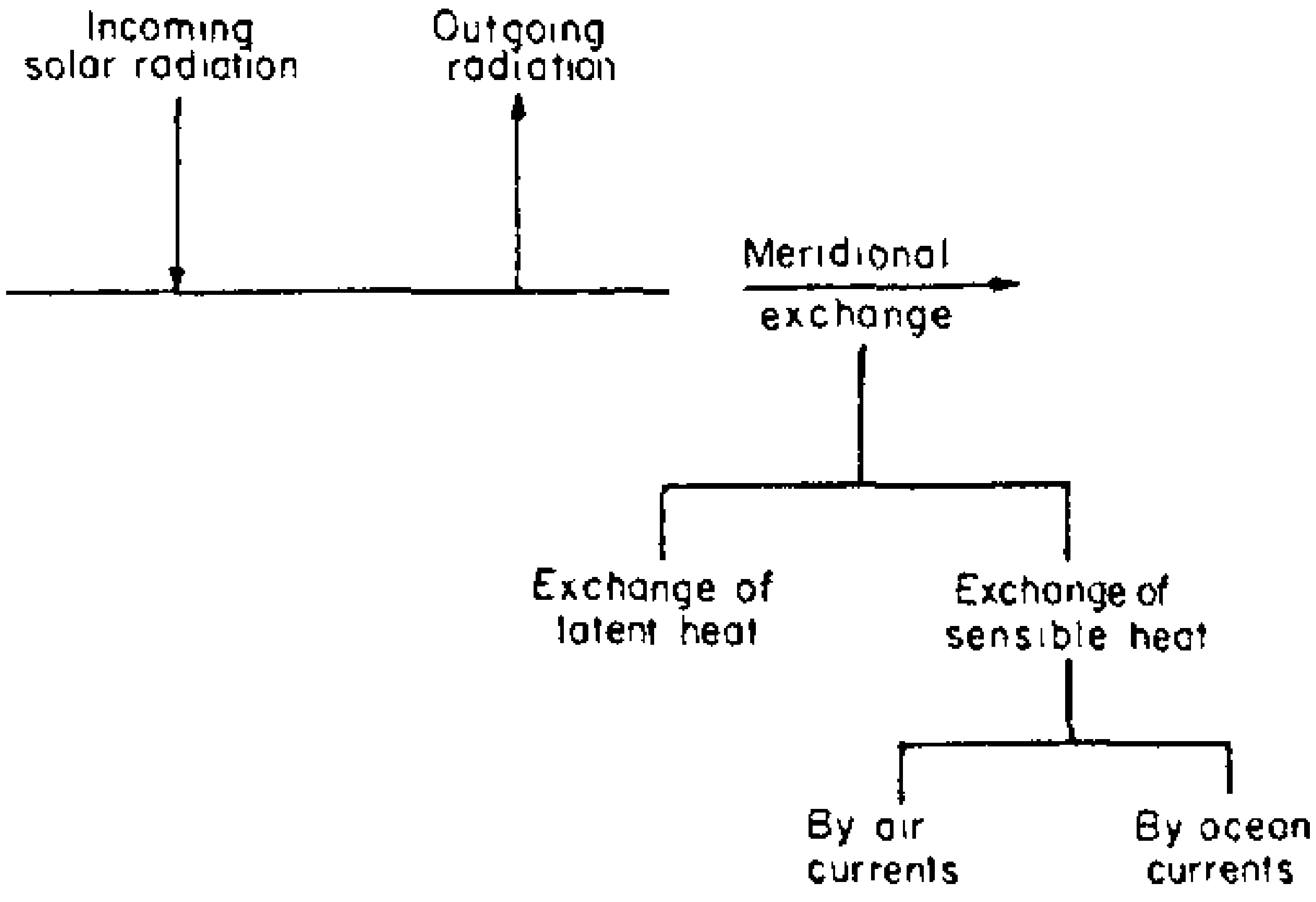

Figure 1. Energy balance diagram

In *stationary solutions*, inflow of heat in a latitudinal strip is taken to be exactly balanced by the meridional outflow of heat. In *time-dependent* solutions, the excess of inflow over outflow of heat causes temperature variations in the strip. Heat *inflow outflow is expressed* in terms of *simple parameters like surface temperature, albedo* of the *earth-atmosphere system and cloud* amount. Surface temperatures are also represented in terms of ice-covered and ice-free surfaces. In more recent models, energy balance is calculated at more than one level.

In spite of gross simplifications used in the parametrizations, the EBM's have provided great insight into the mechanism of climate stability and its variability. When we consider the prohibitive cost and effort required to simulate climate and its variations in a general circulation (GC) model, we at once appreciate the great contribution which the modellers have made in understanding and predicting broad features of climate through these simple energy balance models. Budyko[1,2], and Sellers[3] are regarded as pioneers in this field.

Budyko[4] has presented a lucid summary of his own work and that of others in respect of the simple energy balance models. He refers to these as semi-empirical models since the equations used in these models are based partly on the known laws of physics and partly on empirical relationships between different parameters of the earth-atmosphere system. These empirical relationships are highly simplified parametrized forms of complicated physical processes.

In respect of his own model[1], Budyko presents his ideas in the form of two equations:

$$I_s = a + bT - (a_1 + b_1 T)n \qquad (1)$$

$$Q_s(1-\alpha_s) - I_s = \beta(T - T_p) \qquad (2)$$

I_s = zonally averaged long wave radiation going out in space, expressed in kilocalories per square centimetre per month, T = zonally averaged lower air temperature in degrees celsius, n = cloudiness measured in fractions of a unit, $a = 14.0$; $b = 0.14$; $a_1 = 3.0$ and $b_1 = 0.10$, Q_s = incoming solar radiation at the top of the atmosphere, α_s = albedo of the earth-atmosphere system, T_p = mean planetary temperature of the lower air layer and $\beta = 0.235\ \mathrm{kcal\,cm^{-2}\,month^{-1}\,deg^{-1}}$.

The first equation expresses the concept that the monthly means of out-going emission depend mainly on the air temperature near the earth's surface and on cloudiness, the latter obstructing energy outflow. The second equation represents the concept that in each latitude belt, the excess of incoming over outgoing radiational energy is balanced by meridional heat transfer from warmer to colder regions so as to give equilibrium thermal regime. Neglecting internal-annual variations, this concept is useful for dealing with long term annual temperatures in a latitudinal belt.

Combining these two equations, we get

$$T = \{Q_s(1-\alpha_s) - a + a_1 n + \beta T_p\} / (\beta + b - b_1 n). \qquad (3)$$

With this equation, one can calculate mean annual temperatures at different latitudes.

Budyko[4] quotes ample justification for his two emperical relationships from equations (1) and (2) from the works of Budyko[5], Sawyer[6,7] and Manabe and Wetherald[8].

The results of calculations of the atmospheric thermal regime depend largely on the assumed values of α, the albedo of the earth-atmosphere system.

Budyko[1] used

$\alpha = 0.32$ for ice-free region and
$\alpha = 0.62$ for polar ice region.

The albedo in the polar ice zone was assumed to be constant even if the area of the polar ice changed. Arguments were presented to show that errors due to this assumption were small. Using these values of α and values of other parameters as given above, Budyko compared the model-calculated values with the observed values of mean annual temperatures at different latitudes (figure 2).

The mean difference between the calculated and the observed values is 1.2° which is small compared to the range of variation between different latitudes. This diagram does not show

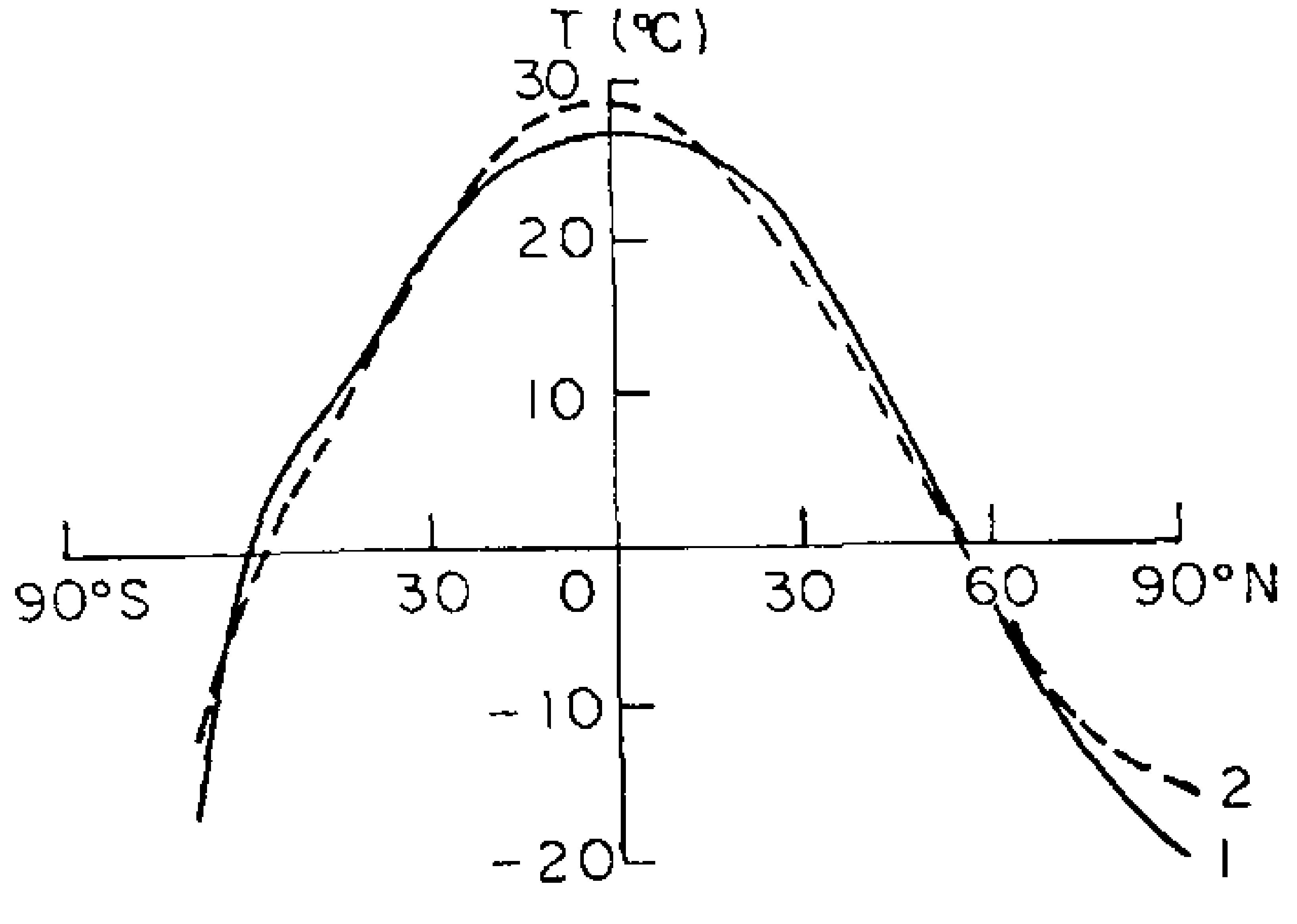

Figure 2. Mean latitudinal temperature distribution for the year as a whole. Curve 1: observed data; Curve 2: calculated results

the two curves for the Antarctic region where the differences between the two curves were large. The discrepancy for the Antarctic was attributed to high elevation of the region and also to the lack of heat transfer by ocean currents in this zone.

Encouraged by this success in respect of annual mean temperatures, Budyko and Vasischeva[9] attempted to simulate seasonal mean temperatures at different latitudes for the warm and the cool seasons. The heat balance relationship was expressed in the form

$$Q_{sw}(1-\alpha_{sw})-I_{sw} = \beta_w(T_w-T_p)+B_s, \quad (4)$$

$$Q_{sc}(1-\alpha_{sc})-I_{sc} = \beta_c(T_c-T_p)-B_s. \quad (5)$$

The subscripts w and c refer to warm and cool seasons respectively. B_s denotes the gain/loss of heat through warming/cooling of the earth-atmosphere system, mainly by warming/cooling of the oceans. What is gained in warm season is lost in cold season so as to give zero loss or gain for the year as a whole. The value of B_s is found by the formula

$$B_s = sy(T_{ow}-T_{oc}), \quad (6)$$

where T_{ow} and T_{oc} denote zonal mean temperatures of the ocean surface during the warm and cold seasons respectively. s is the ratio of ocean area to the total area in a given latitudinal belt; y is a dimensional coefficient. Temperature of the ocean surface was calculated from the formulae

$$R_{ow} = LE_w+P_w+\frac{B_s}{s}, \quad (7)$$

$$R_{oc} = LE_c+P_c-\frac{B_s}{s}+F_0, \quad (8)$$

where R_0 is the radiation balance of the ocean surface, LE is the evaporational loss of heat, P is the turbulent heat flux between the surface of the ocean and the overlying atmosphere. F_0 is the heat transfer by ocean currents which is regarded important during the cold season but negligible during the warm season and hence its absence in the formula for R_{ow}. These quantities were again determined from the formulae:

$$LE = fT_o, \quad (9)$$

$$P = c(T_o-T), \quad (10)$$

$$F_0 = \beta'(T_c-T_p), \quad (11)$$

where T_0 is the ocean surface temperature in degrees celcius and T_c is the air temperature during the cold season. The coefficients f, c and β' are determined empirically. For determining the heat fluxes in kcal/cm^2 per month, the various coefficients were given the following numerical values:

$$y = 3.0, f = 0.4, c = 0.84$$

$\beta' = 0.14$ for northern hemisphere, $\beta' = 0.20$ for southern hemisphere, $\beta_w = 0.22$, $\beta_c = 0.27$ for northern hemisphere south of Arctic ice boundary, $\beta_c = 0.40$ for southern hemisphere north of Antarctic ice boundary, and $\beta_c = 0.22$ for polar ice-covered zones.

The equations given above can be further simplified to become

$$T_w = \{Q_{sw}(1-\alpha_{sw})-a+a_1n_w+\beta_wT_{p1}+lh\}/(b-b_1n_w+\beta_w), \quad (12)$$

$$T_c = \{Q_{sc}(1-\alpha_{sc})-a+a_1n_c+\beta_cT_{p2}+lh\}/(b-b_1n_c+\beta_c), \quad (13)$$

where lh is the gain (or loss) of heat due to cooling (or warming) of the ice cover and freezing (or melting) of ice. The authors adopted $lh = 0.8$ kcal cm^{-2} month^{-1}.

Following approximations were further made: (i) The boundary of polar ice was taken to be the mean latitude where the temperature in the warm half-year is -1°C. (ii) The albedo of the earth-atmosphere system in the polar ice zones was taken to be: 0.62 for the northern hemisphere and 0.72 for the southern hemisphere. (iii) For these latitude zones where there is no permanent snow/ice cover, the albedo was taken from satellite observations as given by Raschke *et al*[10]. (iv) Solar constant was taken as $1.92\ \mathrm{cal\,cm^{-2}\,min^{-1}}$. (v) Mean latitudinal values of the radiation balance at the ocean surface were taken from Budyko[5].

The calculated and the observed values are shown in figure 3.

In most cases, the difference between the observed and the calculated values does not exceed 1 to 2°.

VARIATIONS IN THE EARTH-ATMOSPHERE HEAT BALANCE

With slight alterations, the same semi-empirical technique of estimating mean temperature conditions can be used to study the variations in climate due to variations in the earth-atmosphere heat balance. The latter variations can arise from changes in solar constant, changes in interception of incoming short wave radiation before it reaches the earth's surface, changes in sea surface temperature, changes in the albedo due to variations in ice cover, vegetation and cloudiness, changes in outgoing long wave radiation due to variation in CO_2, water vapour, cloudiness, etc. This type of work has also been abundantly reported in published literature.

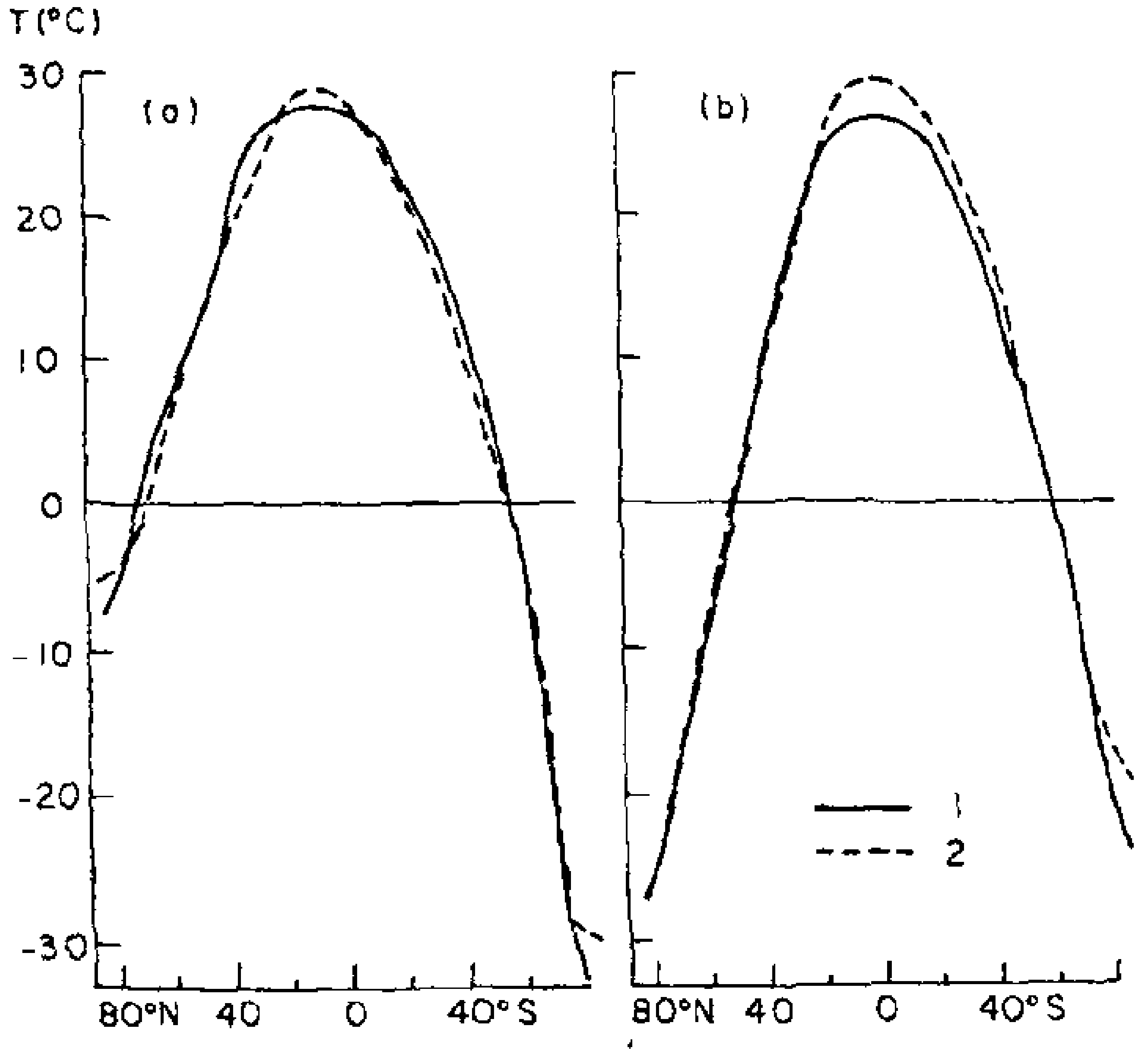

Figure 3. Mean latitudinal temperature distribution for two seasons: (a) the warm half year in the northern hemisphere (b) the cold half year in the northern hemisphere Curve 1: observed data; Curve 2: calculated results

RESPONSE TO HYPOTHETICAL CHANGES IN SOLAR CONSTANT

Using a semi-empirical model of the atmospheric thermal regime, Budyko calculated the dependence of the average latitudinal boundary of Arctic polar ice cover on the solar constant for mean annual conditions. The results are shown in figure 4 where $\Delta Q_{sp}/Q_{sp}$ denotes the relative variation in solar radiation inflow at the top of the atmosphere expressed as a percentage and φ is the average latitudinal boundary of ice cover in the northern hemisphere. Arrows indicate the direction in which we should proceed to interpret the diagram. When we are at point B′ or to the left of it, the southern boundary of the ice cover is at

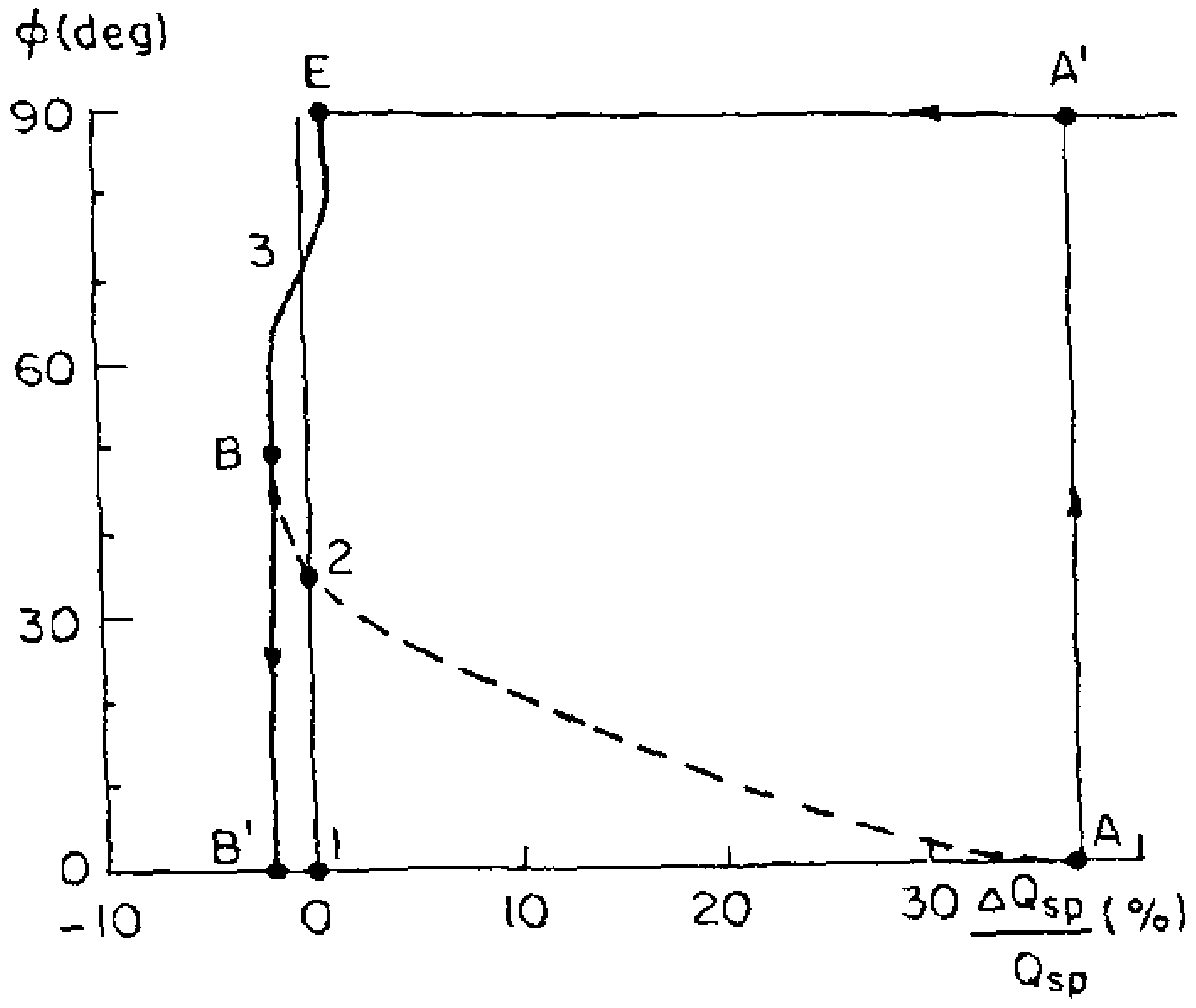

Figure 4. Dependence of the mean latitude of the boundary of polar ice cover on radiation income at the top of the atmosphere.

latitude 0°, *i.e* the whole area from the north pole to the equator is covered with ice. It is the "white earth" situation. The point B′ corresponds to some 2 % smaller value of the solar constant than the present one, the latter being represented by point 1.

As we move from point 1 to point A, the white earth conditions continue *i.e* the whole earth would continue to be covered with ice even if the solar constant were to be higher than the present one by 30–40 %. A slight further increase in the value of the solar constant takes us to point A′, *i.e* a state of "ice-free" earth. In other words, the white earth condition near point A is unstable. Movement from A′ to E shows that ice-free conditions would continue till the solar constant decreases to almost but not exactly to the present value. Further approach of the solar constant to the present value brings us to point 3, *i.e* as the solar constant decreases from its value at *E*, glaciation starts at the pole and spreads equatorwards. Point 3 corresponds to the present-day climate regime. With a further decrease in solar constant, the polar ice sheet would extend to latitude 50° (point B). This glaciation regime at point B is unstable as with a small further reduction in the solar constant, the glaciation would reach the equator (point B′).

The dependence of the polar glaciation on the value of the solar constant has the form of a hysteresis curve with sections AA′ and BB′ representing transition from one solution to another. Other sections of the loop are associated with stable regimes and show the relationship between φ and $\Delta Q_{sp}/Q_{sp}$ for both increasing and decreasing values of solar constant.

We can also interpret the relationship between φ and $\Delta Q_{sp}/Q_{sp}$ represented by the curve AB. This curve shows that increase in $\Delta Q_{sp}/Q_{sp}$ is associated with decrease in φ and vice versa. Budyko believes that this also represents unstable state in which relatively small fluctuations in the solar constant can take the climate regime from a state of white earth to ice-free conditions and vice-versa. Hence, point 2, state corresponding to the present value of the solar constant could exist only temporarily.

As seen from the above, with the present value of the solar constant, three configurations of climate are possible: (a) Corresponding to point 3, the present regime with mean ice cover north of about 70° N; stable regime. (b) Corresponding to point 1, with white earth conditions; stable regime. (c) Corresponding to point 2, with ice cover north of about 35° N; unstable regime.

Various extents of ice cover can also be replaced by mean planetary air temperatures. Relationship between the values of solar constant and the mean planetary air temperature, similar to the one between the value of the solar constant and the polar ice extent, is shown in figure 5.

This relationship is similar in many respects to the corresponding relationship for polar ice boundary and also has the form of a hysterisis loop.

The results shown in figures 4 and 5 quantitatively depend on the adopted values of albedo ($\alpha = 0.32$ for ice-free region, $\alpha = 0.62$ for polar ice region). The model has also been tested for other plausible values of the albedo but the

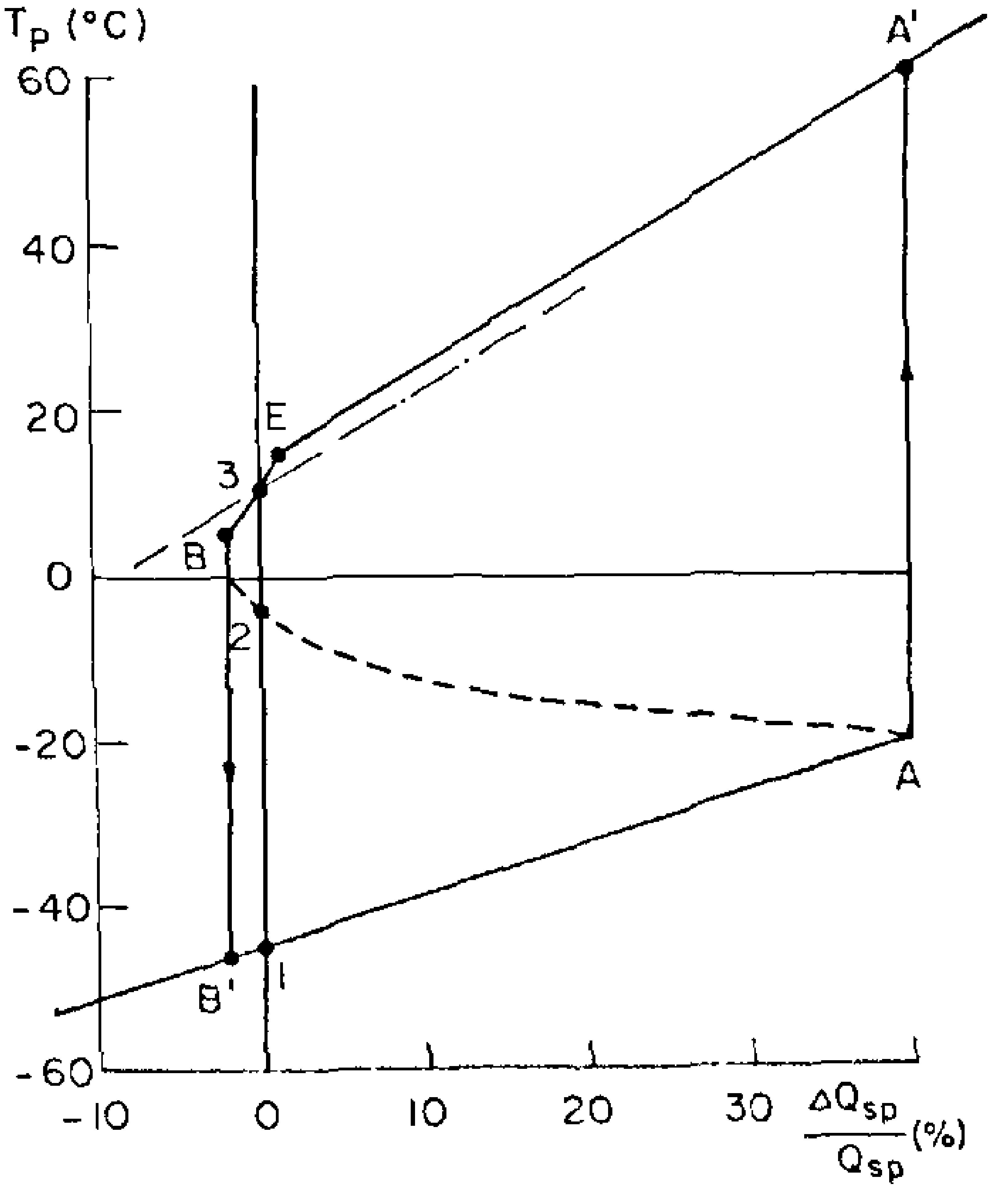

Figure 5. Dependence of the mean planetary temperature T_p on radiation income at the top of the atmosphere.

results remain qualitatively similar to the ones given above.

RESULTS OF OTHER INVESTIGATIONS

Budyko[2] and Sellers[3] are regarded as pioneers in this type of study. After Budyko[1], Sellers[3] was the first who independently constructed another semi-empirical model of the earth's temperature regime based on the energy balance equation of the earth-atmosphere system. In his model, Sellers also included the feedback from polar ice. He estimated the dependence of mean zonal temperatures near the earth's surface on the solar constant, planetary albedo, transparency of the atmosphere to infrared radiation and turbulent exchange coefficients for the atmosphere and the oceans. Sellers used this dependence to estimate the variation in earth's climate resulting from the variation in the polar ice caps, solar constant, infrared transmissivity of the atmosphere and use of stored energy by man. He showed, among other things, that a decrease in the solar constant of less than 5% would be sufficient to start another ice age. A 3% decrease in atmospheric attenuation coefficient for infrared emission to space would put the globe on the brink of an ice age. If the polar ice melts and thus if the albedo of the earth-atmosphere system decreases from 0.62 to 0.32, then the mean annual surface air temperature would rise by 13°C in the polar region and by about 2°C in the tropical region.

Faegre[11] also constructed a semi-empirical model which took into account the feedback between the temperature regime and the polar ice, following essentially Sellers'[3] approach. He found that there are five solutions, corresponding to five climates for the present values of climate parameters like solar constant, albedo of the earth-atmosphere system and diffusion coefficients. One of these five solutions corresponds to the present climate. Another corresponds to ice-covered white earth climate. The third solution lies between the present climate and the white earth climate, with average temperature, 15°C colder than the present climate. The other two solutions were difficult to account for physically and disappeared with slight changes in parametrization of the outgoing infrared radiation. As such, these two solutions were regarded as spurious arising from the inexactness of the original parametrization of the outgoing infrared radiation.

Faegre[11] further studied the stability of the first three physically understandable solutions by giving perturbations amounting to ±1%, ±2% and +4% in the value of the solar constant. He found that, for the present climate, a decrease in solar constant of 2% or an increase of 4% results in instability. The white earth solution is stable for all the perturbations. For the third solution (15°C colder earth than the present one), a decrease in radiation of 2% results in instability.

Schneider and Gal-Chen[12] introduced time-dependency in the heat balance equation in the form

$$m\frac{\partial T}{\partial t} = \{Q(1-\alpha)-I\} + \mathrm{div}.\vec{F} \qquad (14)$$

where m is the coefficient of thermal inertia of the earth-atmosphere system, Q is the solar constant and α is the albedo. $\vec{F}$ denotes the energy flux across a latitude. They concluded that, if the energy input into the tropics is left nearly constant, large changes in the temperature and albedo of the middle and upper latitudes can eventually be ameliorated by the export of sufficient energy from the tropics. They suggested that one possible reason for ice sheets having never proceeded equatorward much below the middle latitudes is that the energy input into the tropics was large to sustain poleward energy fluxes that prevented further equatorward expansion of the ice sheets and in fact eventually led to their recession. If the incoming solar radiation remains at its present value, then the stability of the present thermal regime of the earth-atmosphere system is so great that even if the mean global surface temperature were to decrease to −18°C, the thermal regime of the system would return back to its present state; only with a greater lowering of the mean temperature than this is the complete glaciation of the earth possible.

Held and Suarez[13] used time-dependent version of Budyko's[1,2] model and solved it analytically. They determined the empirical parameters of the models using the results of satellite observations of outgoing long wave radiation. They have confirmed the conclusion that the thermal regime-polar ice area interactions are such as would make boundary of the polar ice cover quite sensitive to the variations in the solar constant. They have also confirmed the existence of "critical latitudes" beyond which the polar ice would expand equatorwards even if the external climate conditions remained unchanged. In the heat balance equation of the earth-atmosphere system, these authors introduced parametrized horizontal heat exchanges due to macroturbulence. This enabled them to obtain a continuous distribution of the mean latitudinal air temperature for an ice distribution concentric with respect to the poles.

Su and Hsieh[14] studied the stability of time-dependent version of the Budyko climate model. While Budyko had used thermodynamical argument to discuss the nature of multiple solutions, these authors used methods of mathematical analysis to study the stability of the different solutions. They confirmed Budyko's conclusions.

Frederiksen[15] made an analytical study of the number, stability and bifurcations of the solutions of time-dependent Budyko-type climate models with various albedo parameterizations. With Budyko's[2] parameterization of the albedo, he found that for the present value of the solar constant, the present climate, white earth solution and also an ice-free earth solution are stable. With Sellers'[3] type albedo, he got the present climate and the white earth solutions as stable ones and also one unstable climate. With Faegre's[11] albedo, he got the present climate as unstable, a stable warmer climate and also a white earth solution. He concluded that latitudinal variations in the albedo may have a profound effect on the number and stability of the solutions.

North *et al*[16] have formulated Budyko-Sellers type climate models from a variational principle. They constructed a functional for the zonally averaged mean annual temperature field such that the extrema of the functional occur when the climate satisfies the usual energy balance equation. Local minima of the functional correspond to stable solutions while saddle points correspond to unstable solutions. This is a relatively new method for investigation of the stability of different types of climatic conditions.

Coakley[17] has emphasised the point that the results of simple semi-empirical models such as those of Budyko[1], Sellers[3] and North[18] do give sufficient indications that decrease in solar constant would take the present climate to white earth conditions, but the extent of reduction required for white earth conditions is rather under disagreement. This disagreement can be expressed in terms of the sensitivity index of a model. This index is generally expressed in terms of decrease in the global mean surface temperature for 1% decrease in the value of the present solar constant. The models of Budyko[1] and Sellers[3] suggest a decrease of 4 to 5°C in the mean surface temperature while GCM's suggest a smaller decrease in the neighbourhood of 2°C. Coakley states that these discrepancies arise out of the different ways in which the parameterization of albedo of the earth-atmosphere system, outgoing long wave radiation and the meridional exchanges of heat energy are studied by different authors. Coakley uses North's[18] constant coefficient diffusion model employing altered radiation parametrization scheme of Cess[19,20] and finds reduced sensitivity of the energy model, coming in the neighbourhood of values given by GCM's.

Robok[21,22] shows that the climate of the earth is more sensitive to the boundary of sea ice over the oceans than to that of snow cover over the land. This is attributed to the double effect which the melting of sea ice produces. Firstly, it reduces the albedo as is done by the melting of the snow. Secondly, in addition, the melting of sea ice increases the thermal inertia of the earth-atmosphere system. As such, its introduction reduces the sensitivity of the climate model to variations in the thermal input from the sun.

Bhattacharya *et al*[23] altered Sellers'[3] scheme of albedo parameterization in terms of zonally averaged surface temperature T. The major change introduced was within the surface temperature range 275° to 285°K. Albedo α was taken to be 0.25 for $T = 275$°K. As T increased from 275 to 280°K, the albedo was taken to increase linearly to a peak value of 0.6 at 280°K. For further increase of T from 280°K to 285°K, α was taken to decrease linearly from 0.6 back to 0.25 at 285°K. The idea behind this parametrization was that near the latitude of ice boundary, there are steep meridional temperature gradients which increase baroclinic activity and hence the generation and movement of extra-tropical cyclones and also increased cloudiness near these latitudes. Albedo increases with cloudiness. Hence albedo attained a peak value near the latitude of maximum cloudiness with surface temperature of 280°K. As stated earlier, the number and stability of the solutions corresponding to a given value of solar constant depends significantly on the scheme of albedo parametrization. In this scheme, Bhattacharya *et al*[23] obtained three stable equilibrium solutions and two unstable equilibrium solutions. The three stable equilibrium solutions had earth's mean surface temperatures 286.6°K (close to present state), 272.9°K and 175.2°K (white earth state). The authors' analysis suggested that the equilibrium state with mean temperature of 272.9°K was the result of special albedo conditions which they had introduced in the surface temperature range 275 to 285°K.

A second major variation in albedo parametrization adopted by Bhattacharya *et al*[23] was to hypothesise a time lag between the earth's surface temperature and the ice cover and hence the planetary albedo. The albedo of that part of the ground which is covered by ice was assumed not to be determined by the temperature at the current time as expressed by many earlier workers but by the temperature of the earlier times up to the current time. The albedo of the ice-free ground was, however, taken to be dependent on the instantaneous temperature near the ground. In other words, advance of the ice is retarded by bringing into consideration the past warmer temperatures affecting the local radiation balance but the retreat of ice immediately permits the establishment of new radiation balance of ice-free region. The build-up of ice sheets is slow but their melting is fast. Time lag between the minimum of surface temperature and the maximum of ice cover was varied from 1,000 to 10,000 years. The solutions with this delayed albedo exhibited quasi-periodic as well as non-periodic behaviour. The spectral analysis of the model's solution in time showed a continuous power background along with discrete peaks superimposed on it. However, in the neighbourhood of the present climate equilibrium state, no oscillations were observed when equilibrium temperatures were equal to or higher than at present. Only for equilibrium temperatures lower than the present one were the oscillations observed. The principal periods of the oscillations were of the order of the lag periods introduced in the albedo parameterization scheme. The results appear to be in accordance with the currently held belief that large climatic oscillations occur during relatively cold epochs rather than during warm epochs. The model also gives some observed long periods which are otherwise unaccounted for by Milankovich process.

VARIATIONS IN CO_2 CONCENTRATION

CO_2 mainly affects the outgoing long wave radiation, this effect now being commonly referred to as the green house effect. This effect has also been parameterized by the energy balance modellers.

Figure 6 shows the expected changes in the

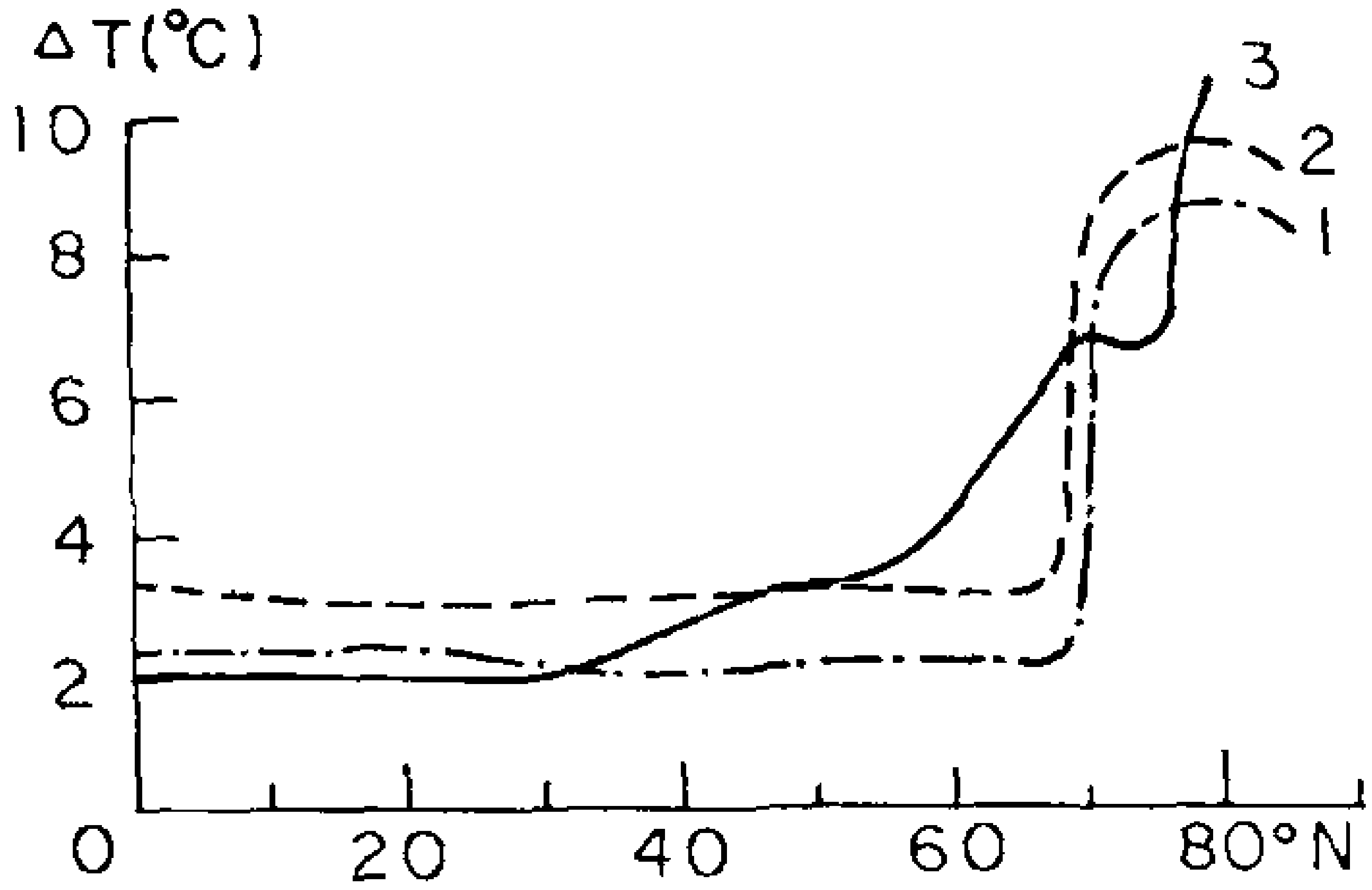

Figure 6. Expected changes in the mean surface air temperature at different latitudes for increase of CO_2 concentration from 0.03 to 0.06%. (Figures 2 to 6 are from Budyko[4].)

mean surface air temperature at different latitudes when the CO_2 concentration is doubled from 0.03 to 0.06%. Curves 1 and 2 are for two different parametrization schemes in the EBM Budyko[20]. Curve 3 is from the GCM of Manabe and Wetherald[21]. Averaged over the northern hemisphere, the temperature increase is 2.5° to 3.5°C by Budyko's energy balance model and 2.9°C by the GCM of Manabe and Wetherald[8]. Subsequently, Manabe and Wetherald[8] found it to be equal to 3°C.

PRESENT POSITION OF EBMs

The present position in respect of the semi-empirical EBMs of climate may be summarised as under:

(i) Budyko[1] and Sellers[3] models have become very popular. Several authors have subsequently studied the climate, using variations of these models employing different parametrization schemes for albedo of the earth-atmosphere system, outgoing long wave terrestrial radiation and meridional exchange of heat. In almost all these models, the climate of the earth-atmosphere system is represented by zonally-averaged surface temperatures for months or years.

(ii) For the extreme simplicity of these models, the results have been surprisingly phenomenal. This accounts for widespread scientific interest in these models.

(iii) Quantitatively, the results have varied between different authors, but qualitatively, the results are similar. It is acknowledged that differences in quantitative values arise from the different ways of parametrization of albedo, outgoing radiation and meridional exchanges employed by different authors.

(iv) One of the outstanding results is that with the present value of the solar constant, three different climates are possible: (a) The present climate. (b) The white earth, *i.e.* total glaciation of the earth from poles to the equator. (c) Climate much colder than the present one but not so cold as to give the white earth.

Climate systems (a) and (b) would be stable but the climate system (c) would be unstable.

A hypothetical way in which the present climate could change to white earth state would be a reduction of the solar constant by a percentage which is given by different authors in the range 2 to 9%. One gets the impression that 2% is on the lower side and 5 to 9% is a more acceptable range.

(v) Parameterization schemes are being improved. In particular, parameterization of radiation is being improved using satellite observations of outgoing long wave radiation, ice/snow cover, cloud amounts and heights, state of vegetation on earth's surface, consideration of more than one level for energy balance, etc.

Energy balance models are becoming useful to study past and future climates of the earth without too much of computer time.

9 March 1984

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NEWS

THE BEAUTY OF SOUNDS

. . . "Are all sounds equally beautiful? Can a sound be beautiful in itself, or does it require a context? And waht are the prevailing standards for beauty? Despite the lack of consensus, it seems evident that the nineteenth century concept of tonal beauty (a smooth, opulent, vibrant, intensely rich tone) has lost some of its force. And, in its place, we hear a shift in the direction of leaner, straighter, edger, more sharply impacted sounds, which I take to be closer to the tonal values of Baroque music as well as a predictable reaction against the tonal preferences of the last century. But, at the same time one must concede that certain genres (notably opera) have proved resistant to these trends, and that large segments of musical society hold the tonal values of Romanticism as tenaciously as ever. We can legitimately inquire what grounds for preference we may apply to the profusion of electronic and environmental sounds in recent music, other than (as always) our instincts and experience. To dismiss the question with 'each in its own way' seems an evasion. I suggest that a new set of tonal values is gradually coalescing amidst what appears to be the chaos of seemingly endless variety. These values may never be proclaimed by consensus, but they are now being demonstrated, and (perhaps) we will recognise them for what they are" (Reproduced with permission from *Press Digest, Current Contents*® No. 22, May 28, 1984. Copyright by the Institute for Scientific Information®, Philadelphia, PA, USA).

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