MODEL SIMULATIONS OF THE EARTH'S MEAN ANNUAL CLIMATE

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Abstract

This paper reviews the physical background of Energy Balance Climatic Models and evaluates the use of Sellers' and North's model in simulating the present climate. The sensitivity of the models - with updated empirical constants - is tested for use in the ice-age problem. In this connection the seasonal model of North and Coakley was extended to include a more realistic continent-ocean distribution. A simulation of the temperature field with a full size Northern-Hemisphere continental ice sheet proved to be in fair agreement with paleoclimatic proxy data.

INTRODUCTION

During the last decade substantial progress has been made in understanding the fundamental mechanisms of climate and climatic change using quantitative models. There exists today a wide hierarchy of climate models such that basic problems in climatology need no longer be treated in a qualitative and phenomenological way. The simplest models, containing only a few degrees of freedom, are the so called energy balance models (EBM's). They became popular since the pioneering studies of BUDYKO (1969) and SELLERS (1969).

The question emerged to what extent the models of BUDYKO and SELLERS are equivalent and to what extent pre-satellite data influenced the extreme sensitivity initially encountered. In this article models of both types will be tested using updated data based on satellite measurements. Attention will also be given to the general theory of EBM's and their suitability and applicability in the research on the origin of Ice Ages.

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This study is based on DUMMEL and VOLKERT (1978) for the SELLERS model and on NORTH (1975) for an EBM which is essentially of the BUDYKO-type but differs by its mathematical approach. It will be denoted further as the NORTH-model. A detailed description of the models and the numerical techniques involved can be found in HUYBRECHTS (1984).

2. PHYSICAL BASIS OF EBM'S

EMB's find their physical ground in the thermodynamical law on the conservation of energy. This principle leads to a description of the main characteristics of the climatic system by an energy balance that consists of a radiation balance (the net vertical energy exchange) and a heat balance which describes the heat transport along the earth's surface.

Fig. 1 shows a vertical column of the earth-atmoshpere system and a simplified representation of the components of its energy balance. The bottom of the column is defined as the surface where vertical energy gradients become negligible.

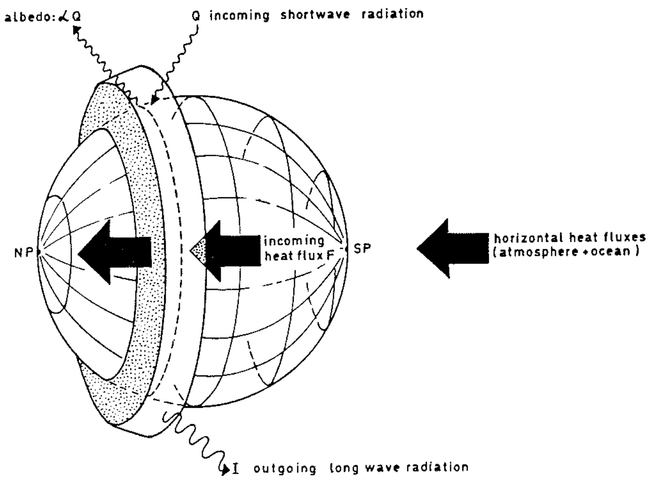


fig. 1. *Energy Balance*

Of the incident shortwave solar radiation an amount $Q(1-\alpha)$ is absorbed by the atmosphere and the earth's surface, Q being the insolation at the top of the atmosphere and the planetary albedo. I is the longwave radiation emitted to space and is the net result of infrared radiation and absorption in the considered column. On a mean annual basis the radiation balance will be positive at lower latitudes and negative at higher latitudes. This geographical imbalance of the radiation budget is the driving force of the global weather machine and its associated wind and ocean circulation systems. As a consequence energy on the globe is redistributed resulting in a net poleward heat flux. This heat flux consists of a flux of latent heat and a flux of sensible heat of both the atmosphere and the ocean. As shown in fig. 1, the local radiation balance should, in case of equilibirium, equal the difference between the incoming and outgoing total heat fluxes. On a global scale however, dynamical heat fluxes will disappear in the energy balance.

A simple one-dimensional (i.e. zonally averaged) and vertically integrated (i.e. describing a vertical mean state) EBM can then be formulated on a latitude circle by the following time-dependant equation:

$$C \frac{\partial T}{\partial t} = Q(1-\alpha) - I + div(F) \qquad (1)$$

The left side represents the temperature change in case of an unbalanced energy budget. T is the temperature, t the time and C represents the heat capacity of the system. Q equals 1/4 of the solar constant, since the area of interception of the solar beam is one quarter of the total area of the earth a value of 1360 W/m^2 is currently accepted for the solar constant and will also be used in the model simulations. The divergence term expresses the difference between the incoming and outgoing atmospheric and oceanic heat fluxes F.

If all terms in (1) are expressed in terms of the single variable T, the sea-level temperature can be found by solving the energy balance equation for a given Q. This approach, essential in EBM's, implies that the mean vertical temperature profile is similar at all latitudes (BARRY, 1979). It also requires the parameterisation of all climatic variables in terms of the sea-level temperature.

3. MODEL DESCRIPTIONS

In this section only a brief outline will be given of the basic assumptions and parameterisations employed in the tested models. Both models describe a mean annual climate assuming a steady state which excludes any form of heat storage or loss in the system. In terms of eq. 1 this implies that the left side is made equal to zero. Boundary conditions are set such that meridional heat transport is not possible across the poles (SELLERS and NORTH model) and across the equator (NORTH-model). The NORTH-model is also symmetric with respect to the equator.

3.1. *Net infrared radiation*

According to Stefan-Boltzman's law the infrared radiation is proportional to the fourth power of temperature. This holds for the surface of the earth which can be regarded as a black body. In spite of the complex character of atmospheric emissivity BUDYKO (1969) found that the infrared radiation of the earth-atmosphere system, ultimately emitted to space, could be approximated by a linear function of sea-level temperature T:

$$I = A + B\,T \qquad (2)$$

Where A and B are empirical constants that can be derived from a least squares analysis.

SELLERS (1969) used a more complex expression of the form:

$$I = \varepsilon(T)\ \sigma T^4 \qquad (3)$$

where σ is Stefan-Boltzman's constant, $\varepsilon(T)$ represents the effective emissivity of the atmosphere. However it was shown by NORTH (1975) that eq. (3) behaved like a linear function in the case of sea-level temperatures. As a consequence, eq. (2) and eq. (3) are essentially describing the net infrared cooling in a similar way.

3.2. *Albedo*

NORTH (1975) considers an absorption function:

$$a(x,x_s) = 1 - \alpha(x,x_s)$$

in which α is the planetary albedo

$$a(x,x_s) = \begin{cases} b_0 & x \geq x_s \\ a_0 + a_2 P_2(x) & x < x_s \end{cases} \qquad (4)$$

where x = sine (latitude), x_s = sine (latitude of the ice edge), P_2 (x) the second Legendre polynomial. The ice-line is defined as the mean annual isotherm of -10°C. The empirical constants a_0, a_2 and b_0 can be found from a Legendre analysis of the albedo distribution. BUDYKO (1969) initially proposed a step function related to the ice boundary, thus by setting $a_2 = 0$ in eq. (4).

SELLERS (1969) used a more complex parameterisation in terms of the real surface temperature T_s:

$$\alpha = \begin{cases} b - 0.009\, T_s & T_s < 283.16K \\ b - 2.548 & T_s \geq 283.16K \end{cases} \qquad (5)$$

where b is a latitude dependant empirical constant. Linking the albedo to temperature, an essential feature in these models, allows the models to account for the albedo-temperature feedback. Albedo's in the SELLERS-model become temperature dependant for a surface temperature < 10°C, which must be interpreted as a boundary value for seasonal snow cover. North however chooses the -10°C mean annual isotherm as a rupture between an ice cap albedo = 1 - b_0 and albedo's that are insensitive to temperature (eq. 4) but dependant on latitude (or geography).

3.3. *Horizontal heat transport*

NORTH models the meridional heat transport as a thermal diffusion, stating that the total heat flux is proportional to the local temperature gradient:

$$\mathrm{div}(F) = -\nabla.(D\nabla T) = -\frac{d}{dx}(1-x^2)D\frac{dT(x)}{dx} \qquad (6)$$

where D is a phenomenological thermal diffusion coefficient. The factor $(1-x^2)$ results from a transformation in spherical coordinates, x being the sine of latitude. Of course, the net meridional heat transport results from a complex circulation pattern, involving the Hadley cell, mid-latitude eddies, ocean currents etc. ... However it was shown by several authors that the individual circulation systems need not necessarily be computed explicitly but that a general diffusive transport mechanism might well be suited for modelling purposes (e.g. GAL - CHEN and SCHNEIDER, 1976). Nevertheless there exists currently some doubt about the validity of the diffusive transport parameterisation in the Tropics where temperature gradients are small.

SELLERS on the other hand chooses to compute the components of the heat transport explicitly. He accounts for an atmospheric and oceanic flux of latent heat, with contribution of a mean meridional motion and large-scale eddies. This rather cumbersome approach gives rise to the existence of 119 latitude dependant empirical constants.

3.4. *Solving methods*

Both models differ fundamentally in the mathematical techniques used to solve the energy balance equation (1).

In the SELLERS-model the globe is divided in 18 latitude belts bounded by 19 latitude circles and the solution is obtained iteratively. Starting from the north pole, where the temperature is specified, the radiation balance in each latitude belt is matched out by the heat fluxes across its southern latitude circle in terms of the single unknown ΔT, i.e. the sea level temperature difference between two adjacent latitude belts. The temperature at the north pole is then adjusted in function of the calculated heat flux at the south pole and this is carried out iteratively until the heat flux at the south pole becomes negligible small.

In the NORTH-model the temperature is represented as a two-term Legendre-series

$$T(x) = T_0 + T_2P_2(x)$$

After substitution in the energy balance equation and making use of the orthogonality of the Legendre-polynomials eq. (1) is solved for the coefficients T_0 and T_2. This analytical approach allows to simulate the global temperature by a continuous function of x. This distribution is however confined to the general form of the Legendre-expansion.

4. SIMULATION OF THE PRESENT MEAN ANNUAL CLIMATE

Both models were programmed on CDC-computer using updated input data (for details see HUYBRECHTS, 1984). Empirical constants for the infrared, albedo and transport parameterisations were obtained by tuning the respective equations to the reference climate data presented as 10°-latitude belt mean annual and zonally averaged values in CESS (1976) and VAN DEN DOOL (1980). The values for the albedo and net infrared radiation were originally compiled from Nimbus 3 and NOAA measurements by ELLIS and VON DER HAAR (1976). Mean annual and zonally averaged surface temperatures were taken from CRUTCHER and MESERVE (1970) for the Northern Hemisphere and from TALJAARD (1969) for the Southern Hemisphere. These temperatures were reduced to sea level using a mean lapse rate $\gamma = 0.0065 \ K\,m^{-1}$ and zonally averaged altitudes as given by SELLERS (1969). Insolation components were computed for the 1950.0 orbit using a solar constant $S = 1360\ W/m^2$ with the method as outlined by BERGER (1978): fig. 2. Derived quantities are the radiation balance ($=Q(1-\alpha)-I$) and the effective emissivity ($\varepsilon=I/\sigma T^4$).
Figs. 3 - 8 show the mean annual and zonally averaged reference

climate (bottom) and the model simulations with the SELLERS-model (top) and the NORTH-model (center). The accuracies of the computed model-climates is indicated by the weighted rms-errors with respect to the reference climate (table 1).

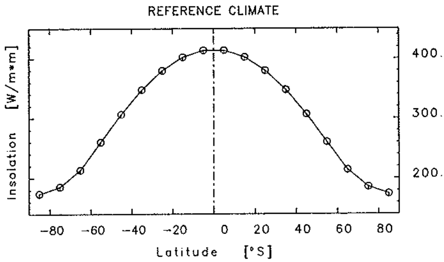
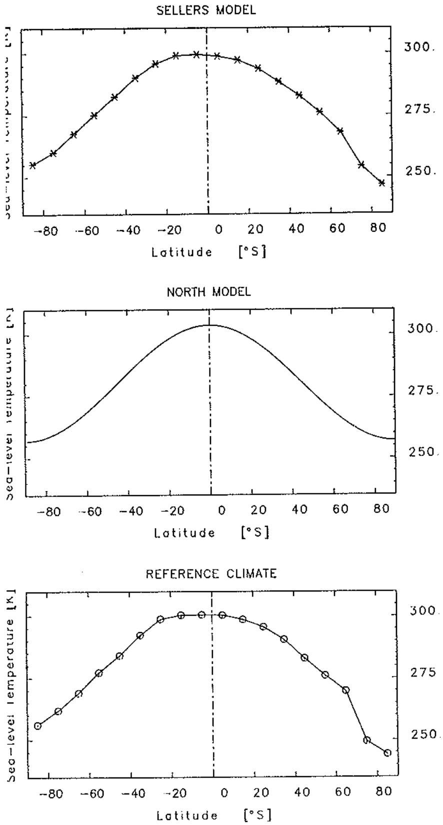


fig. 2. *Insolation at top of the atmosphere (calculated)*

A conspicuous feature of the global temperature profile is the interhemispheric asymmetry which is especially marked by the large temperature gradient between 65°S and 75°S caused by the presence of an ice-covered Antarctic continent (fig. 3). From an energetic point of view this is explained by the high snow and ice albedo by which less solar energy can be transformed into heat. Another phenomenon, typical for the Antarctic, are the cold air masses flowing down the huge ice cap (katabatic winds) influencing also the climate in the surrounding seas. Note that, fig. 3 shows sea-level temperatures, the surface temperatures on the ice sheet itself are about 15 K lower. The SELLERS-model manages to simulate these zonal temperatures best with a rms-error of 1.95 K which corresponds to a relative error of only 0.6%. The NORTH-model is obviously limited by the form of the Legendre polynomials and the forced interhemispheric symmetry: temperature is too high in the tropics and polar areas and too low at midlatitudes. The model also fails to simulate the extreme low temperature at the south pole and this explains to a large extent the rather important rms-error (table 1).

table 1: *Weighted rms-errors*

	Sellers-model	North-model
Temperature [K]	1.95	3.57
albedo	0.0034	0.00267
IR radiation [Wm^{-2}]	7.56	8.48



g.3. *Simulated temperature (top and central) and reference climate (bottom)*

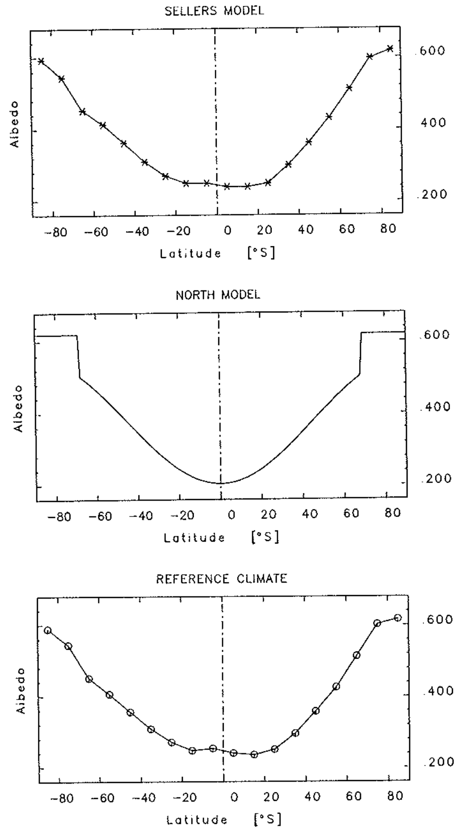


fig.4. *Simulated albedo (top and central) and reference climate (bottom)*

Planetary albedo's are simulated very well in the SELLERS-model (fig. 4) because of the proper choice of the empirical constants b in eq. 5. Large albedo's at high latitudes result from the excessive snow and ice cover. This albedo-relation produces the so called albedo-temperature positive feedback : by lowering the temperature the albedo is increased which in turn will lower the temperature further. This snow-ball effect will however die out after a certain time because in the end infrared emission will also decrease and this establishes a new balance between the energy fluxes. The albedo parameterisation of NORTH gives rise to a discontinuous albedojump along the ice line. In reality however albedo's at the ice edge will be smoothed because of the seasonal waxing and waning of the ice and snow cover. This phenomenon is less conspicuous in the Antarctic where the reference climate shows an albedo-discontinuity.

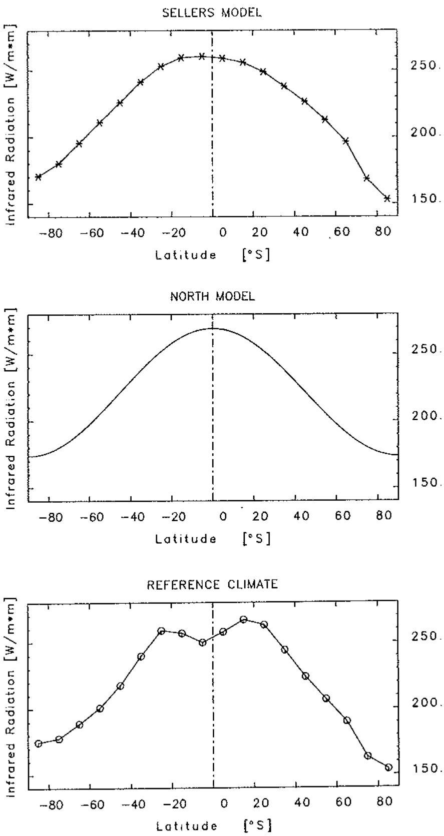


fig.5. *Simulated infrared radiation (top and central) and reference climate (bottom)*

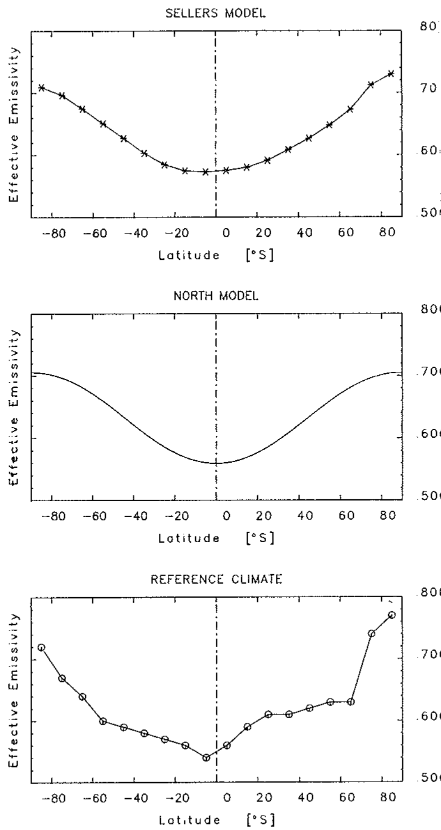


fig.6. *Simulated effective emissivity (t and central) and reference clim (bottom)*

Note the slightly higher albedo in the tropical part of the Northern Hemisphere which might be explained by the cloud cover associated with the monsoons.

Infrared-emission is highest in the subtropics with a maximum in the latitude belt 10°-20° S (fig. 5).
In spite of the higher temperatures in the equatorial zone, IR-emission is almost 20 Wm^{-2} lower, because an important fraction is absorbed in the cloud cover, generally absent in the subtropical high pressure zones. The difference here between the Northern and Southern Hemisphere might also be due to the monsoon effect.. Because of the linear relationship between temperature and net infra-red cooling (eq. 2) none of the models simulates this specific feature. The IR-parameterisation could be ameliorated by adding a term that accounts explicitly for the cloud cover.

The effective emissivity or atmospheric transmission factor (fig. 6) is a derived quantity of the reference climate and defined as the ratio of the infrared radiation over the potential infrared emission (σT^4). It is low in the equatorial zone due to absorption by clouds, CO_2 and dust. At the south pole almost $4/5^{th}$ of the terrestrial radiation is transmitted by a dustfree atmosphere. The models reflect essentially the same situation.

The radiation balance shows a surplus roughly between 35°N and 35°S and a deficit at higher latitudes (fig. 7). This is because, on a mean annual basis, the outgoing IR-flux decreases less rapidly towards the pole than the incoming energy flux. This causes the main climatic zoning on the globe and induces the poleward energy transport. The heat sink of the Southern Hemisphere is not situated at the pole itself but in the surrounding latitude belt 70-80°S. This can be explained by the extreme low temperatures governing in the quasi-permanent inversion layer on the high and central ice cap. Note that the weighted radiation balance for the entire earth-atmosphere system is set equal to zero for mean annual conditions (a steady state was put forward).

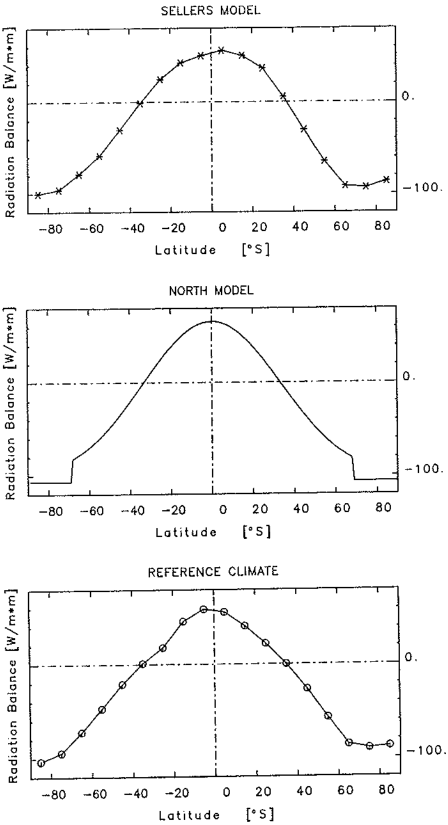


fig. 7. *Simulated radiation balance (top and central) and reference climate (bottom)*

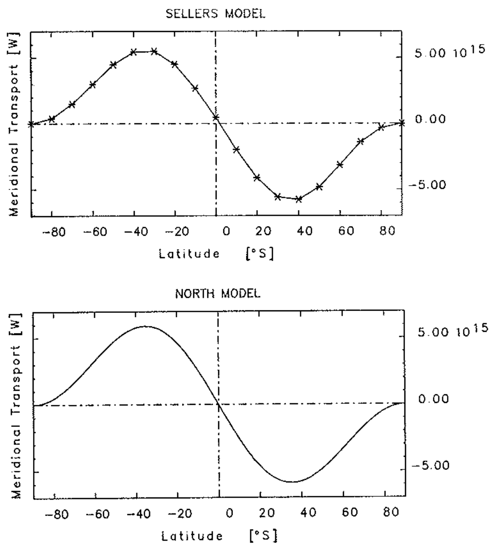


fig. 8. *Simulated meridional heat transport*

Fig. 8 shows a maximum poleward heat transport around 40° latitude of about 5.6 10^{15} W corresponding to the belt of zonal westerlies. In the NORTH-model both hemispheres form separate and closed energy systems whereas the SELLERS-model indicates an energy transport across the equator from the southern to the northern hemisphere. Nevertheless both models are remarkably similar implying that the rather tedious and cumbersóme calculations of the individual heat fluxes in the SELLERS-model can be adequately replaced by a diffusive transportmechanism with only one empirical constant (NORTH).

However one must admit that the SELLERS-model specifies the present annual and zonally climate best. This is not surprising in view of the tuning possibilities of the model and the multitude of available empirical constants. Obviously the NORTH-model is limited by the a-priori reproduction of climate-variables in a Legendre expansion but the model finds its strength in its simplicity and transparency. Although both models give only a rough picture of the world climate one should not overlook the fact that these models were developed in the first place to test different hypotheses such as global stability and that the simulation experiments also served a validation purpose.

5. APPLICATION OF THE MODELS: THE ICE AGE PROBLEM

As stated above quantitative models provide a tool for testing hypotheses. In particular attention has been paid to the several feedback mechanisms, present in the climate system, and their mutual strength as well as their possible importance in enhancing climatic sensitivity. Simple EBM's of the type studied here, however, contain only a few degrees of freedom. An obvious test of climate sensitivity is an experiment in which the solar constant is changed. In this way the effect of atmospheric contamination, for instance by a volcanic dust cloud, or what comes to the same, a lowering of the luminosity of the sun, can be investigated. The fundamental sensitivity parameter ß can be expressed as follows:

$$\beta = \frac{Q}{100} \frac{dT}{dQ} \qquad (7)$$

It is the temperature drop that results from a lowering of the solar constant with 1%. Our experiments indicate a substantial diminishing (ß=1.4 for both models) of the extreme sensitivity (SELLERS, 1969: ß = 3.18; NORTH, 1975: ß = 4.33) encountered in the early model versions. This must, in the first place be attributed to the differences in the albedo parameterisation but also to a different value of B in eq. (2) as was shown analytically by COAKLEY (1979).

Typical ice-age conditions (ice-boundary near 60° latitude) correspond with a solar constant drop of about 5%. According to both models the mean annual global temperature would then be lowered by 8 K whereas the meridional temperature gradient remains the same. It is assumed in these experiments that empirical constants, determined under present conditions, remain the same when changing the solar constant. This is of course questionable. Indeed, the experiments also point out that multiplying the diffusion coefficient by a factor 0.5 (as a result of a reduced ability of the atmosphere and oceans to transport heat polewards) produces an equator-pole temperature gradient more in accordance with paleoclimatic proxy data.

Another feature that received considerable attention was the stability of the models and maybe of the real climate itself (e.g. SCHNEIDER and GAL-CHEN, 1973; GHIL, 1976; DUMMEL and VOLKERT, 1980). This question achieved interest since the early pre-satellite versions of the models indicated that a reduction of the solar constant with only 2% would lead to a completely ice-covered earth and this through the temperature-albedo amplification mechanism. Fixing the external conditions the models in this study give rise to 3 steady-state solutions as shown in table 2.

table 2: *steady-state solutions of fixed external conditions*

Mean annual global temperature	Sellers-model	North-model
$\overline{T}1$	287.4K	288.1K
$\overline{T}2$	255.0K	252.3K
$\overline{T}3$	235.1K	235.0K

A first and stable steady-state solution ($\overline{T}$ 1) corresponds with the present interglacial climate. A stable solution means here that small perturbations in the temperature field will be restored in time. It can be shown that the second solution $\overline{T}$ 2 (glacial mode) is unstable while the third stable solution corresponds with a completely ice-covered earth. The number of solutions turns out to be quite sensitive to changes in the solar constant. However, our experiments with updated constants for albedo and infrared radiation

showed substantially increased climate stability with respect to the early versions. A 5% (SELLERS-model) and even 14% (NORTH-model) drop in the solar constant is now necessary for an irreversible shift from the present model-climate to a completely ice-covered earth. This corroborates recent EBM-studies by OERLEMANS and VAN DEN DOOL (1978), COAKLEY (1979) and others.
It must be pointed out here that experimenting with a changing solar constant is seldom of more than theoretical interest. A decrease of the solar constant of the order of 5% is not supported by any observations, not more than the completely ice-covered earth, a state that to our knowledge never occured in the history of the earth's climate.

Milankovitch's astronomical theory of the Ice Ages, which postulates that perturbations in parameters of the orbit of the earth around the sun cause changes in the latitudinal and seasonal distribution of the incident solar radiation, is now thought to be the pacemaker of the Pleistocene cycle of Ice Ages (HAYS at al., 1976). Evidently, to test the Milankovitch hypothesis, the mean annual models have to be extended to include a seasonal cycle. Such a model has been developed by NORTH and COAKLEY (1979) using similar analytic procedures as in NORTH (1975). Their model was extended to include a more realistic continent-ocean distribution and a numerical solving technique (HUYBRECHTS, 1984). However, the response of the temperature field to orbital perturbations turned out, once more, to be very small and insignificant with respect to the observations. Because of the discrepancies between the observations and the model predictions it must be concluded that feedback-mechanisms, other than the albedo-temperature relation, must be present in the climatic system and are able to enforce the imposed solar insolation variations. The missing sensitivity might very well be due to mechanisms present in the ice sheet itself, as was shown by POLLARD et al. (1980) and more recently by WATTS and HAYDER (1983) with EBM's containing a crude ice sheet model. This view is also supported by model studies that concentrate on the height-mass balance feedback of the ice sheet and the effect of crustal downwarping and rebound due to the changing iceload (OERLEMANS, 1980; POLLARD, 1983).

Although seasonal EMB's of the present type fail to produce ice sheet sizes as they occurred during the Pleistocene, they provide an excellent tool to study the effect of large continental ice caps on the energy balance of the earth. Fig. 9 shows the response of the temperature field in an experiment in which a full-size Northern-hemisphere continental ice sheet (extending to 50°N) and a sea-ice cover (up to 60°S and 60°N) are introduced in the seasonal energy balance equation (HUYBRECHTS, 1984).
The figure makes clear how the temperature field is mainly affected in the summer of the Northern Hemisphere because the energy needed to bring the summer warmth is lost due to reflection by the snow and ice cover.

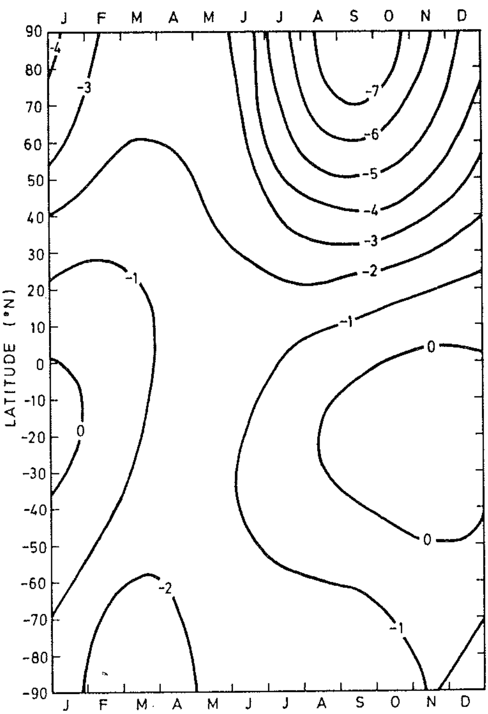


fig. 9.
Temperature deviation over the globe due to the effect of a full-size Northern-Hemisphere continental ice- sheet.

On the other hand, the decrease in temperature in the Tropics and the Southern Hemisphere remains modest. These results are in fair agreement with paleoclimatic proxy data (PETERSON et al., 1979; GATES, 1976) although the latter show a larger amplitude. Within the confines of the model it can be concluded here that the increased reflectivity of the earth during the glaciation maximum must be held responsible for a significant part of the temperature anomalies.

6. CONCLUSION

In the past it has been argued whether it is meaningful to describe a phenomenon as complex as the earth's climate with a "simple" computer model. In view of the encouraging results obtained with the SELLERS' and the NORTH model this question has now to be answered in the affirmative. It was indeed shown that the global temperature field could be estimated by a simple energy balance containing only four terms including empirical formulations for the infrared radiation, planetary albedo and meridional heat transport. Both models were indeed shown to simulate the broad aspects of the present climate very well. Tuned to the same reference climate they basically reflect a similar sensitivity and show with respect to pre-satellite model versions an enhanced stability. In the sensitivity experiments however, the numerical results should not be taken too literally in view of the model assumptions and the crudeness of the parameterisations. In this respect they must rather be regarded as a useful tool for testing climatological hypotheses and for teaching purposes where they can provide insight in the interacting mechanisms governing the climatic system. It should be added that a lot is to be expected from similar modelling in other fields of physical geography using theoretical formulations based on sound physical principles. The response of EBM's of the present type to insolations variations, considered as a link between external and internal factors in Milankovitch's theory of climatic variations, constitutes a weakness in this classical type of climatic model and is calling for further research. Adding realistic geography in connection with the precipitation cycle and ablation mechanisms might lead to significant improvements along this line in the near future.

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