EXPERIMENTS AIMING AT MONTHLY AND SEASONAL NUMERICAL WEATHER PREDICTION[1]

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ABSTRACT

The author's thermal model for monthly and seasonal numerical prediction of temperatures is generalized, so that besides radiation other forms of heating (or the anomalies of heating) are generated within the model. This is done by expressing such heating as a linear function of variables predicted in the model.

The anomalies directly incorporated are those in the storages of thermal energy which are introduced by prescribing in the previous interval the temperature of the surface water in the oceans and the temperature of the midtroposphere, as well as the anomalies in the short-wave radiation absorbed by the surface; which in turn are introduced by prescribing the albedo (snow cover) at the end of the previous interval.

The numerical experiments show that important anomalies of the evaporation at the surface, of the vertical turbulent transport of sensible heat from the surface, of the condensation of water vapor in the clouds, and of the cloudiness are introduced by the anomalies of the computed temperature fields. Furthermore, these induced anomalies of the heating functions and of the cloudiness in turn introduce changes in the anomalies of the temperature fields.

1. INTRODUCTION

In recent years the author has been engaged in attempting to formulate a numerical prediction model for periods of a month or a season. The basic equations used are those of conservation of thermal energy at the surface of the earth and in the mid-troposphere. The model predicts the anomalies of temperature at the underlying surface and in the mid-troposphere.

In the oceans, where there exists a great storage of energy, the temperature of the surface waters in the previous interval is prescribed. This introduces anomalies in the storage of energy that are due to the anomalies of the radiation balance, the evaporation, the vertical transport of sensible heat, and the transport by ocean currents.

In the surface layer of continents the storage of energy is small, therefore as a first approximation the excess of radiation at the surface is equated to the energy lost by evaporation and by vertical transport of sensible heat. Since we neglect the storage of energy, a small anomaly in these heating components will introduce large anomalies in the temperature field, as shown in [3].

Since the continents have no storage of thermal energy, we can not prescribe the temperature of the previous month as input data. However, we can use another abnormality of the underlying surface that will introduce anomalies in the heat budget of the troposphere-surface of the earth system. For this purpose we introduce the albedo of the surface of the earth, defined as the percentage of short-wave radiation reaching the surface which is not absorbed by the surface. The albedo depends on the character of the underlying surface.

Extensive synoptic research by Namias [6] suggests that energy feed-back between the atmosphere and earth's surface, especially when the thermal state of the surface is very abnormal, is important in influencing large-scale (in both space and time) circulation patterns. Therefore, the troposphere is coupled with the layer below the surface of the earth so that we have to deal with the whole system and predict the anomalies of the temperature fields and of the heating functions, as well as of the albedo and other factors that introduce anomalies of the heat budget.

The energy that feeds the system is the solar radiation, which is a function of latitude and season. This incoming short-wave radiation is distributed in the system so that part is absorbed by the surface of the earth, part by the cloudless troposphere, and part by the cloud cover.

The short-wave radiation absorbed by the surface is a function of the albedo. Therefore, anomalies in the albedo introduce anomalies in the absorption of this energy by the surface. The most important factor that produces changes of the albedo is the extent of the snow cover. Even when the anomaly of snow cover is of small extent, it is very important because being located during winter over the more heavily populated parts of the continents (e.g. the United States and Europe), it can play a very important role in contributing to the creation of severe winters in these areas.

The troposphere is heated by the excess of long and short-wave radiation, by the energy released in the clouds by condensation of water vapor, and by vertical turbulent

[1] This work was carried out in the Extended Forecast Division, National Meteorological Center, U.S. Weather Bureau, where the author is a consultant.

transport of sensible heat. Furthermore there is a turbulent horizontal transport due mainly to the migratory cyclones and anticyclones of the middle latitudes. Finally there is a transport by direct advection by the horizontal wind, which so far has been neglected in these experiments.

The cloud cover immersed in the troposphere plays a very important role in the heat budget. It will be considered to absorb or emit long-wave radiation as a black body, as is true of the earth's surface. As described in [1] in this first approximation theory the cloudless atmosphere will also be considered as a black body for long-wave radiation, except in the region from 8 to 13 microns where a transparent window will be postulated, through which energy can go directly from the surface of the earth and of the clouds to outer space, and from the clouds to the surface and vice versa. Because of this, an anomaly of the cloud cover affects profoundly the thermal field, especially the surface temperature.

In a recent paper [2] the author introduced a preliminary model attempting to formulate mathematically the ideas described above. In the model developed there, the only heating that is generated is that due to radiation. For the other heat sources the normal values for the given period (month or season) are prescribed.

The purpose of this paper is to generalize the author's model so that, besides radiation, other forms of heating (or the anomalies of heating) are generated within the model. For this purpose we shall express the energy lost at the surface by evaporation and by vertical turbulent transport of sensible heat and the heat gained by condensation of water vapor in the clouds as empirical functions of variables predicted in the model. Furthermore the anomalies of the cloudiness will be introduced as a linear function of the anomalies of the heat of condensation.

As neating functions we will use the available empirical functions suitable for the model. However it is clear that the model can be improved by using more realistic empirical heating functions. We are aware of the low degree of accuracy of some of the empirical functions used, but we have used them in order to set up the model in a concrete way, hoping to improve it when better heating functions are available.

2. NOTATION

We shall use the previous notation [2], that for the sake of clarity is given in this section:

H Height of the upper radiating boundary.

$H'=H-H_0$ where H_0 is constant and $H'<<H_0$.

Δt Time interval (one month or a season).

T_m Mean temperature in the troposphere (or temperature at a height equal to $H/2$) in the Δt time interval.

$(T_m)_i$ Mean temperature in the troposphere in the previous time interval.

$T'_m=T_m-T_{m_0}$, where T_{m_0} is a constant and $T'_m<<T_{m_0}$.

$(T'_m)_i=(T_m)_i-T_{m_0}$ where $(T'_m)_i<<T_{m_0}$.

T_s Mean temperature at the surface of the earth, in the Δt time interval.

$(T_s)_i$ Mean temperature at the surface of the earth, in the previous time interval.

$T'_s=T_s-T_{s_0}$ where T_{s_0} is a constant and $T'_s<<T_{s_0}$.

$(T'_s)_i=(T_s)_i-T_{s_0}$ where $(T'_s)_i<<T_{s_0}$.

T_c Temperature in the cloud layer.

$T'_c=T_c-T_{c_0}$ where T_{c_0} is constant and $T'_c<<T_{c_0}$.

E_A Excess of radiation in the troposphere (excluding the cloud layer).

E_c Excess of radiation in the cloud layer.

E_s Excess of radiation in the surface of the earth.

G_2 Sensible heat given off from the surface of the earth to the troposphere by turbulent vertical conduction.

G_3 Heat energy lost from the surface of the earth by evaporation.

G_5 Heat given off to the troposphere by condensation of water vapor in the clouds.

K Austausch coefficient.

I Insolation on a horizontal surface at the top of the atmosphere.

ϵ Fractional cloud amount.

a_2 Fractional absorption of insolation by the water vapor and dust in the troposphere.

ϵb_3 Fractional absorption of insolation by clouds.

α Albedo of the surface of the earth.

$M=2/(1+\sin\varphi)$ map scale factor in a polar stereographic projection, where φ is the latitude.

∇_M^2 Two-dimensional Laplace operator in the map coordinates.

$(Q+q)_0$ Short-wave radiation received by the surface with clear sky.

3. OUTLINE OF THE GENERAL FORMULATION OF THE MODEL

The model presented in [2] consists of the following set of equations:

$$\frac{\gamma_3}{\Delta t}[T'_m-(T'_m)_i]-\gamma_3 KM^2\nabla_M^2 T'_m=E_A+E_c+G_2+G_5 \quad (1)$$

$$d_s[T'_s-(T'_s)_i]=E_s-G_3-G_2 \quad (2)$$

$$E_A=A''_2T'_m+A_3T'_s+a_2I+A_6 \quad (3)$$

$$E_s=B''_2T'_m+B_3T'_s+B_6+\epsilon B_7+[1-\epsilon(1-k)](1-\alpha)(Q+q)_0 \quad (4)$$

$$E_c=\epsilon(D_3T'_s+D'_6+b_3I) \quad (5)$$

Where k is an empirical function of latitude given in [2], γ_3, A''_2, A_3, A_6, B''_2, B_3, B_6, B_7, D_3, D'_6 are constants defined in [1] and [2]; and d_s is equal to zero in the continents and equal to $\rho_s c_s h/2\Delta t$ in the oceans. ρ_s is the density of the surface waters, c_s the specific heat, and h the depth below which the temperature does not vary.

Equations (1) and (2) are the equations of conservation of thermal energy in the troposphere and surface of the earth respectively, and (3), (5), and (4) those of radiation balance in the cloudless troposphere, in the cloud layer, and in the surface of the earth respectively.

In this model, to compute T'_m, T'_s, E_A, E_c, and E_s, we need to prescribe G_2, G_5, G_3, ϵ, and α.

Since equations (2), (3), (4), and (5) are linear and algebraic, the solution of the system (1), (2), (3), (4), (5), is obtained by solving a linear differential equation of the type

$$M^2K\nabla^2_M T'_m - F_1 T'_m = F_2 \tag{6}$$

This is an elliptic type of equation that can be solved by prescribing T'_m at the closed boundary.

To introduce G_2, G_5, G_3, and ϵ as variables we shall express them as linear functions of T'_s, T'_m, $\partial T'_m/\partial x$, $\partial T'_m/\partial y$, and E_s, obtaining four new equations that can be combined with (1), (2), (3), (4), and (5). If in equation (5) we replace ϵ by its normal value, ϵ_N, we obtain now a differential equation of the type

$$M^2K\nabla^2_M T'_m + F''_1 \frac{\partial T'_m}{\partial x} + F'''_1 \frac{\partial T'_m}{\partial y} + F'_1 T'_m = F'_2 \tag{7}$$

where F'_1, F''_1, F'''_1, F'_2 are known functions of the map coordinates x and y. This equation is also elliptic and can be solved along similar lines as (6).

4. THE EMPIRICAL HEATING FUNCTIONS AND THE CLOUD COVER

For the condensation of water vapor at the clouds (G_5) and the cloud cover (ϵ) we will use the following formulas developed by Clapp et al.[5]:

$$G_5 = G_{5_N} + (G_5)^1_0 \left\{ b'(T'_m - T'_{m_N}) + d''\left[\frac{\partial T'_m}{\partial x} - \frac{\partial T'_{m_N}}{\partial x}\right] + c''\left[\frac{\partial T'_m}{\partial y} - \frac{\partial T'_{m_N}}{\partial y}\right]\right\} \tag{8}$$

$$\epsilon = \epsilon_N + d_2(G_5 - G_{5_N})(G_5)^1_0 \tag{9}$$

where G_{5_N}, ϵ_N, and T_{m_N} are the normal values of G_5, ϵ, and T'_m respectively, x and y are the rectangular "map" coordinates, $c''=2Dc'$, and $d''=2Dd'$; d_2 is a constant and b', c' and d' are empirical functions of x and y, given in[5], D is the constant grid interval, and $(G_5)^1_0$ is equal to one or zero to get the abnormal or the normal case of G_5, respectively. In (9), ϵ is in percent and G_5 is in cal. cm.$^{-2}$ day^{-1}.

For the heat lost by evaporation at the surface (G_3) and the turbulent vertical transport of sensible heat from the surface (G_2), we will use the formulas:

$$G_3 = G_{3_N}\{G''_2 + (1-G''_2)[1-(\delta_2)^1_0]\} + (G_3)^1_0\{G''_2 K_4 B V_{a_N}[0.981(T'_s - T'_{s_N}) - U_N(T'_m - T'_{m_N})]\} + (G'_3)^1_0\{(1-G''_2)(\delta_2)^1_0[(1-d_7)E_s - d_8]\} \tag{10}$$

$$G_2 = G_{2_N} + (G_2)^1_0\{[K_2G''_2 + (1-G''_2)K_3]V_{a_N}[(T'_s - T'_{s_N}) - (T'_m - T'_{m_N})]\} \tag{11}$$

where G_{3_N}, G_{2_N} and T'_{s_N} are the normal values of G_3, G_2, and T'_s respectively; K_2, K_4, and B are constants given in [5]; $(G_2)^1_0$, $(G_3)^1_0$, $(G'_3)^1_0$ and $(\delta_2)^1_0$ are equal to zero or one; G''_2 is equal to one on the oceans and zero on the continents; d_7 and d_8 are empirical functions of x and y, given in [5], V_{a_N} is the normal value of the surface wind speed and U_N is the normal value of the surface relative humidity.

When $(G_3)^1_0 = (G'_3)^1_0 = (G_2)^1_0 = (\delta_2)^1_0 = 0$ formulas (10) and (11) reduce to the specification of the normal values $G_3 = G_{3_N}$ and $G_2 = G_{2_N}$.

When $(G_3)^1_0 = (G_3')^1_0 = (G_2)^1_0 = (\delta_2)^1_0 = 1$ formulas (10) and (11) reduce over the oceans to

$$G_3 = G_{3_N} + K_4 B V_{a_N}[0.981(T'_s - T'_{s_N}) - U_N(T'_m - T'_{m_N})] \tag{12}$$

$$G_2 = G_{2_N} + K_2 V_{a_N}[T'_s - T'_{s_N}) - (T'_m - T'_{m_N})] \tag{13}$$

and over the continents to

$$G_3 = (1-d_7)E_s - d_8 \tag{14}$$

$$G_2 = G_{2_N} + K_3 V_{a_N}[(T'_s - T'_{s_N}) - (T'_m - T'_{m_N})] \tag{15}$$

The detailed derivation of (12), (13), and (14) is given by Clapp et al. [5]. In the numerical experiments we will take $K_3 = K_2$. Therefore we will use the same formula for G_2 for the continents as for the oceans.

5. THE MATHEMATICAL MODEL AND ITS SOLUTION

The solution of the system of equations (1), (2), (3), (4), (5), (8), (9), (10), and (11) can be obtained as follows:

From (2), (4), (10), and (11) we obtain:

$$T'_s = F_8 T'_m + F_9\epsilon - \frac{F_6 - 1}{F_7}(Q+q)_0[1-\epsilon(1-k)]\alpha + F_{13}T'_{s_N} + F_{14}T'_{m_N} + F_{15} \tag{16}$$

where

$$F_3 = G_{2_N} + G_{3_N}\{G''_2 + (1-G''_2)[1-(\delta_2)^1_0]\}$$

$$F_4 = V_{a_N}(G_2)^1_0[K_2G''_2 + (1-G''_2)K_3]$$

$$F_5 = V_{a_N}(G_3)^1_0 G''_2 K_4 B$$

$$F_6 = (G'_3)^1_0(1-d_7)(\delta_2)^1_0(1-G''_2)$$

$$F'_6 = d_8(1-G''_2)(\delta_2)^1_0(G'_3)^1_0$$

$$F_7=-d_s-[F_4+0.981F_5+(F_6-1)B_3]$$

$$F_8=-\frac{F_4+U_NF_5-(F_6-1)B_2''}{F_7}$$

$$F_9=\frac{F_6-1}{F_7}[B_7-(1-k)(Q+q)_0]$$

$$F_{13}=-\frac{F_4+0.981\,F_5}{F_7}$$

$$F_{14}=-F_8+\frac{F_6-1}{F_7}B_2''$$

$$F_{15}=\frac{F_3}{F_7}-(d_s/F_7)(T_s')_i+\frac{F_6-1}{F_7}[B_6+(Q+q)_0]-\frac{F_6'}{F_7}$$

Combining (1), (3), (4), (5), (8), (9), (10), (11), and (16) we get the following differential equation:

$$M^2K\nabla_M^2T_m'+(F_{22}+\alpha F_{22}')\frac{\partial T_m'}{\partial x}+(F_{23}+\alpha F_{23}')\frac{\partial T_m'}{\partial y}$$
$$+(F_{24}+F_{24}'\alpha)T_m'=(F_{22}+\alpha F_{22}')\frac{\partial T_{m_N}'}{\partial x}+(F_{23}+\alpha F_{23}')\frac{\partial T_{m_N}'}{\partial y}$$
$$+(F_{27}+F_{27}'\alpha)T_{m_N}'+F_{28}T_{s_N}'+F_{30}\alpha+F_{31} \quad (17)$$

where

$$F_{17}=A_3+\epsilon_ND_3+F_4$$

$$F_{18}=A_2''-F_4+F_{17}F_8$$

$$F_{20}=\frac{F_{17}(F_6-1)}{F_7}(Q+q)_0(1-k)$$

$$F_{21}=(G_5)_0^1[1+F_{17}F_9d_2(G_5)_0^1]$$

$$F_{21}'=(G_5)_0^1F_{20}d_2$$

$$F_{22}=\frac{d''F_{21}}{\gamma_3}$$

$$F_{23}=\frac{c''F_{21}}{\gamma_3}$$

$$F_{22}'=\frac{d''F_{21}'}{\gamma_3}$$

$$F_{23}'=\frac{c''F_{21}'}{\gamma_3}$$

$$F_{24}=\frac{F_{18}+b'F_{21}-(\gamma_3/\Delta t)}{\gamma_3}$$

$$F_{24}'=\frac{b'F_{21}'}{\gamma_3}$$

$$F_{27}=-\frac{1}{\gamma_3}[F_{17}F_{14}+F_4-b'F_{21}]$$

$$F_{27}'=\frac{b'F_{21}'}{\gamma_3}$$

$$F_{28}=-\frac{1}{\gamma_3}[F_{17}F_{13}-F_4]$$

$$F_{30}=-\frac{1}{\gamma_3}[F_{20}\epsilon_N-(F_{17}(F_6-1)/F_7)(Q+q)_0]$$

$$F_{31}=-\frac{1}{\gamma_3}\Big\{(D_6'+b_3I+F_{17}F_9)\epsilon_N+a_2I+F_{17}F_{15}+G_{5_N}+G_{2_N}F_3'+\frac{\gamma_3}{\Delta t}(T_m')_i+A_6\Big\}$$

From equation (17) we compute T_m', and from (16), (3), (4), (5), (8), (9), (10), and (11) we compute T_s', E_A, E_s, E_c, G_5, ϵ, G_3, and G_2 respectively.

6. THE NUMERICAL EXPERIMENTS

Equation (17) will be solved as a finite difference equation by the Liebmann relaxation method described by Thompson ([7], p. 19). We will use the same number of grid points and the same region of integration as in [2]. Furthermore, besides the new constants and fields introduced in section 4, we shall use the same constants and fields as in [2].

The empirical functions (8), (9), (10), and (11) include the following cases that will be studied in this series of experiments:

Model No. 1. When $(\delta_2)_0^1=(G_2)_0^1=(G_3)_0^1=(G_5)_0^1=(G_3')_0^1=0$, we have that $G_5=G_{5_N}$, $G_2=G_{2_N}$, $G_3=G_{3_N}$ and $\epsilon=\epsilon_N$. Therefore we obtain the model used in [2], which we will call model no. 1.

Model No. 2. When $(\delta_2)_0^1=(G_2)_0^1=(G_3)_0^1=(G_5)_0^1=(G_3')_0^1=1$ we have that G_5 and ϵ are given by (8) and (9) respectively; G_2 is given by (13) for both land and ocean when $K_2=K_3$; and G_3 is given by (12) on the oceans and by (14) on the continents.

The normal case of model no. 2 is obtained when $(\delta_2)_0^1=(G_3')_0^1=1$ and $(G_2)_0^1=(G_3)_0^1=(G_5)_0^1=0$.

Besides experimenting with these two models, we shall also carry out computations with sub-models. For example when $(\delta_2)_0^1=(G_2)_0^1=(G_3)_0^1=(G_3')_0^1=1$ and $(G_5)_0^1=0$ we obtain model no. 2 except that the heat of condensation and the cloud cover have their normal values ($G_5=G_{5_N}$, $\epsilon=\epsilon_N$). This type of computation allows us to determine the role of the different components of the heating.

In all the cases, to compute the normals we prescribe the normal temperature in the mid-troposphere and the surface of the oceans for the previous month, and the normal albedo at the end of the previous month.

To make a prediction for a given month we use the corresponding computed normals, and prescribe the temperatures in the mid-troposphere and surface of the oceans for the previous month, and the albedo at the end of the previous month.

In the numerical computations we shall proceed as follows:

(1) We first compute the normal mid-tropospheric temperature field for $K=0$. In this case equation (17)

becomes algebraic and can be solved readily for T'_m.

(2) The normal mid-tropospheric temperature field for $K \neq 0$ is computed, using at the boundary and as a first guess the normal mid-tropospheric temperature for $K=0$.

(3) The mid-tropospheric temperature field for the given month is obtained using the computed mid-tropospheric normal temperature field at the boundary and as a first guess. Also on the right side of (17) we use the computed normal mid-tropospheric temperature and its derivatives (T'_{m_N}, $\partial T'_{m_N}/\partial x$, $\partial T'_{m_N}/\partial y$, as well as the computed normal temperature at the surface, T'_{s_N}).

(4) Using (16), (3), (4), (5), (8), (9), (10), and (11) we compute T'_s, E_A, E_s, E_c, G_5, ϵ, G_3, and G_2, as well as their normal values.

(5) Finally we compute the departures from the computed normal.

We shall apply the model to the prediction for January 1963, which was already studied in [2] using model no. 1. We shall use therefore the same data, namely, the anomalies in December 1962 of ocean temperatures and of 700-mb. temperatures, and the anomalies of the snow cover on December 31, 1962. ([2], p. 101).

Figure 1 shows the anomalies of G_3, G_2, G_5, and ϵ generated when using model no. 2. In model no. 1 these anomalies are equal to zero.

Figure 2A shows the anomalies of the temperature at the surface using model no. 1 [2], and 2B those when using model no. 2. We see that in both models the pattern of the anomalies is the same. However, in general, the anomalies computed with model no. 2 are smaller than those computed using model no. 1. The positive anomalies of the surface temperature have decreased about half a degree Celsius for the oceans and the strong negative anomalies have decreased about 2°C. in the United States and Europe, and about 3° or 4°C. in Asia. The positive anomaly in Asia has decreased less than half a degree.

These results show that over the continents strong changes in the anomalies of the surface temperature (2°C.) can be produced by rather weak anomalies of G_2 and G_3 (25 ly./day). But over the oceans, the changes in the anomalies of the surface temperature are weak (0.5°C.) even if they are produced by large anomalies of G_2 and G_3 (50 cal.cm.$^{-2}$ day^{-1}).

Figure 3A shows the mid-tropospheric temperature anomalies computed using model no. 1 and 3B those computed using model no. 2. The positive mid-tropospheric anomalies have a magnitude of less than half a degree. Over the Pacific they are about the same in both solutions and over the Atlantic the anomalies of model no. 2 are slightly larger than those of model no. 1. Over the continents the negative mid-tropospheric temperature anomalies of model no. 2 are smaller than those of model no. 1, by about 0.25°C. over the United States, 0.5° over Europe, and 1° over Asia. The anomalies in both solutions are considerably weaker than the observed ones, as shown in [2].

Figure 3C shows the mid-tropospheric temperature anomalies computed with the sub-model in which the heat of condensation and the cloud cover have their normal values $((\delta_2)_0^1=(G_2)_0^1=(G_3)_0^1=(G'_3)_0^1=1$ and $(G_5)_0^1=0)$. Its comparison with figure 3B shows the combined effect of the anomalies of heat of condensation and cloudiness in the mid-tropospheric temperature anomalies.

If we take $(G_2)_0^1=(G_3)_0^1=(G_5)_0^1=0$ and $(G'_3)_0^1=(\delta_2)_0^1=1$ then the computed anomalies (not shown) are the same as those of model no. 1. In both cases we use the normal values of G_2, G_3, G_5, and ϵ, except that a different normal for G_3 is used. In the first case we take $G_3=d_7E_{s_N}-d_3$ where E_{s_N} is the computed normal excess of radiation at the surface, and in model No. 1 we use $G_3=G_{3_N}$. *This shows that apparently the anomalies do not depend critically on the specification of the normals which we therefore do not need to know with great accuracy.*

7. INTERPRETATION OF RESULTS AND SUGGESTIONS FOR FUTURE WORK

We have attempted the formulation of a scheme by which an energy feedback mechanism can be introduced into long-range numerical weather prediction, and we have shown clearly that small anomalies in the heating parameters can produce significant temperature changes. However, the heating functions used in the present model are very crude and in some cases of doubtful validity. *It is therefore essential for the successful application of this method to get better empirical heating functions.*

Comparison of figure 1A with 1C shows that on the average the anomalies of heat lost by evaporation at the surface are considerably larger than those of heat released by condensation of water vapor in the clouds, implying a monthly storage of latent energy, probably unrealistically large. Furthermore, comparison of figure 1A with 1C shows that in general the anomalies of G_3 are of opposite sign to those of G_5, implying that an increase of evaporation produces a decrease of precipitation, a result that does not seem realistic. Therefore, *it is essential to introduce some condition relating G_3 and G_5 to insure that there exists no violation of the conservation of water in the troposphere.*

Further extensions of this work that would possibly improve the results are the following:

(1) Since, as admitted in [5], formula (9) is of doubtful validity, *it is essential to introduce a more realistic formula for the cloud cover.* Furthermore we can introduce a more realistic vertical distribution of cloud cover and, through the use of satellite data [4], attempt to use the information of the cloud cover for the previous interval.

[2] These anomalies differ slightly from those shown in figure 9A of [2] as a result of minor corrections of the input data.

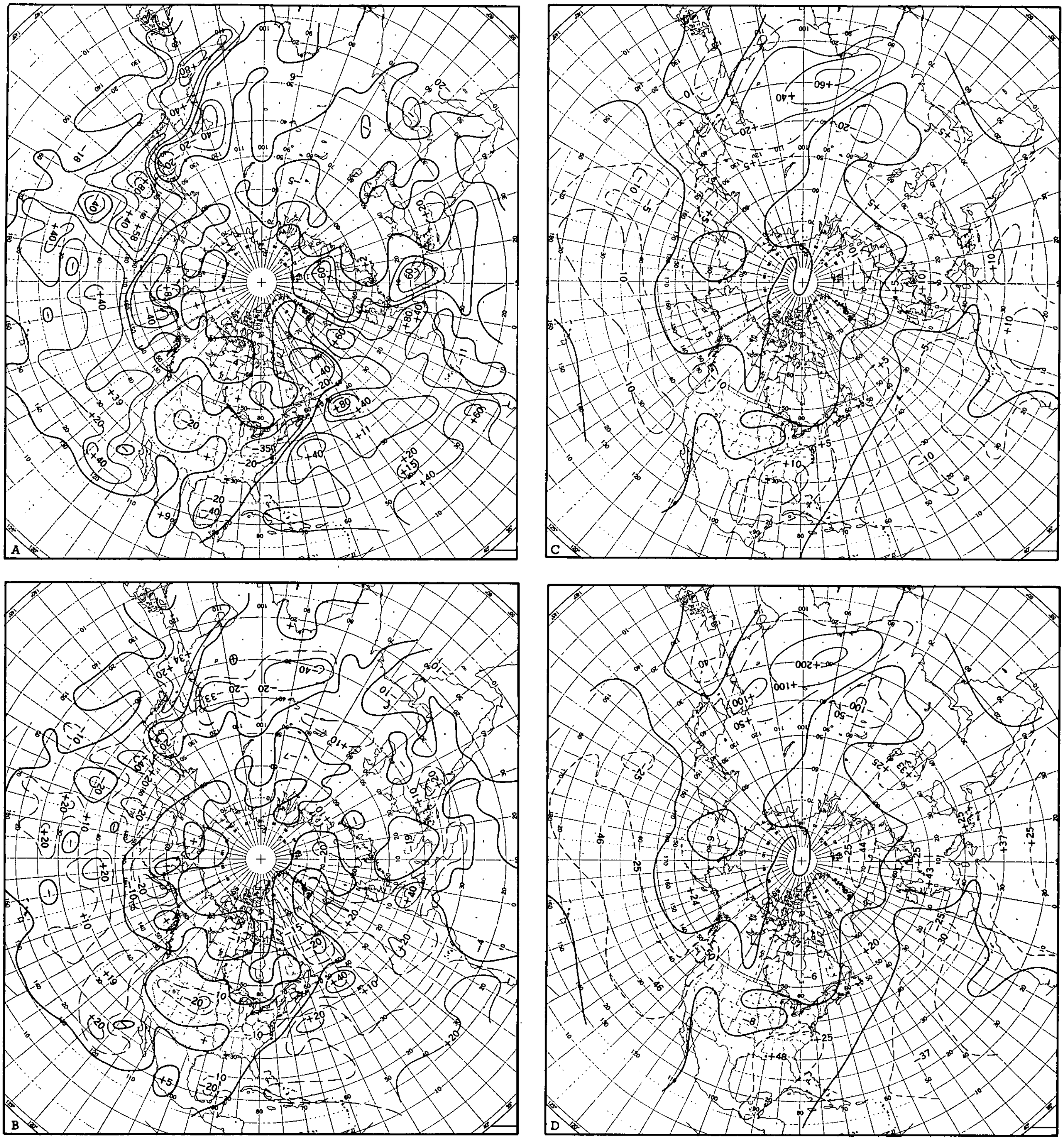


FIGURE 1.—Anomalies, besides those of radiation, that are generated using model no. 2, in the prediction for January 1963. (A) and (B) show the anomalies, in cal. cm^{-2} day^{-1}, of the heat lost by evaporation and by vertical turbulent transport of sensible heat respectively. (C) shows the anomalies, in cal. $cm.^{-2}$ day^{-1}, of the condensation of water vapor at the clouds; and (D) the anomalies of the cloud amount, in percent multiplied by 10.

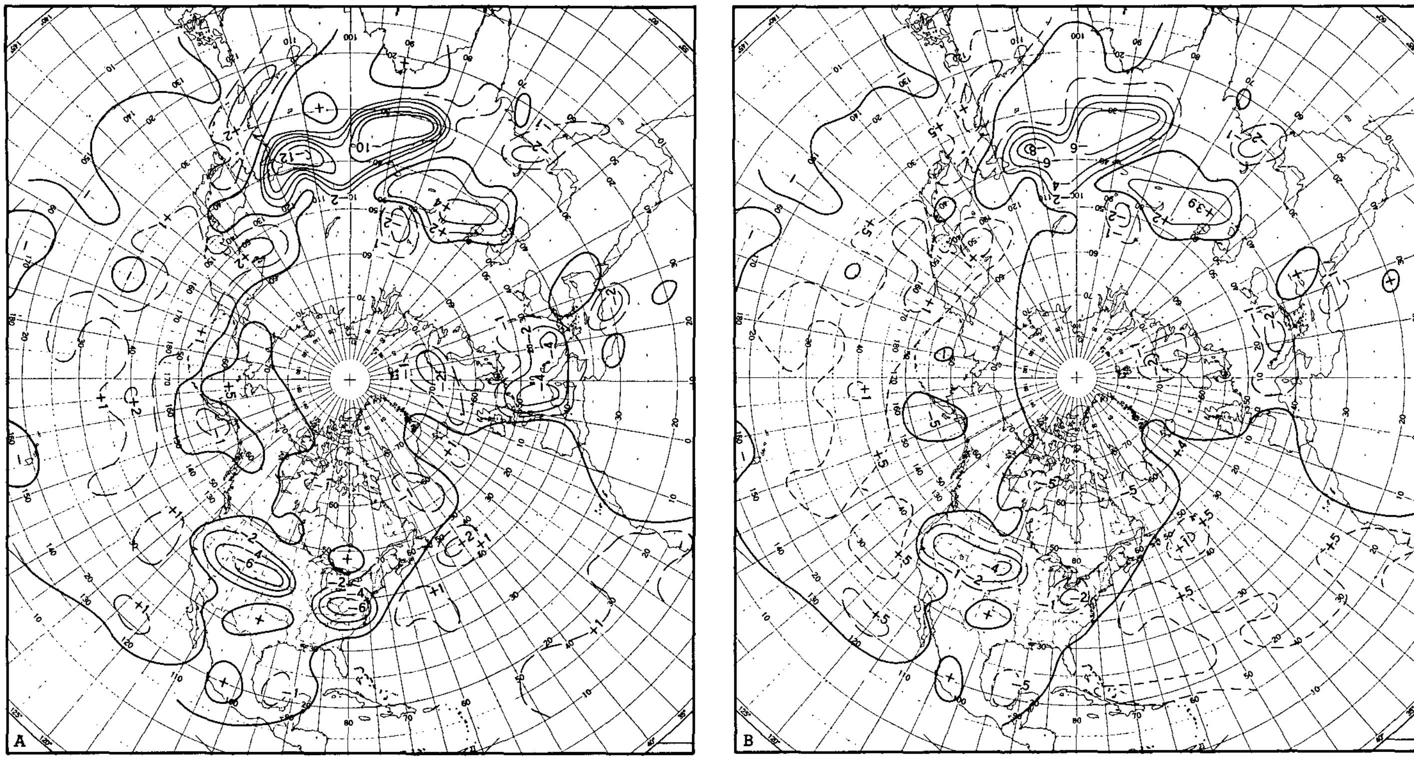


FIGURE 2.—Predicted departures from normal of the surface temperature for January 1963: (A) using model no. 1 and (B) using model no. 2.

(2) Introduction of a more refined radiation model, and construction of a multiple layer model.

(3) Introduction of advection of thermal energy by the mean wind.

(4) In addition to forecasting anomalies of temperature and the heating functions, the anomalies of albedo should be predicted as well. The only anomalies of the albedo introduced so far are those due to the extent of the snow cover. To predict the anomalies of the temperature field for a given month we have prescribed the snow cover at the end of the previous month and have kept it fixed.

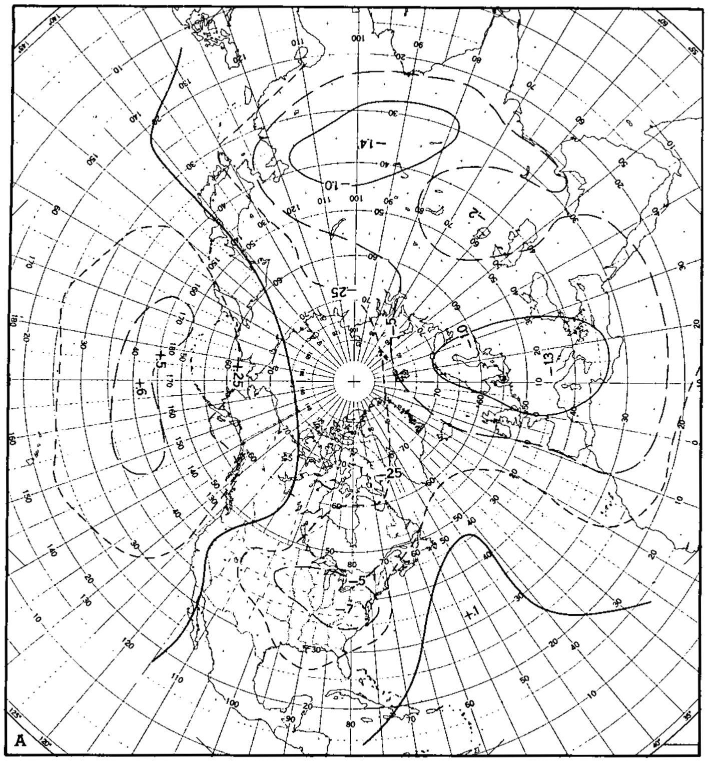
The idea of using as initial data the snow cover for the previous month or at the end of it seems to give a good first approximation to the anomaly of albedo. However, it is evident that the restriction of keeping it fixed should be removed. We must try, therefore, to introduce a mechanism by which the extent of the snow cover can vary. For this purpose, experiments were carried out in which the snow cover was varied by coupling it to the thermal field, postulating that the 0° C. surface isotherm coincides with the snow boundary.

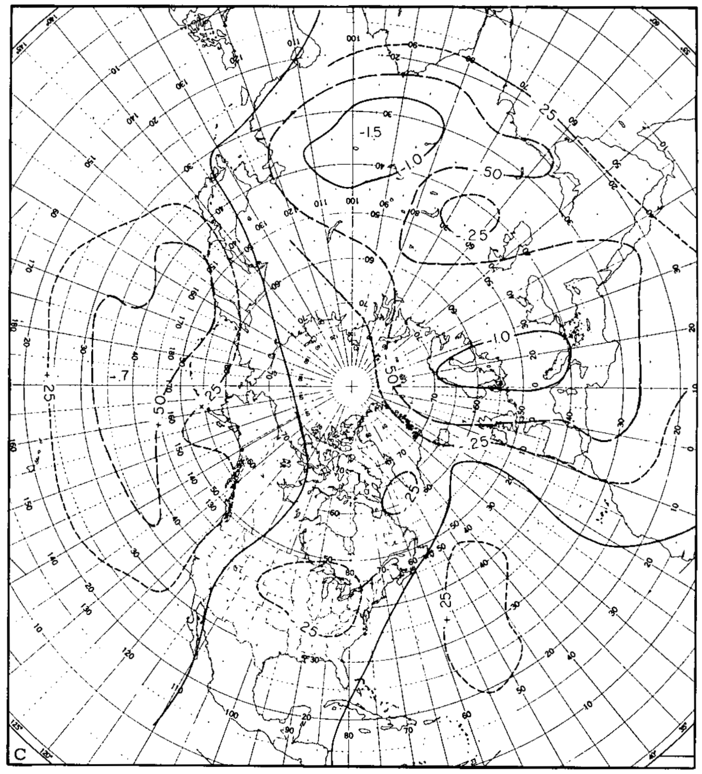
In these experiments we first used the albedo corresponding to the snow cover at the end of the previous month to compute the temperature field. This computed surface temperature was used to compute an albedo such that the snow cover coincided with the 0° C. isotherm. This new albedo was used to compute a new temperature field, which in turn was used to compute a new albedo and so forth. We stopped the computations when the last computed snow boundary coincided with the following 0° C. surface isotherm. This procedure introduces a true feedback mechanism that allows the snow cover to melt with above-freezing temperatures and to stay with below-freezing temperatures. Furthermore the increase of snow cover decreases the temperature.

However the assumption of the coincidence of the boundary of the snow cover with the 0° C. surface isotherm is unrealistic and therefore does not lead to satisfactory results. In fact a comparison of the observed snow boundary with the 0° C. isotherm shows that such a simple coupling does not exist. We must look therefore for a realistic coupling between the snow cover and the thermal field, and introduce if necessary other parameters such as the precipitation, the thickness of the snow cover, and the expenditure of heat by melting of snow.

ACKNOWLEDGMENTS

The author is indebted to Mr. J. Namias and Mr. P. F. Clapp for their encouragement and very stimulating discussions. Thanks are also due to Mr. T. Johnson for preparing the program for the numerical computations and to Mr. R. Taubensee for preparing some of the charts used in the paper.





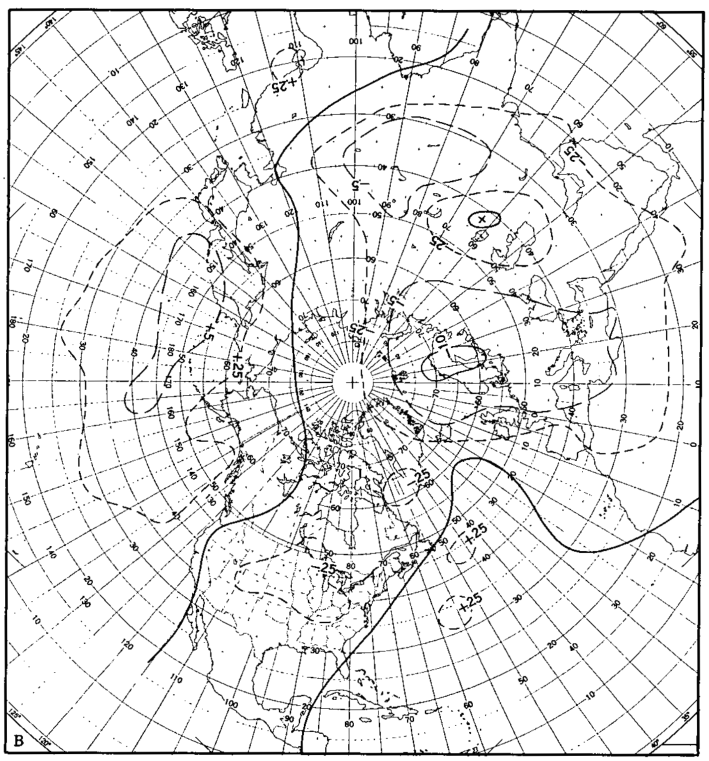


FIGURE 3.—Predicted departures from normal of the mid-tropospheric temperature for January 1963. (A) using model no. 1, (B) using model no. 2, and (C) using model no. 2 but with normal values of G_5 and ϵ.

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[Received April 2, 1965; revised May 19, 1965]

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