MONTHLY WEATHER REVIEW

VOLUME 92, NUMBER 3

MARCH 1964

ON THE PHYSICAL BASIS FOR THE NUMERICAL PREDICTION OF MONTHLY AND SEASONAL TEMPERATURES IN THE TROPOSPHERE-OCEAN-CONTINENT SYSTEM

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ABSTRACT

The equations of conservation of thermal energy in the troposphere and at the surface of the earth are used as the basis for predicting the temperature of the troposphere-ocean-continent system for periods of time as long as a month or a season.

Computations of the normal temperature for January in the mid-troposphere and at the surface of the earth are carried out, and the results agree well with observations.

Using as data the temperature in the oceans and in the mid-troposphere in December 1962 and the abnormal snow cover of December 31, 1962, a numerical temperature prediction is carried out for January 1963, obtaining good agreement with observations.

1. INTRODUCTION

To describe the dynamical and thermal state of the troposphere in all its scales of time and space we need to formulate a complete fluid dynamics problem and use the laws of conservation of momentum, mass, and thermal energy. The solution of the complete problem is very complex and there exists at present no satisfactory general theory although extensive studies are being carried out on the theory of the general circulation.

Rossby [16], realizing the complexity of the problem, concentrated on the dynamical part. He used the equations of horizontal motion and of conservation of mass as basic ones, and reduced to trivial equations those of conservation of thermal energy, by assuming that no heat was added to the system. This simplifying approach led to the application of numerical models for short-range prediction by the use of electronic computers, which was undertaken for the first time by Charney, Fjørtoft, and von Neumann [6], and of which the so-called barotropic model is the best known. Starting with the barotropic model, the Joint Numerical Weather Prediction Unit in 1955 inaugurated operational numerical predictions of the large-scale flow at the mid-troposphere for the Northern Hemisphere for 1, 2, and 3 days [18].

The pure dynamical approach to the problem is successful because the time of the predictions is short. An extension of the period of prediction would require the solution of the complete problem, including the complex coupling of the dynamical and thermodynamical equations.

However, if we extend our prediction to a larger time scale, say a month or a season, the thermodynamical equations become the important ones, and we can think of a simplification similar to that in use in the barotropic model for short-range prediction, but in which instead of the conservation of momentum we use the conservation of thermal energy and subordinate to this the dynamical part of the problem. We will get, in this way, the equations that describe the mean temperature and mean circulation for a month or a season, and treat what is left out of the averaged state as turbulent eddies which can

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be incorporated into the heat transport mechanism by the use of an austausch coefficient.

In two previous papers the author [1], [2] developed the basic equations for such an approach, and carried out numerical experiments with a one-dimensional model of the troposphere to predict the mean temperature, as a function of the latitude, during a month and a season. Since the results agreed well with observations he was encouraged to extend the model to a two-dimensional one which could explain the observed normal [2] temperature field in the troposphere-ocean-continent system over the Northern Hemisphere, and possibly could be used to predict the actual mean temperature field for a given month or a season. The computed normal thermal field must agree with the observed one and will be taken, by definition, as the theoretical normal from which the departures from normal for a given month or a season are computed, with the final goal of making numerical weather predictions for such extended periods of time.

2. NOTATION

We shall use the same notation employed in the previous papers [1], [2], except that we shall drop the bars from the temperature and other averaged variables and write T_m for $\overline{T}_m$, T_s for $\overline{T}_s$, etc. For the sake of clarity we summarize the meaning of some of the letters and symbols that will be used:

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 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.
I_0: solar constant.
ϵ: fractional cloud amount.
α_1: fractional absorption of insolation by the surface of the earth.
α_2: fractional absorption of insolation by the water vapor and dust in the troposphere.
α_3: fractional absorption of insolation by clouds.
α: albedo of the surface of the earth.
∇^2: two-dimensional Laplace operator in spherical coordinates.
β: constant vertical lapse rate.
ρ^*: density in the troposphere.
ψ: longitude in radians.
ϕ: latitude in radians.

[2] Actual observations for some quantities presented in this paper are not available for computing the normals in accordance with recommended international usage. However, for uniformity, the term "normal" has been used for all measures of long term average.

3. EQUATIONS OF RADIATION BALANCE

We shall assume that the temperature of the cloud cover is constant and therefore will take $T'_c=0$. Furthermore, we shall assume that the net transfer of long-wave radiant energy from the clouds to the troposphere is negligible.

We shall introduce the relation $H'=AT'_m$ ([1], p. 107) where $A=2H_0/(4T_0+\beta H_0)$. This assumption introduces the constraint of not allowing for large variation of the density, ρ^*, as is actually observed in the real troposphere.

With the above assumptions, the formulas for E_A, E_s, and E_c given by the author ([1], p. 105) become:

$$E_A=A''_2T'_m+A_3T'_s+A_6+\alpha_2 I \tag{1}$$

$$E_s=B''_2T'_m+B_3T'_s+B_6+\epsilon B_7+\alpha_1 I \tag{2}$$

$$E_c=\epsilon(D_3T'_s+D'_6)+\alpha_3 I \tag{3}$$

where $A''_2=A_2(1-\beta A/2)+A_5A$; $B''_2=-A_5(\beta-A/2)$; $B_3=-D_3-A_3$; and $D'_6=-2B_7-B_6$, where in the last expression we have assumed that $T_{s_0}=T_0+\beta H_0$. Furthermore, the constant coefficients A_2, A_3, A_5, A_6, B_3, B_5, B_6, B_7 and D_3 are given by the author ([1], p. 106). $\alpha_1 I$, $\alpha_2 I$, and $\alpha_3 I$ are the total short-wave solar radiation amounts absorbed by the surface of the earth, by the tropospheric water vapor and dust, and by the clouds, respectively.

The short wave radiation from sun and sky absorbed by the upper layer of the earth is given by $(Q+q)(1-\alpha)$, where $Q+q$ is the total radiation received by the surface of the earth and α is the fractional albedo, therefore

$$\alpha_1=\frac{Q+q}{I}(1-\alpha) \tag{4}$$

Using the Savino-Ångström formula ([5], p. 30)

$$Q+q=(Q+q)_0[1-(1-k)\epsilon] \tag{5}$$

where $(Q+q)_0$ is the total radiation received by the surface with clear sky, k is a function of latitude, and ϵ is the fractional cloud cover.

If we define

$$\alpha_1 = a_1 - \epsilon b_1$$

from (4) and (5) we get

$$a_1 = \frac{(Q+q)_0}{I}(1-\alpha) \tag{6}$$

$$b_1 = a_1(1-k) \tag{7}$$

The values of $(Q+q)_0$, as function of latitude and month, and those of k, as function of latitude, are given by Budyko ([5], p. 32).

We shall assume that $\alpha_2 = a_2$ and $\alpha_3 = \epsilon b_3$, where a_2 and b_3 are functions of latitude and season.

Using the data of London ([10], pp. 66–69) we can make a rough estimate of a_2 and b_3. Furthermore we shall compute the insolation, I, using the Milankovitch formula ([1], p. 104).

The January values of $(Q+q)_0$, I/I_0, k, a_2, and b_3, obtained from the above mentioned sources, are given in table 1.

TABLE 1.—*January values of the ratio of the insolation to the solar constant* (I/I_0), *of the total short wave radiation received by the surface of the earth with clear sky* $(Q+q)_0$ *and of the empirical functions of the latitude* k, a_2, *and* a_3.

Latitude (degrees)	I/I_0	$(Q+q)_0$ (kg. cal. cm.$^{-2}$ month^{-1})	k	a_2	a_3
0	0.304	18.5	0.35		
5	.287	18.0	.34	0.137	0.033
10	.269	17.4	.34		
15	.245	16.6	.33	134	.032
20	.222	15.5	.33		
25	.201	14.3	.32	.126	.039
30	.181	12.7	.32		
35	.153	10.8	.32	.115	.036
40	.125	8.7	.33		
45	.100	6.6	.34	.104	.044
50	.076	4.7	.36		
55	.053	3.0	.38	.100	.049
60	.030	1.7	.40		
65	.015	0.8	.45	114	.039
70	0	0.2	.50		
75	0	0.1	.55	167	0
80	0	0	.55		
85	0	0	.55	0	0
90	0	0	.55	0	0

4. THE CONSERVATION OF ENERGY EQUATIONS

The conservation of thermal energy equation for the troposphere can be written as

$$\frac{\gamma_3}{\Delta t}[T'_m - (T'_m)_i] - \gamma_3 K \nabla^2 T'_m = E_A + E_c + G_2 + G_5 + R_1 \tag{8}$$

where $\gamma_3 = A_1(1+\beta A/2)$, and A_1 has been defined previously ([1], p. 106). $T'_m = T_m - T_{m_0}$ where T_m is the mid-tropospheric temperature in the considered time interval, in Kelvin degrees, and T_{m_0} is a constant such that $T_{m_0} >> T'_m$. The first term on the left of equation (8) represents the storage of energy, where $(T'_m)_i = (T_m)_i - T_{m_0}$ and $(T_m)_i$ is the mid-tropospheric temperature in the previous time interval, in Kelvin degrees. The storage term can be perhaps improved by evaluating $(T_m)_i$ following the method outlined in [2]. The term $\gamma_3 K \nabla^2 T'_m$ is the rate of change of thermal energy due to the horizontal turbulent transport. $E_A + E_c$, G_2, and G_5 are respectively, the rates of change of thermal energy gained by radiation, by the turbulent vertical conduction from the earth's surface, and by the condensation of water in the clouds. R_1 includes other terms and will be neglected.

Equation (8) was obtained by applying the conservation of thermal energy law to a vertical column in the troposphere that includes the cloud layer. In the previous work we used a slightly different equation (eq. (20) of [1] or eq. (11) of [2]) which was obtained by applying the same law to a vertical column, excluding the cloud layer.

We shall use the energy equation for the surface of the earth as given in [2], which is the following:

$$d_s[T'_s - (T'_s)_i] = E_s - G_3 - G_2 \tag{9}$$

where $d_s = \rho_s c_s h / 2\Delta t$, h is the depth below which the temperature does not vary, ρ_s is the density, and c_s the specific heat. $T'_s = T_s - T_{s_0}$, where T_s is the surface temperature in the considered time interval, in Kelvin degrees, and T_{s_0} is a constant such that $T_{s_0} >> T'_s$. The term to the left of (9) is the storage term, where $(T'_s)_i = (T_s)_i - T_{s_0}$ and $(T_s)_i$ is the surface temperature in the previous time interval in Kelvin degrees. E_s is the excess of radiation per unit time and unit area, and G_2 and G_3 are respectively the energy given off to the atmosphere by vertical turbulent conduction and by evaporation. Equation (9) does not contain the horizontal transport by the ocean currents, which can be locally important. However, the overall magnitude is small compared with the transport that takes place in the troposphere, and therefore will be neglected in these preliminary experiments.

For winter, in the continents, in the snow-covered areas and in the Arctic the storage of energy will be neglected. Therefore, by taking $d_s = 0$ in such regions equation (9) becomes:

$$0 = E_s - G_3 - G_2 \tag{9'}$$

5. THE MATHEMATICAL MODEL

The conservation of energy equations (8) and (9) can be combined with the radiative balance equations (1), (2), and (3) to get a solution for T'_m, T'_s, E_A, E_s, and E_c, as follows:

From (2) and (9) we get

$$T'_s = -\frac{B''_2}{B_3 - d_s} T'_m - \frac{1}{B_3 - d_s}\{B_6 + \epsilon B_7 + d_s (T'_s)_i - G_2 - G_3 + (a_1 - \epsilon b_1) I\} \tag{10}$$

Substituting (10) in (1) and (3) and the resultant values of E_A and E_c in (8) we get the following equation:

$$K \nabla^2 T'_m - F_1 T'_m = F_2 \tag{11}$$

where

$$F_1 = \frac{1}{\Delta t} - \frac{A''_2 - \gamma_1 B''_2}{\gamma_3} + \epsilon \frac{\gamma_2 B''_2}{\gamma_3}$$

and

$$F_2=-\frac{1}{\gamma_3}\{a_2-(\gamma_1+\epsilon\gamma_2)a_1+\epsilon[b_3+(\gamma_1+\epsilon\gamma_2)b_1]I\}$$
$$-\frac{1}{\gamma_3}\{[1+(\gamma_1+\epsilon\gamma_2)]G_2+(\gamma_1+\epsilon\gamma_2)G_3+G_5\}$$
$$-\frac{1}{\gamma_3}\{A_6+\epsilon D'_6-(\gamma_1+\epsilon\gamma_2)B_6-\epsilon(\gamma_1+\epsilon\gamma_2)B_7\}$$
$$+\frac{\gamma_1+\epsilon\gamma_2}{\gamma_3}d_s(T'_s)_i-\frac{1}{\Delta t}(T'_m)_i$$

where

$$\gamma_1=A_3/(B_3-d_s) \text{ and } \gamma_2=D_3/(B_3-d_s)$$

The solution of (11) gives T'_m and using (10), (1), (2), and (3), we compute the other variables. When $K=0$ the solution of (11) is

$$T'_m=-F_2/F_1 \qquad (12)$$

To get the solution, we need to prescribe the cloudiness ϵ, the austausch coefficient K, the albedo of the surface of the earth α, the heat given off to the troposphere by condensation of water vapor in the clouds G_5, the sensible heat given off to the troposphere by vertical turbulent conduction from the surface of the earth G_2, and the energy released by the surface of the earth by evaporation G_3. Therefore in this first experiment the only heat source that will be generated within the model will be radiation. For the other heat sources we will take the normal values for the month or the season.

6. THE NUMERICAL SOLUTION FOR THE NORMAL WINTER

Equation (11) will be solved as a finite difference equation by the Liebmann relaxation method described by Thompson ([19], p. 92). Figure 1 shows the total region of integration and the position of the grid points.

At the boundary we shall prescribe the solution for $K=0$, given by (12). This is also used as the first guess in the relaxation method to get the solution in the interior.

We will start by computing the normal case for January. We will use the normal values of G_2, shown in figure 2A, obtained using estimates of Budyko [5] by a procedure similar to that of Clapp [7]. Fields of G_3 and G_5 (figs. 2B and C) were derived in a similar fashion from the work of Budyko [5] and Möller [11] respectively. The chart of albedo at the surface of the earth (fig. 2D) was constructed by Posey and Clapp [15] by putting together information from a variety of sources dealing with the average albedo of different surfaces, the extent of snow and ice, and continental vegetative cover. The chart of the normal temperature of the air at the surface was prepared by R. Taubensee using the best available data (unpublished). The values of the normal cloud cover were taken from [9], and those of the normal ocean temperatures from [20]. The normal mid-tropospheric temperature was computed from upper-air height data prepared by Hennig [8].

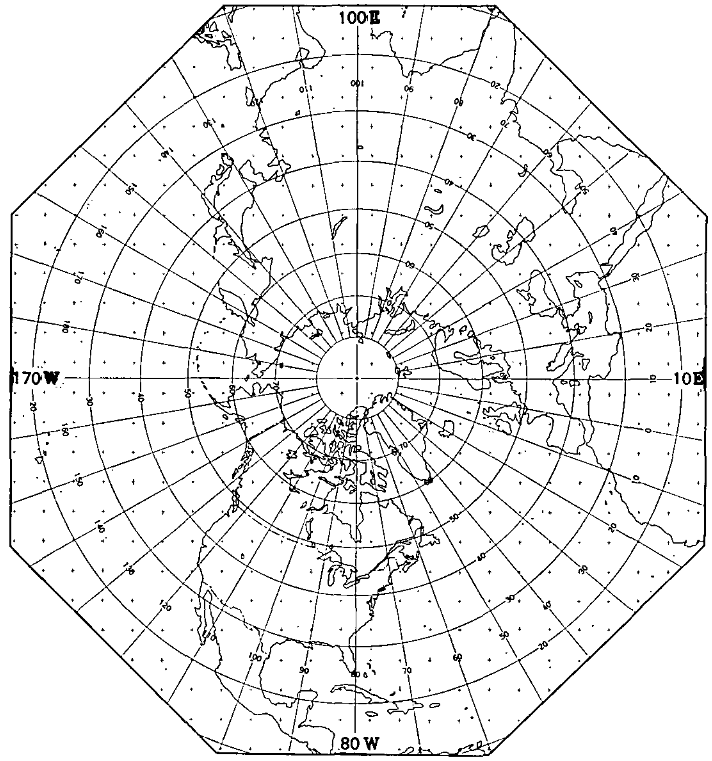

FIGURE 1.—Region of integration and position of the grid points.

In agreement with Berson [4] we shall choose a value of 60 m. as depth of the mixing layer in the ocean, h. The constants A_1, A_2, A_3, A_5, A_6, B_6, B_7, D_3, will be computed with the formulas and basic constants used in a previous paper [1]. The only changes in the basic constants that have been introduced are the following:

$T_{c_0}=261°$ K. $\quad p_0=0.264\times10^6$ gm. cm.$^{-1}$ sec.$^{-2}$
$H_0=10\times10^5$ cm. $\quad \rho_0=0.42\times10^{-3}$ gm. cm.$^{-3}$
$T_0=223°$ K.

Furthermore we will take
$\rho_s=1$ gm. cm.$^{-3}$ $\quad h=6\times10^3$ cm.
$c_s=4.184\times10^7$ cm.^{2} sec.$^{-2}$°K.$^{-1}$ $\quad \Delta t=0.265\times10^7$ sec.

Using the c.g.s. system, the derived constants have the following values:

$A_1=0.5493\times10^{10}$	$B''_2=0.4039\times10^4$
$A_2=0.5042\times10^4$	$B_3=-0.5474\times10^4$
$A''_2=-0.5841\times10^4$	$B_6=-0.1259\times10^6$
$A_3=-0.3355\times10^4$	$B_7=0.7641\times10^5$
$A_5=-0.2181$	$D_3=0.2119\times10^4$
$A_6=-0.1105\times10^6$	$D'_6=-0.2695\times10^5$
$A=0.2090\times10^4$	$\gamma_3=0.5866\times10^{10}$

Figure 3 shows the temperature profile used in our model (i.e., a constant lapse rate of 6.5°C. km.$^{-1}$) and the normal one observed in winter at different latitudes. The observed temperature profiles were constructed using

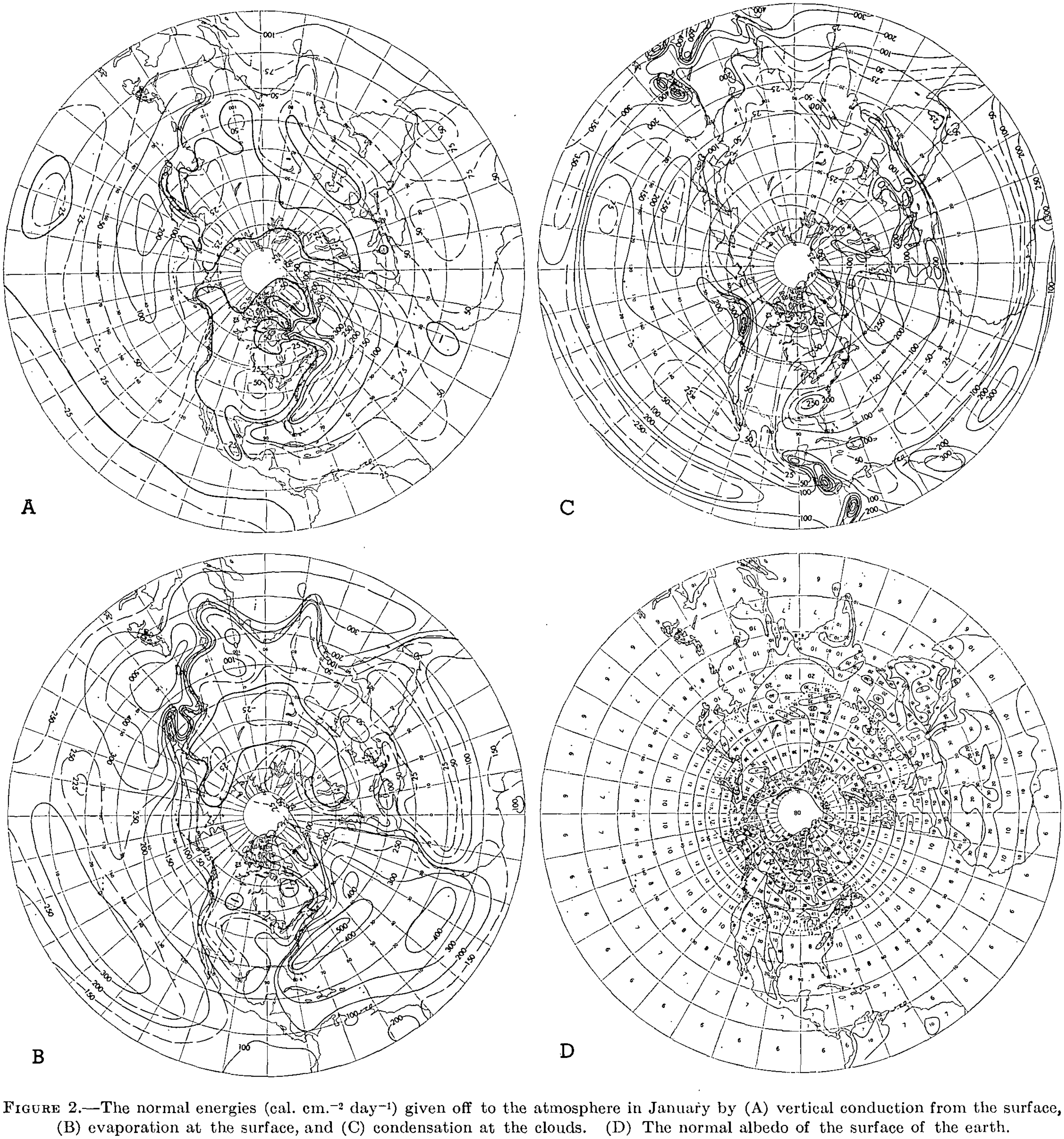

FIGURE 2.—The normal energies (cal. cm.$^{-2}$ day^{-1}) given off to the atmosphere in January by (A) vertical conduction from the surface, (B) evaporation at the surface, and (C) condensation at the clouds. (D) The normal albedo of the surface of the earth.

London's [10] data. The abscissa in figure 3 is equal to the temperature minus the temperature at the surface. From figure 3 it is clear that the mean theoretical te-m perature is somewhat lower than the observed one which is located about 1 km. higher. Therefore we must add 3.25°C. to the computed mean temperature for January (which is at a height of 5 km. in the model) when comparing it with the observed temperature at 5.5 km., corresponding to the 500-mb. level.

Figure 4A shows the result of the computations for the case in which there is no transport (K=0). Figures 4B and 4C are the computed mid-tropospheric temperatures for an austausch coefficient K equal to 2 and 3×10^{10} cm.^{2} sec.$^{-1}$ respectively. Figure 4D is the normal 500-mb. temperature.

Comparison of figure 4A with figures 4B and 4C shows the remarkable smoothing accomplished by the transport term, which transforms the complex pattern of A into those of B and C. These agree well with the real mid-tropospheric temperature represented in figure 4D.

With an austausch coefficient of 2×10^{10} we get the normal pattern. If we increase the austausch coefficient to 3×10^{10} we get practically the same solution, with little evidence of a significant increase in the heat transport.

Figures 5A, B, and C show the computed temperature at the surface of the earth for K equal to 0, 2, and 3×10^{10} cm.^{2} sec.$^{-1}$ respectively. Figure 5D is the observed normal temperature of the air at the surface which is in fair agreement with the theoretically computed values.

Figure 6A shows the computed excess of radiation at the surface of the earth (E_s) and 6B, the same variable as evaluated by Budyko [5], in cal. cm.$^{-2}$ day^{-1}.

Figures 7A and 7C show the computed excess of radiation in the troposphere (E_A+E_c) and the difference between the incoming and the outgoing radiation at the top of the troposphere ($E_A+E_c+E_s$) respectively. Figures 7B and 7D show the same variables as evaluated by Clapp [7] and Simpson [17], in cal. cm.$^{-2}$ day^{-1}.

Computations of the normal temperatures for the other seasons are presented in another paper [3]. Furthermore, in this paper a discussion is given of the sensitivity of the temperature fields to changes in cloudiness, heating other than radiation, horizontal turbulent transport, and storage of thermal energy in the oceans and troposphere.

7. PREDICTION OF THE JANUARY 1963 DEPARTURES FROM NORMAL

The above results for the normal thermal state of the troposphere are encouraging and suggest a possible way of predicting the departures from normal for a given month or a season.

The prediction is obtained in one time step and depends on the temperature at the surface of the oceans and in the middle of the troposphere in the previous month. It also depends on the albedo of the surface of the earth.

There are important cases in which anomalies in ocean temperature and albedo persist for extended periods and affect profoundly the weather during a month or a season. For example, during December 1962 temperatures in the North Atlantic and North Pacific were abnormally warm. On the other hand, on December 31, 1962, the snow cover was abnormally increased in area in most parts of the world, as compared with the normal conditions of December or January.

Since at present the available normal temperatures at 700 mb. are more reliable than those for 500 mb., we will use 700-mb. data and will compare the upper-level temperature departures with the observed ones at this level.

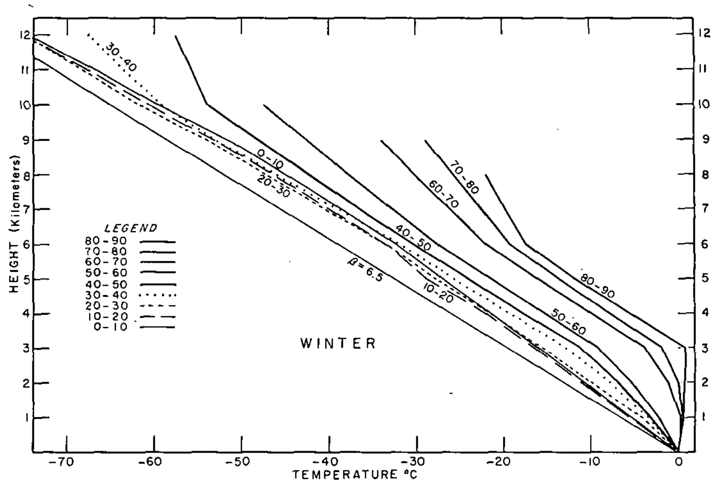

FIGURE 3.—The winter temperature as a function of the height for the different latitudes. The dashed line corresponds to a constant lapse rate of 6.5°C. km.$^{-1}$ which is used in the theoretical model.

Figure 8A shows the normal southern extent of snow cover for January (continuous line) and the observed condition on December 31, 1962 (dashed line). Figure 8B shows the departures from normal of the ocean temperature in December 1962 and figure 8C the departures from normal of the 700-mb. temperatures during the same month.

Using the observed temperature fields at the surface and 700 mb. for December 1962, and the albedo for December 31, 1962, and keeping everything else as in the normal case, we computed the temperature fields for January 1963. From these, together with the corresponding computed normals (figs. 4B and 5B), the departures shown in figures 9A and 10A were obtained. Their comparison with the observed air temperature departure at the surface and at 700 mb., shown in figures 9B and 10B respectively, reveals a fair agreement in the general pattern, especially in middle latitudes. However, the values of the predicted anomalies in the upper level are too small.

Figure 10C shows the prediction when we use the normal December values of 700-mb. temperature instead of those observed in December 1962. Comparison of figure 10C with 10A shows that, in general, the anomalies in sea temperature and snow cover over land determine the temperature pattern at the upper level. However, the initial anomalies at the upper level in the month of December 1962 operate to accentuate the pattern and to increase the values of the anomalies in the right way.

The predicted anomalies at the surface are in general of the correct order of magnitude and are practically independent of the initial conditions at the upper level.

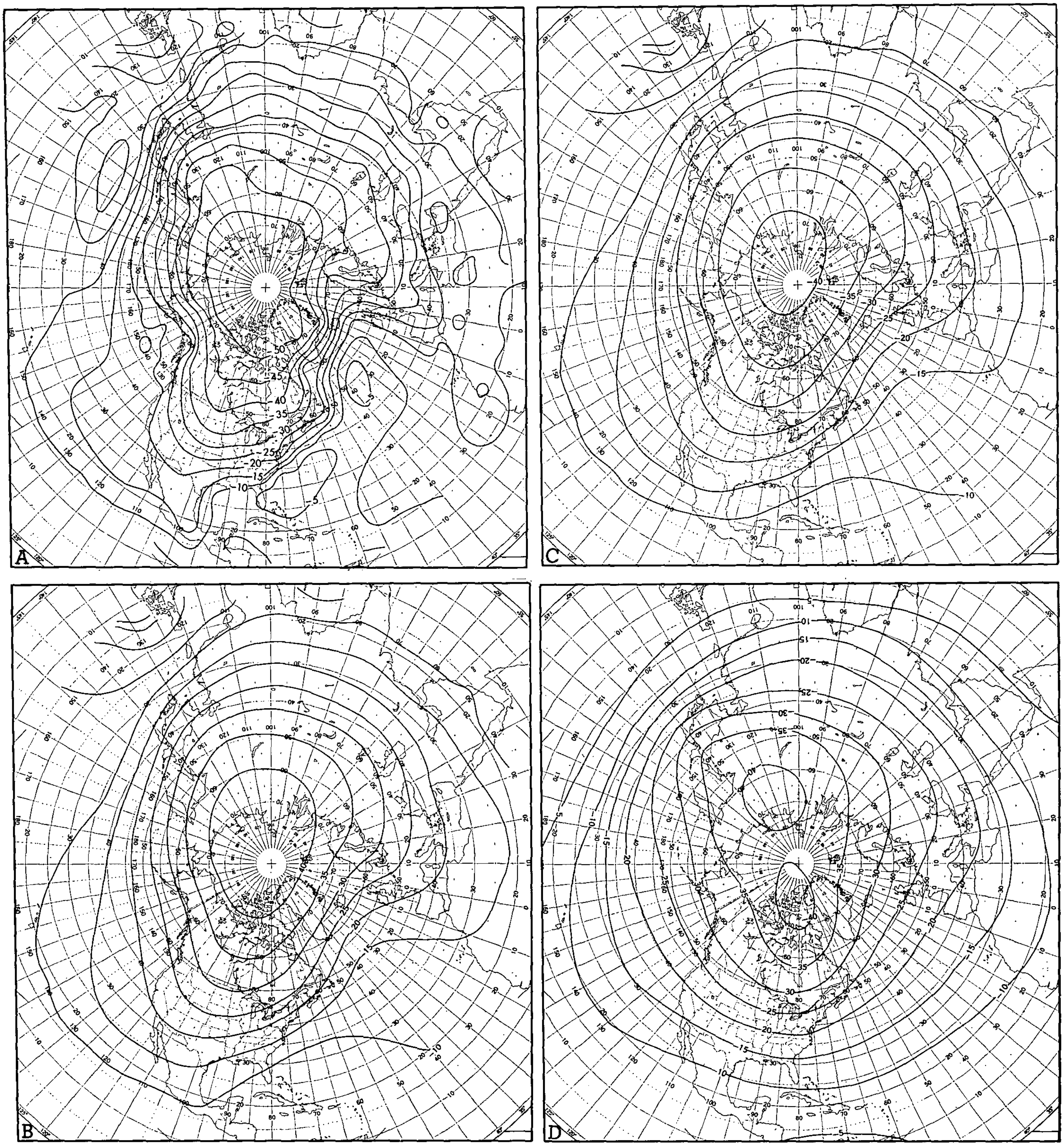

FIGURE 4.—The mid-tropospheric temperatures, in degrees Celsius: (A) computed for case with horizontal transport neglected, (B) and (C) computed using an austausch coefficient equal to 2 and 3 $\times$ 10^{10} cm.^{2} sec.$^{-1}$ respectively, and (D) the corresponding observed 500-mb. values.

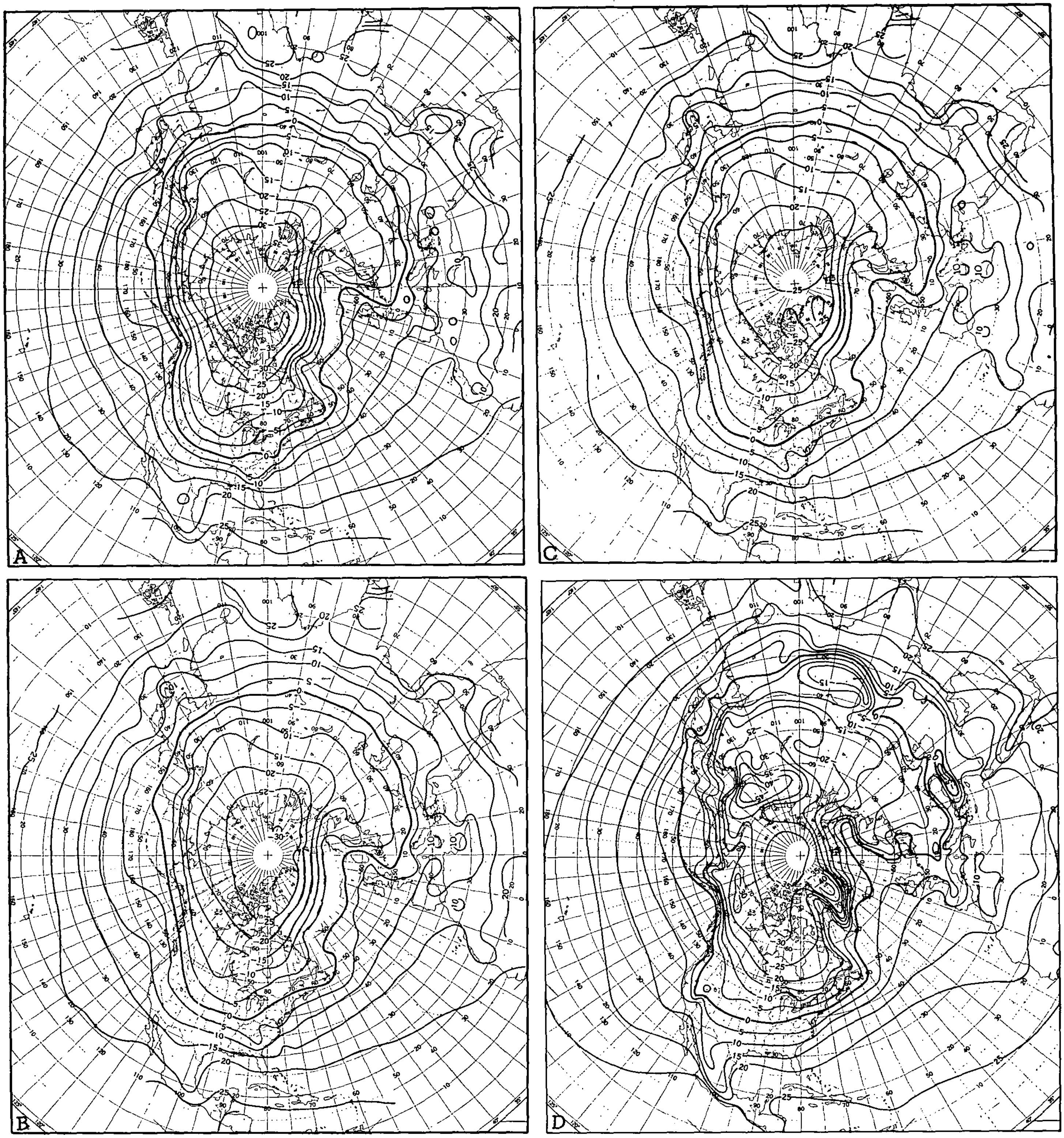

FIGURE 5.—The temperature at the surface of the earth, in degrees Celsius: (A) computed with horizontal transport neglected, (B) and (C) computed using an austausch coefficient equal to 2 and 3 × 10^{10} cm.^{2} sec.,$^{-1}$ respectively, and (D) the observed normal values.

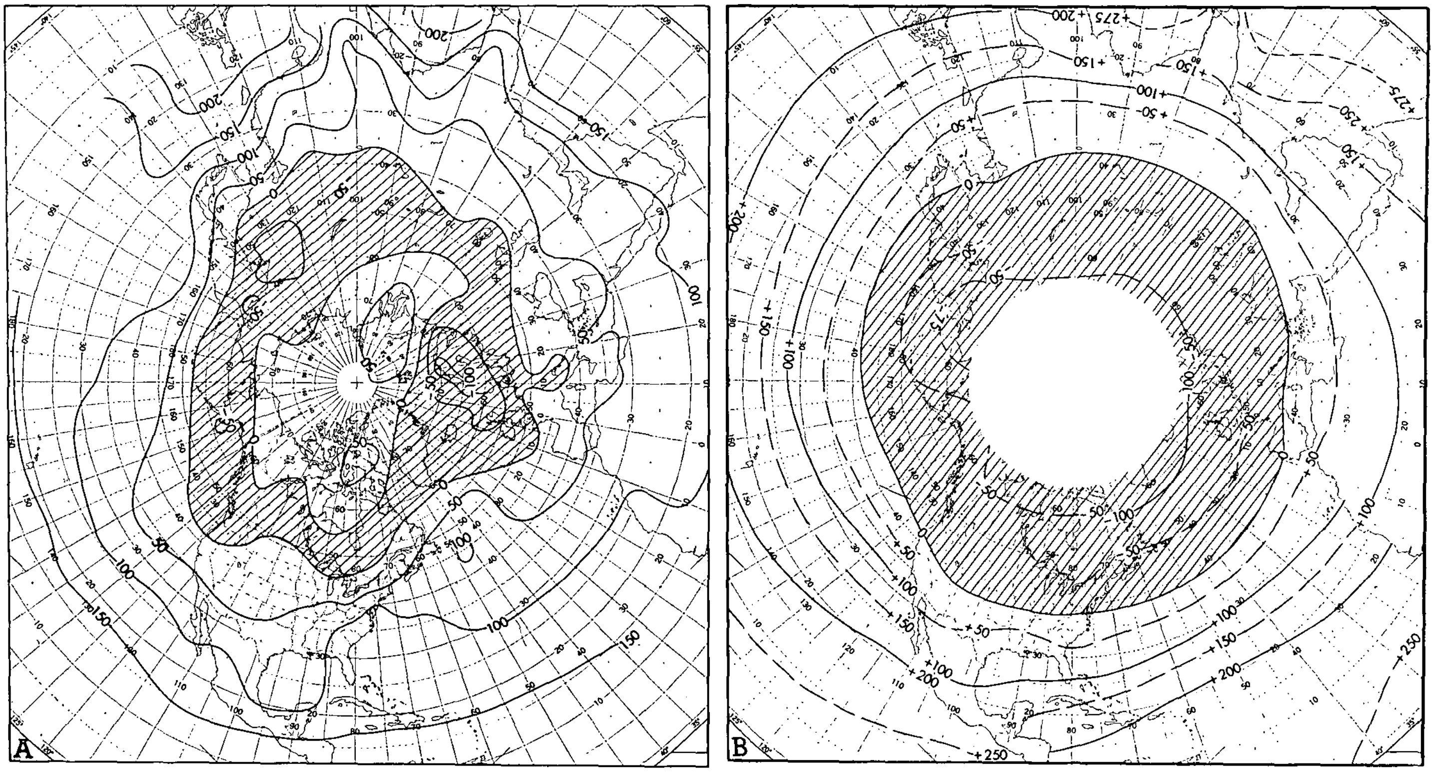

FIGURE 6.—(A) Computed normal excess of radiation at the surface of the earth (E_s), and (B) the corresponding values computed by Budyko [5] in cal. cm.$^{-2}$ day.$^{-1}$

8. FINAL REMARKS AND CONCLUSIONS

We have shown that the large-scale normal pattern of the temperature field for periods of time of a month or a season can be explained using the equations of conservation of thermal energy.

Secondly, by prescribing the temperatures in the oceans and in the mid-troposphere and the snow cover in the previous month, we succeeded in making a qualitative prediction for the January 1963 temperatures at the surface of the earth and in the middle of the troposphere.

The prediction of the departures from normal depends among other things on the initial temperature fields and on the albedo. The changes of albedo due to variations in snow cover greatly affect the temperature. Change in snow cover is the only source of departure from normal in the albedo that we have introduced so far. However, the method allows the introduction of other anomalies of albedo (e.g., those due to changes in wetness of surface) that could persist and produce abnormal conditions during a month or a season.

The importance of the effect of the anomalies of ocean temperature and of snow cover on the atmospheric circulation has been pointed out by Namias [12, 13, 14].

In our computations we have shown that anomalies in the winter of 1963 in the Northern Hemisphere can be predicted using as data the abnormally warm temperatures of the North Atlantic and North Pacific, as well as the abnormally displaced snow cover in the early part of the season. However, it is clear that these abnormal conditions at the underlying surface can themselves be due to the conditions in the tropospheric circulation. However, what we have shown is that once they appear, their influence on the circulation is very important for maintaining an anomalous state that can persist for an extended period.

We have generated heating by radiation within the model and have prescribed the normal value of other heat sources and sinks. A natural extension of this work is to try to generate in the model the energy given off to the atmosphere by condensation of water vapor in the clouds and by evaporation and vertical turbulent conduction of sensible heat at the surface, as well as the cloudiness and the anomalies of the surface albedo.

A detailed knowledge of the austausch coefficient is not essential, and for winter it is sufficient to use a constant value of about 2×10^{10} or 3×10^{10} cm.^{2} sec.^{1}. This value is in agreement with the one obtained previously by the author [1].

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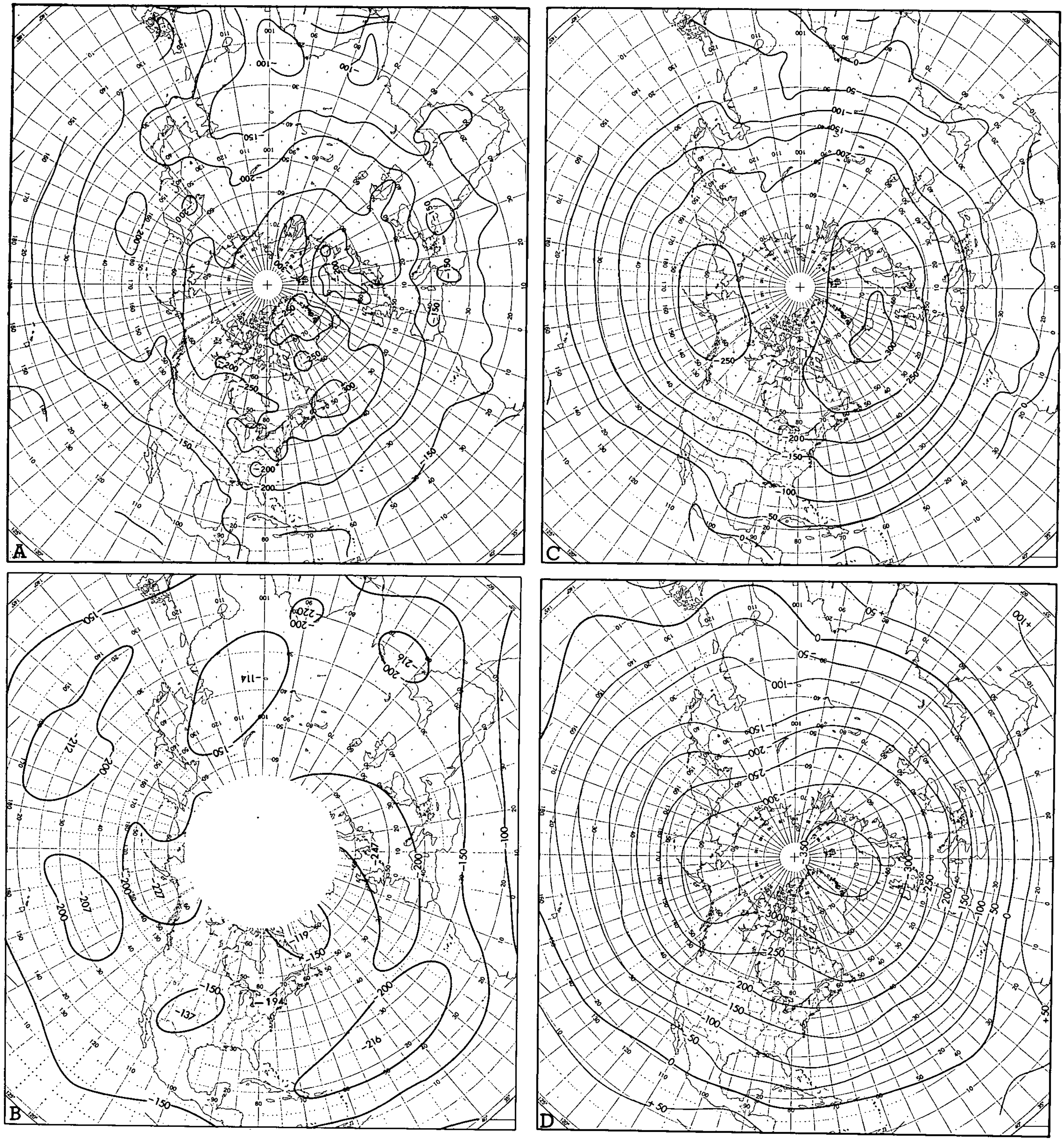

FIGURE 7.—(A) Computed normal excess of radiation in the troposphere (E_A+E_C), and (B) the corresponding values computed by Clapp [7]. (C) Difference between incoming and outgoing radiation at the top of the troposphere $(E_A+E_c+E_s)$, and (D) the corresponding values computed by Simpson [17], in cal. cm.$^{-2}$ day.$^{-1}$

ACKNOWLEDGMENTS

The author is indebted to Mr. J. Namias and Mr. P. F. Clapp for their encouragement and very stimulating discussions and to Mr. B. Lewis and Mr. T. Johnson for preparing the program for the numerical computations.

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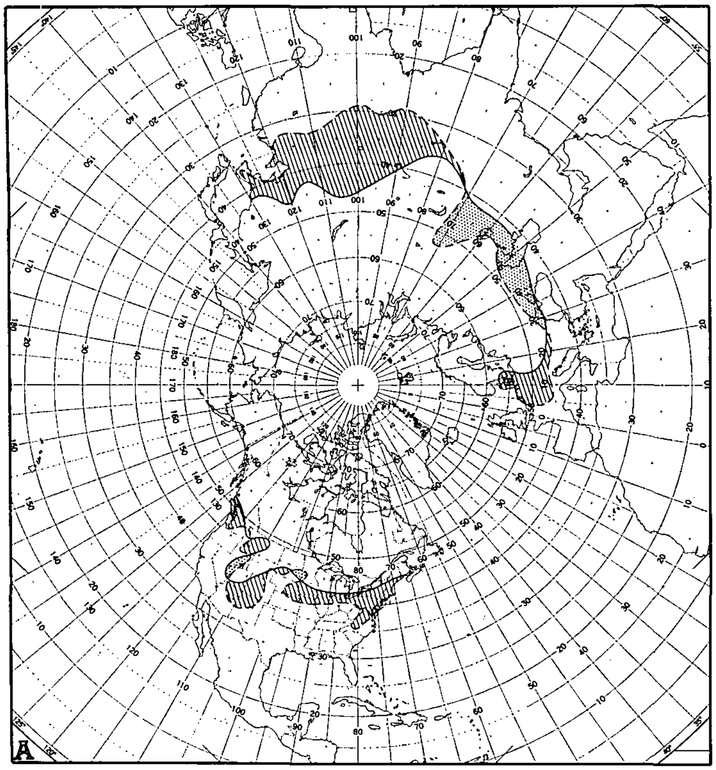

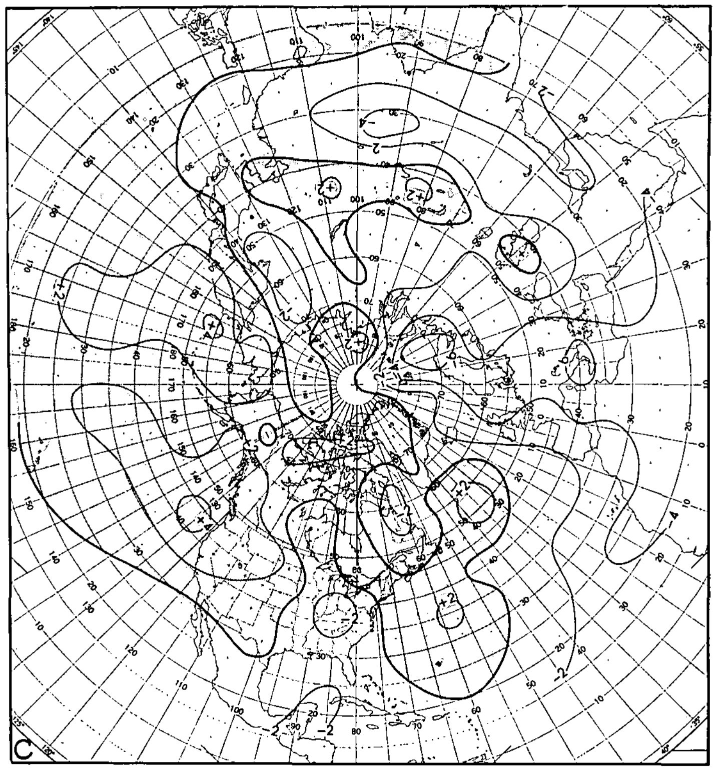

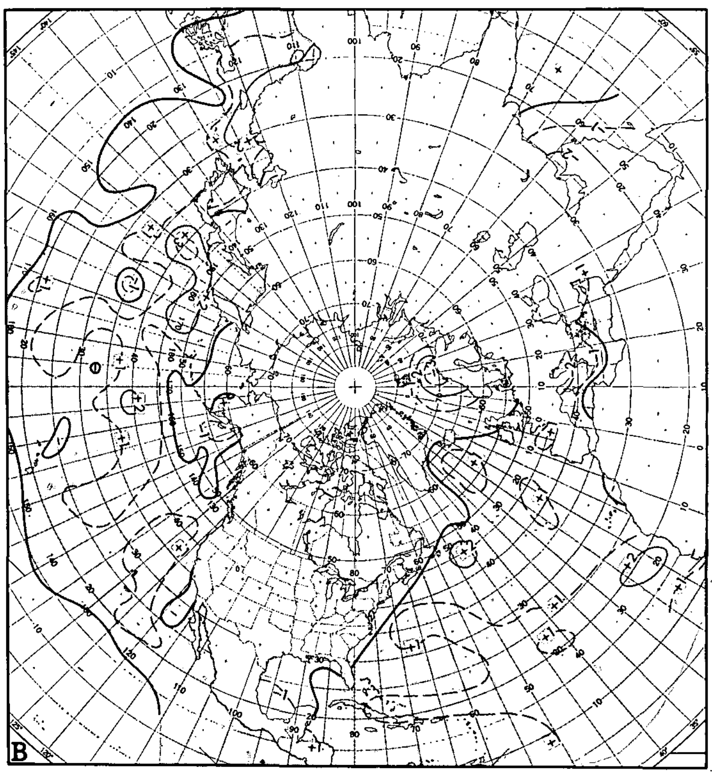

FIGURE 8.—Data used in the prediction for January 1963. (A) shows (dashed line) the boundary of the snow cover on December 31, 1962, and (solid line) the normal boundary in January. (B) and (C) show respectively the departures from normal (°C.) of the ocean temperatures and the 700-mb. temperatures in December 1962.

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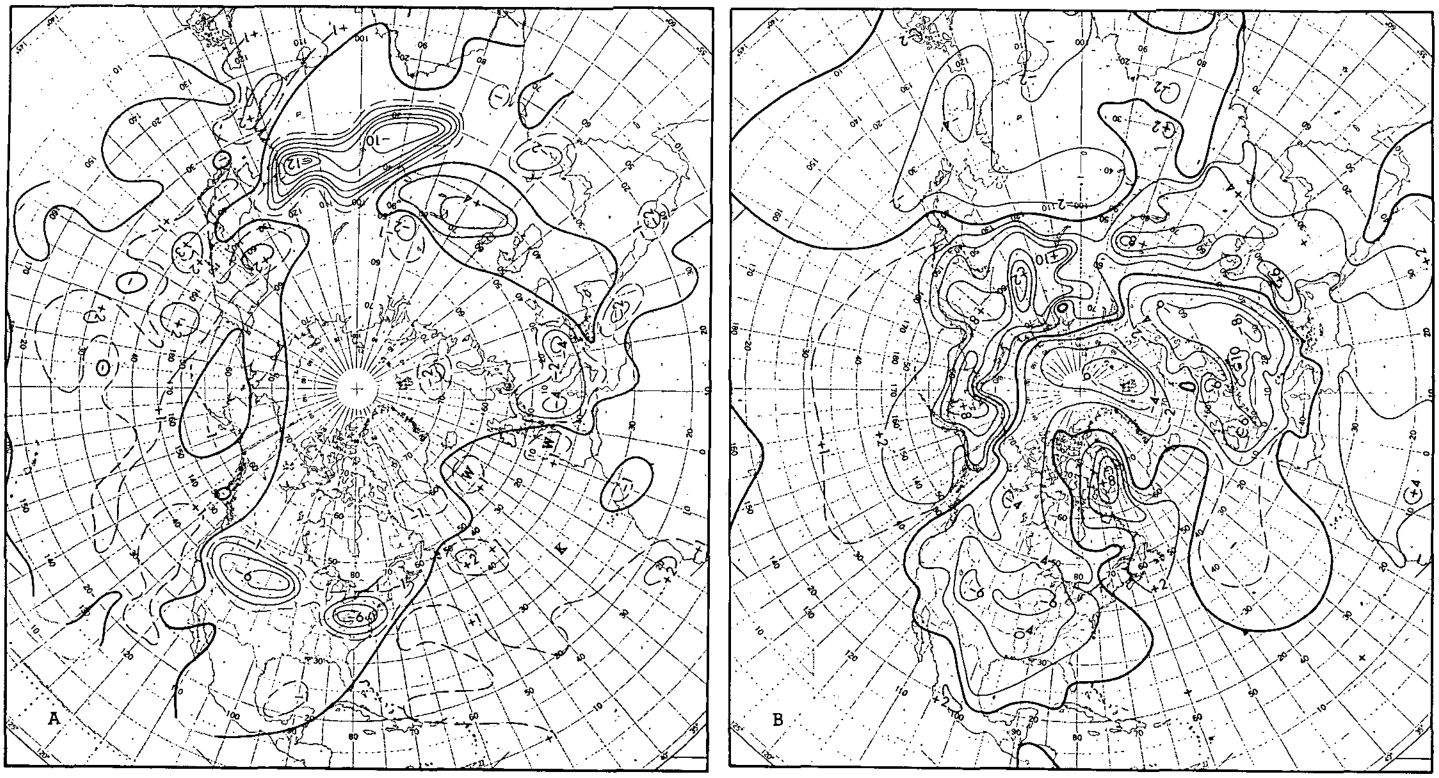

FIGURE 9.—Temperature departures (°C.) from normal at the surface of the earth for January 1963. (A) Predicted, (B) observed.

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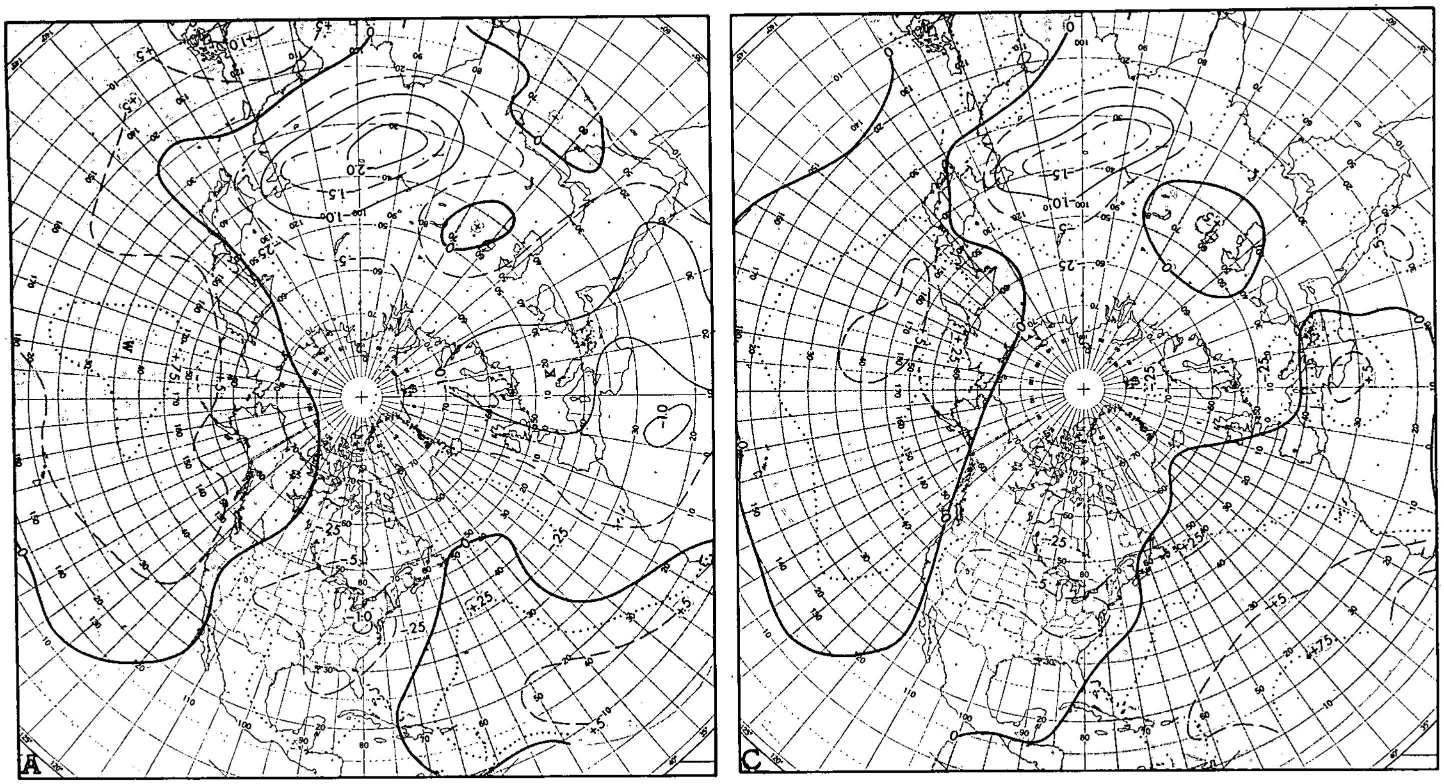
[*Received September 30, 1963; revised October 31, 1963*]



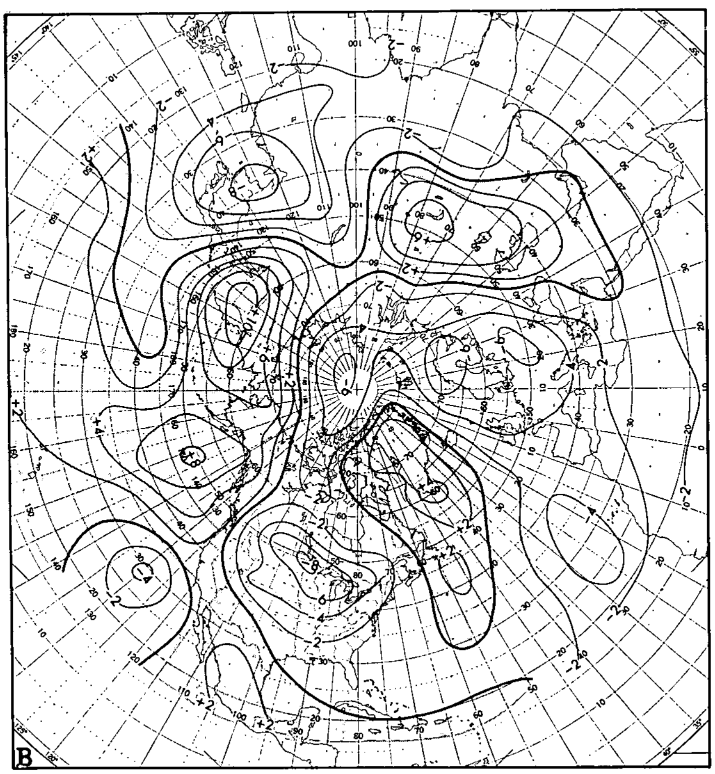


Figure 10.—700-mb. temperature departures (°C.) from normal for January 1963. (A) Predicted, (B) observed. (C) The predicted values when the temperature anomalies at 700 mb. for December are neglected.