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DEPARTMENT OF TRANSPORT
METEOROLOGICAL BRANCH

Technical Memoranda

DESIGN AND EVALUATION OF A TEPHIGRAM OVERLAY FOR PREDICTING MAXIMUM TEMPERATURES

BY

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ABSTRACT

An overlay to be applied to the Canadian Tephigram (Form 63-2394) for the prediction of maximum temperature is described in this paper. In order to apply the overlay, the amount of energy which is available for raising the temperature of air in the lower layers of the atmosphere must be known. A procedure for computing this energy which accounts for the depletion of solar radiation by reflection, absorption and terrestrial radiation is described. This method of maximum temperature prediction was evaluated using six months (May - October, 1967) of data for Edmonton, Alberta. When cases of temperature advection were excluded so that the temperature change was a result of solar insolation alone, it was found that useful predictions were possible. An error analysis made of 93 cases when advection was absent gave a mean absolute error of 2.68 degrees F and a RMS error of 3.45 degrees F between predicted and observed values of maximum temperature.

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CONCEPTION ET ÉVALUATION D'UNE SURCHARGE DE TÉPHIGRAMME POUR LA PRÉVISION DE LA TEMPERATURE MAXIMALE

par

N. H. Kagawa

RÉSUMÉ

L'auteur décrit une surcharge à appliquer au téphigramme canadien (formule 63-2394) en vue de la prévision de la température maximale. Pour appliquer cette surcharge, il faut connaître la somme d'énergie disponible pouvant amener une hausse de la température de l'air dans les couches inférieures de l'atmosphère. Il décrit une procédure de calcul de cette énergie qui tient compte du tarissement de la radiation solaire par la réflexion, l'absorption et la radiation terrestre. Cette méthode de prévision de la température maximale a été évaluée en utilisant des données portant sur une période de six mois (de mai à octobre 1967) pour Edmonton (Alb.). Après avoir exclu les cas d'advection de température pour ne tenir compte que des changements de température dus au seul rayonnement solaire, l'auteur a découvert que des prévisions utiles étaient possibles. Une analyse d'erreur de 93 cas d'absence d'advection a donné une erreur absolue moyenne de 2.68 degrés F et une erreur moyenne quadratique de 3.45 degrés F entre les valeurs prévues et les valeurs observées de température maximale.

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(Manuscript received May 21, 1968)

1. Introduction

The prediction of maximum temperature is a problem the forecaster must cope with daily. It would therefore be useful to have an objective method based on physical principles for handling this problem. In the United States and Britain, transparent overlays which are to be applied over a thermodynamic diagram have been designed for this purpose. The technique involves the calculation of that portion of solar radiation which contributes to raising the temperature of the air and adding this amount of energy to the sunrise temperature sounding. Forecasts made in this way have been found to give useful and consistently good answers.

Because of the success achieved with this method, this study was undertaken to design an overlay which could be applied to the Canadian Tephigram (Form 63-2394) and to evaluate its usefulness at a Canadian location.

2. Theory

On a true thermodynamic diagram such as a Tephigram, a closed area is directly proportional to energy. If a suitable relationship can be found between these two quantities i.e. heat added and area on a Tephigram, then a Tephigram overlay can be designed for use in predicting maximum temperatures.

Godson (3) has shown that the heat input Q_a is related to area on the Tephigram by the following equation:

$$Q_a = \frac{C_p}{Rg} \cdot \bar{p} A \qquad (1)$$

Where Q_a = heat added to the lower atmosphere due to solar insolation

C_p = specific heat of air at constant pressure = 0.240 cal g^{-1} ^{o}K^{-1}

R = gas constant for dry air = 6.8557×10^{-2} cal $g^{-1}\ {}^{o}K^{-1}$

g = acceleration due to gravity = 980 cm sec^{-2}

$\overline{p}$ = mean pressure of the layer of air immediately above the earth's surface which is warmed by solar insolation.

A = area on the Tephigram.

If Q_a is expressed in cal/cm^2, A in cal/g and $\overline{p}$ in mb, equation (1) may be written

$$A = \frac{0.28\ Q_a}{\overline{p}} \qquad (2)$$

On the Canadian Tephigram (Form 63-2394) an area of 1 cm^2 = 1/106 cal/g.

The area A in equation (2) can therefore be expressed in cm^2 instead of cal/g as follows:

$$A\ (cm^2) = \frac{0.28\ Q_a\ (cal/cm^2) \times 106}{\overline{p}\ (mb)} \qquad (3)$$

Rearrangement of equation (3) gives

$$Q_a\ (cal/cm^2) = \frac{\overline{p}\ (mb) \times A\ (cm^2)}{29.7} \qquad (4)$$

3. Design of the Tephigram Overlay

A Tephigram overlay for predicting maximum temperature is shown full size in Fig. 1. Its construction is based on equation (4) which relates heat input to a closed area on the Tephigram. The description and details of its construction are given below:

1. In Fig. 1, the triangular areas $AB_{50}C_{50}$, $AB_{100}C_{100}$, $AB_{200}C_{200}$, $AB_{700}C_{700}$ represent heat or energy equal to 50, 100, 200, 700 cal/cm^2.

2. The first side of the triangle AB was chosen along the 10 deg C or 50 deg F isotherm.

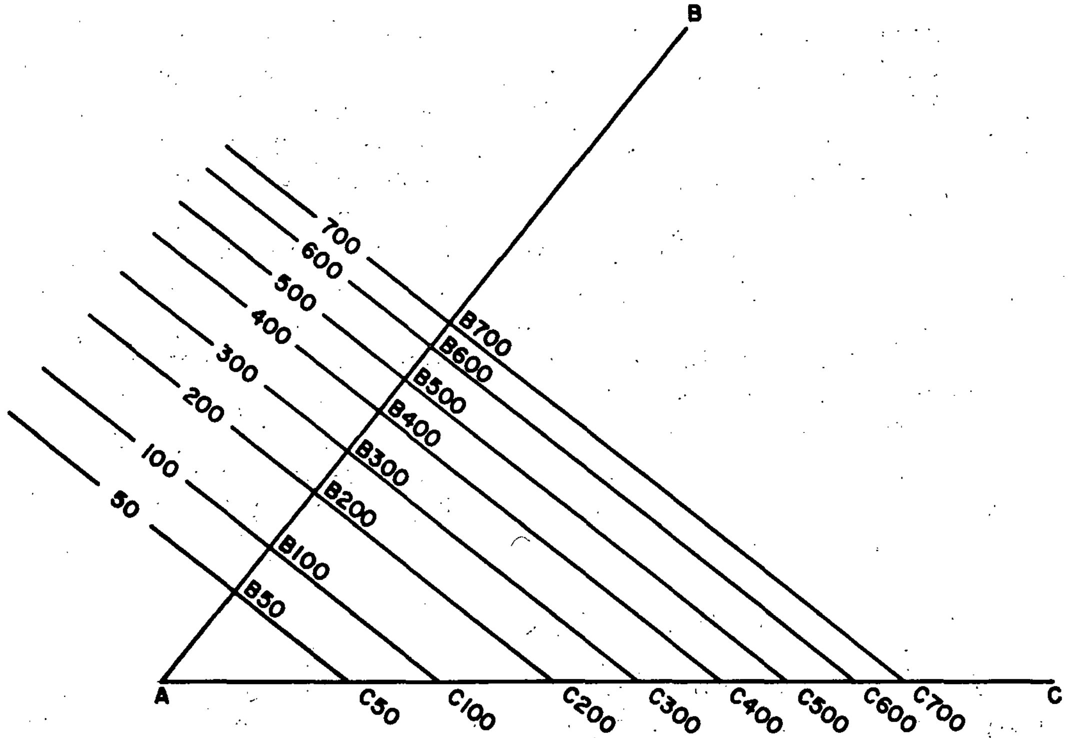

Figure 1

Tephigram Overlay for Predicting Maximum Temperature
Scale: Full Size

3. The second side of the triangle AC was chosen along the 1000 mb isobar on the Tephigram. Isobars on the Tephigram are very slightly curved. However, in designing the overlay, the 1000 mb isobar was approximated by the straight line AC.

4. The third side of the triangle was constructed parallel to the dry adiabats and was found by trial and error. For example to find the area equal to 200 cal/cm^2 of energy, a triangle $AB_{200}C_{200}$ such as in Fig. 1 was drawn as a first approximation. The area A of this triangle was then computed and the mean pressure $\overline{p}$ was determined by averaging the pressure at point B_{200} and 1000 mb (the pressure along the base of the triangle AC_{200}). These values of A and $\overline{p}$ were substituted into equation (4) and a value for Q_a was computed. This trial and error process was repeated until a triangle whose area represented 200 cal/cm^2 was found.

   In a similar manner, triangular areas proportional to 50, 100, 300, 400, 500, 600 and 700 cal/cm^2 of energy were found.

4. Use of the Tephigram Overlay

The purpose of this section is to describe the mechanics of applying the Tephigram overlay. This can best be demonstrated by considering the examples shown in Fig. 2A and 2B.

Consider first Fig. 2A and assume that an amount of insolation equal to 400 cal/cm^2 is available for heating the lower atmosphere. To predict the maximum temperature, it is necessary to add an area corresponding to 400 cal/cm^2 to a temperature sounding taken through the atmosphere at sunrise. If the overlay were superimposed onto the sounding, a picture such as Fig. 2A would result where the triangular area $AB_{400}C_{400}$ represents 400 cal/cm^2. To add area $AB_{400}C_{400}$ to the sounding, note that it is the sum of the two areas $B_{400}C_{400}$ ZY and AYZ. If the overlay is adjusted such that area AYZ = area $XB_{400}Y$, area $XB_{400}C_{400}$ ZY then represents 400 cal/cm^2 of heat added to the sunrise sounding and the maximum temperature which can be attained is the temperature at point C_{400}. Note that during the adjustment of the overlay to obtain area AYZ = area $XB_{400}Y$, the base of the overlay should parallel as closely as possible the isobar through point Z.

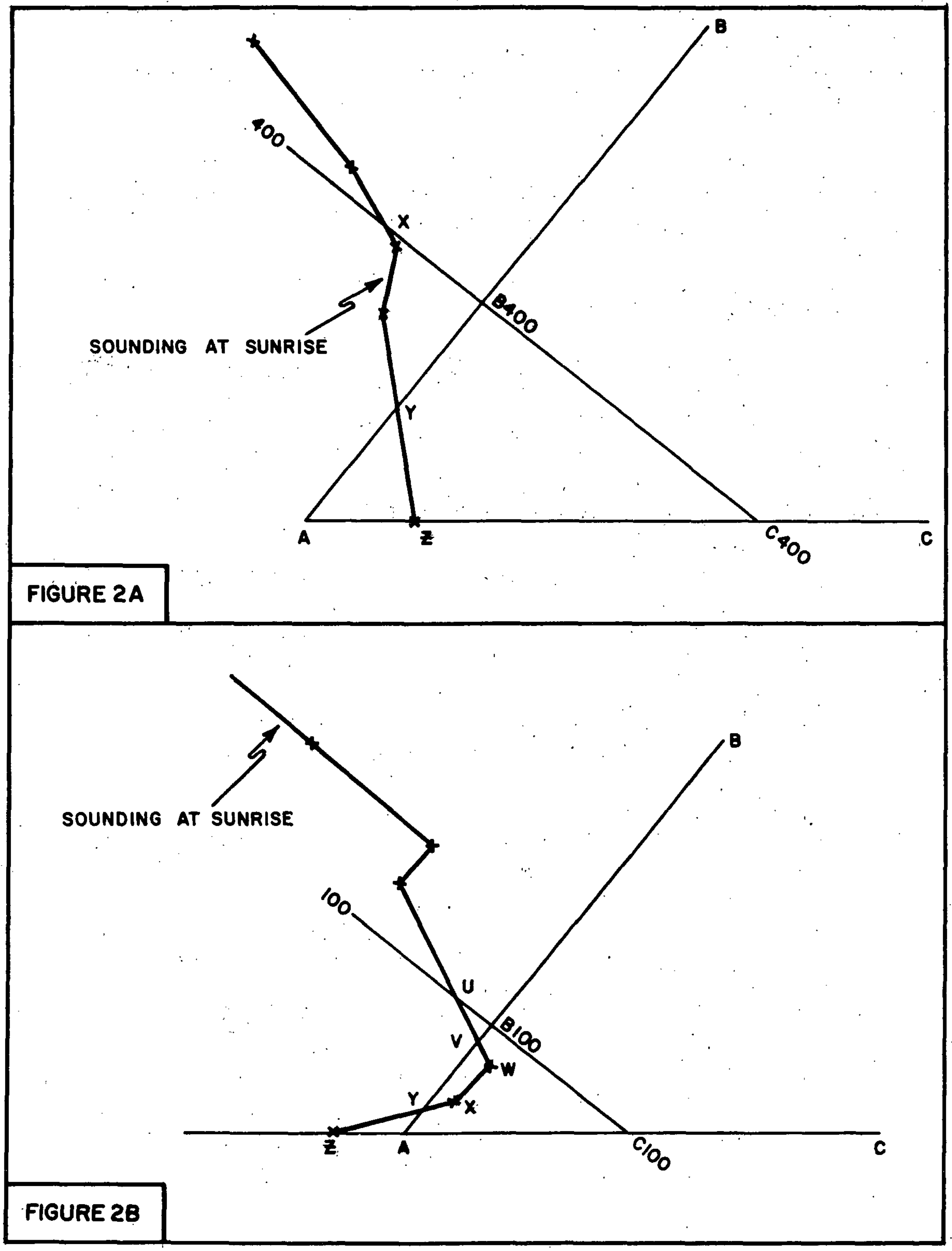

Figure 2

Use of the Tephigram Overlay

With regard to Fig. 2B, it is assumed that 100 cal/cm^2 of insolation is available for heating and raising the temperature of the lower atmosphere. It is therefore necessary to add area $AB_{100}C_{100}$ to the sunrise sounding to obtain a prediction of maximum temperature. This is done by adjusting the overlay until area XWVY = area UVB_{100} + area AYZ and the maximum temperature forecast is the temperature at point C_{100}.

In a similar manner, it is possible to apply the overlay to any temperature sounding regardless of its configuration, and thus arrive at a prediction of maximum temperature.

5. Computation of Energy Available for Heating the Lower Atmosphere

In order to forecast maximum temperatures using the Tephigram overlay, it is necessary to obtain a quantitative estimate of the energy available for raising the temperature of the air near the ground. A procedure for accomplishing this has been suggested by Myers (7) and Dickey (1). Their method is described below with only minor changes.

1. Enter Fig. 3 (of the Appendix) with the date, the predicted amount of cloud cover in tenths of sky, and the station latitude. Read off the insolation in cal/cm^2. Fig. 3A represents insolation values for latitude 45 degrees N and Figs. 3B, 3C and 3D, the values for latitudes 50, 55 and 60 degrees N respectively. Values given by these graphs represent energy available for warming the lower atmosphere after accounting for loss of solar radiation by reflection from the sky and clouds.

   The graphs of Fig. 3 were designed as follows. The amount of solar energy in cal/cm^2 which would be incident on the earth's surface in one day if there were no atmosphere was determined from data by Shaw (10). Following Myers (7), 80 per cent of these values was taken to find the amount of energy which contributes to raising the surface temperature to the daily maximum. These energy amounts were then reduced to account for reflection by sky and clouds according to albedo values given in Table 1.

2. In addition to reflection of solar radiation by clouds and sky, reflection by the earth's surface reduces the energy available for raising the temperature of the air as shown by Dickey (1). Enter Table 2 of the Appendix and find the albedo of the earth's surface at the location where the forecast is to be made. Reduce the insolation found in Step 2 by an amount corresponding to the albedo of the surface.

3. Part of the incoming solar energy must contribute to heating the soil and is therefore not available for raising the temperature of the air. Myers (7) suggests that on the average, approximately 20 per cent of the insolation between sunrise and maximum temperature time goes into heating the soil. Therefore the insolation calculated in Step 3 above should be reduced further by 20 percent.

4. The earth radiates approximately as a black body at a rate proportional to the temperature of the earth's surface. To estimate the net loss of long-wave terrestrial radiation with clear skies, enter Table 3 of the Appendix with the expected average temperature and the length of time between sunrise and maximum temperature. The mean times of maximum temperature for various locations in Canada may be found in data published by Harley (4).

   Table 3 after Hewson and Longley (12), gives the long wave terrestrial radiation values with clear skies. If clouds are present, the net loss of terrestrial radiation will be less than with clear skies and can be computed using the formula

$$S_o(n) = S_o(1-kn) \qquad (5)$$

   where

   $S_o(n)$ = net loss of long-wave terrestrial radiation with n tenths of cloud.

   S_o = net loss of long-wave terrestrial radiation with cloudless skies.

   k = a constant depending on the cloud type and cloud height. Reuter (9) suggests the following values for k,

Cloud Type	Value of k.
Cirrostratus	0.031
Altostratus	0.063
Stratus	0.085
Nimbostratus	0.099

n = number of tenths of sky covered by cloud.

The value of $S_o(n)$ computed in this manner must now be subtracted from the value obtained in Step 3.

The amount of energy remaining after Step 4 represents that portion of the original incoming solar radiation which contributes to raising the temperature of the air. The Tephigram overlay can now be used to add this value of heat to a plot of the sunrise radiosonde ascent and to predict the maximum temperature.

It should be noted that evaporation from the earth's surface will further reduce the amount of energy for heating the air in the lower levels but has been assumed small or negligible in the above analysis. If, however, the evaporation amount is known quantitatively, the heat required to produce this evaporation can be deducted from the value obtained in Step 4, or otherwise, a qualitative adjustment can be made.

6. Experiments in Forecasting Maximum Temperatures With the Tephigram Overlay.

Predictions of maximum temperature were made for Edmonton, Alta., during the period May 1 - October 31, 1967. Since the Tephigram overlay cannot be applied on occasions when temperature advection contributes to the temperature change, these cases were eliminated from the test data. To assess whether or not advection was a factor contributing to the change of temperature, the 1200 GMT radiosonde ascents were plotted on a Tephigram and examined. If the 700 mb temperature changed by 3 degrees C or more in the following 24 hour period, it was assumed advection had taken place and the case was rejected. When this criterion was employed to assess advection, 93 days of this six month period were found acceptable as "no-advection days". The experiments with the overlay were then performed on these 93 days.

It was realized that the method of determining advection used here has limitations since advection can occur at levels below 700 mb leaving the 700 mb temperature virtually unchanged. However, in the majority of cases, experience shows 700 mb and lower level temperature advection occur simultaneously.

In the first experiment, it was assumed that the amount of energy available for raising the temperature of the lower atmosphere was equal to the clear sky insolation amounts given in Fig. 3. The depletion of solar energy by reflection and absorption by the ground, and long-wave terrestrial radiation from the earth's surface were not accounted for. It was therefore expected that these values of energy would result in maximum temperature forecasts which would be too high. However, it would provide an objectively determined upper limit on the forecast.

The results of this forecast experiment are shown in Fig. 4. As expected, the forecasts were too high as in only 1 of the 93 cases was the predicted maximum temperature greater than the reported value.

In the second experiment, the heat available for raising the temperature of the lower atmosphere was calculated by the method outlined in Section 5 of this paper, which accounts for the depletion of incident solar radiation by reflection, absorption and long-wave terrestrial radiation. The method was simplified slightly by (1) ignoring the effect of cirrus clouds on the reflection of incident solar radiation and (2) assuming low and middle clouds affect radiation in the same way. An example of such a computation is presented below for Edmonton, Alta., for June 29, 1967.

Required data.

(a) Average amount of low and middle cloud between sunrise and time of maximum temperature - 4/10 ths.

(b) Time in hours between sunrise and the time of maximum temperature = 11.

Calculations.

1. Enter Figure 3C with the date and cloud amount and determine the insolation to be 550 cal cm^{-2}. This represents the energy remaining after accounting for depletion by reflection from clouds and atmosphere.

2. From Table 2 of the Appendix, the albedo of the earth's surface will likely be between 8 and 20 percent. Assuming an albedo of 15 per cent, the insolation lost by reflection from the earth's surface is 550 x 0. 15 = 83 cal cm^{-2}. The energy remaining is then 550 - 83 = 467 cal cm^{-2}.

3. Twenty per cent of the 467 cal cm^{-2} can be assumed to go toward heating the soil. This leaves 467 - 93 = 374 cal cm^{-2}.

4. From Table 3 of the Appendix, the net loss of long-wave terrestrial radiation from sunrise to maximum temperature time at an average temperature of 50 degrees F. and with clear skies is 120 cal cm^{-2}. This value must be reduced to account for cloud cover according to the equation $S(n) = S_o(1 - kn)$. In the computations made for this experiment, k was taken to be 0.063 so that $S = 120 (1 - 0.063 \times 4) = 90$ cal cm^{-2}. The remaining energy is 374 - 90 = 284 cal cm^{-2} which represents the amount of heat available for increasing temperature of air in the lower atmosphere.

   This amount of energy was added to the 1200Z Edmonton radiosonde ascent using the Tephigram overlay. The same procedure was followed to arrive at a maximum temperature forecast in the remaining 92 cases. The predicted maximum temperatures were compared with the reported maximum temperature and are illustrated in the scatter diagram of Fig. 4, which shows that reasonably accurate forecasts were made. An analysis of the errors gave a mean absolute error of 2.68 degrees F. and an RMS error of 3.45 degrees F.

7. Summary.

The results of Section 6 show that the Tephigram overlay used in combination with the method for computing the energy available for heating the lower atmosphere described in Section 5 will give useful forecasts of maximum temperature. It should be noted that the tests were conducted during the warmer months of May to October. Some difficulty should be anticipated if this technique is attempted during winter particularly at the higher latitude stations. The difficulty arises because the amount of energy available for warming the lower atmosphere is small and it is even possible that this quantity be negative i.e., there is a net loss of energy. Because of this it is necessary that radiosonde ascent temperatures and their plotting be extremely accurate in the atmospheric boundary layer. Where radiosonde ascents must be forecast in order to apply this method, small errors in ascent temperatures can result in large errors in the maximum temperature forecast and seriously limits its usefulness under these conditions.

The Tephigram overlay is applicable only when temperature advection is absent. However on days when temperature advection is apparent, a forecast can be made assuming there is no advection and then adjusting for the advection qualitatively.

The method of forecasting maximum temperatures described in this paper represents an attempt to solve the radiation balance of the lower atmosphere and earth in quantitative manner. For this reason, the method has instructional as well as practical value.

8. Acknowledgement.

The author wishes to express his appreciation to Mr. G. A. McPherson for his aid and suggestions with the thermodynamic theory.

APPROVED

J.R.H. Noble,
Director,
Meteorological Branch.

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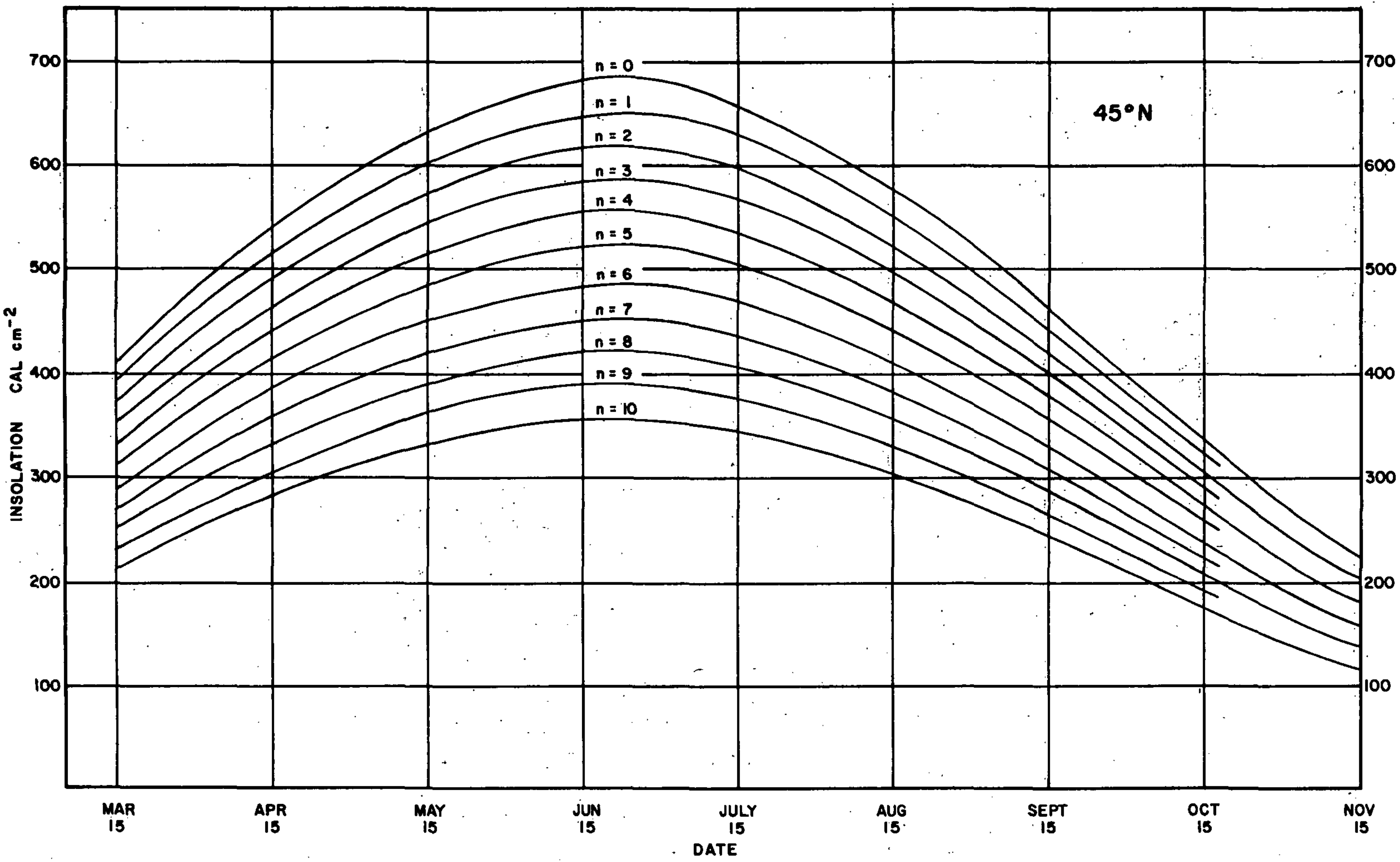

Figure 3A

Insolation Values at 45°N. Latitude for Different Cloud Amounts "n"

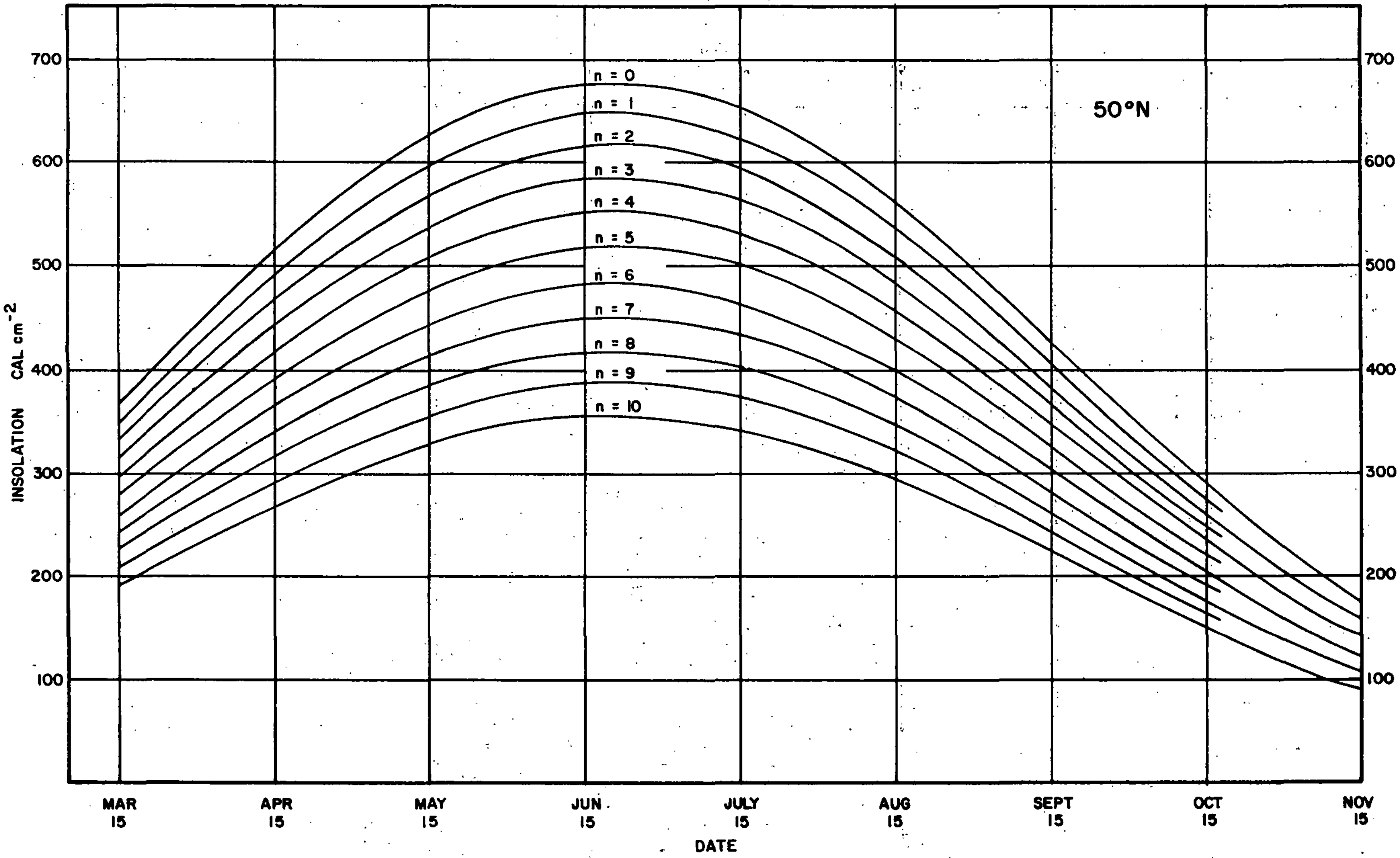

Figure 3B

Insolation Values at 50°N. Latitude for Different Cloud Amounts "n"

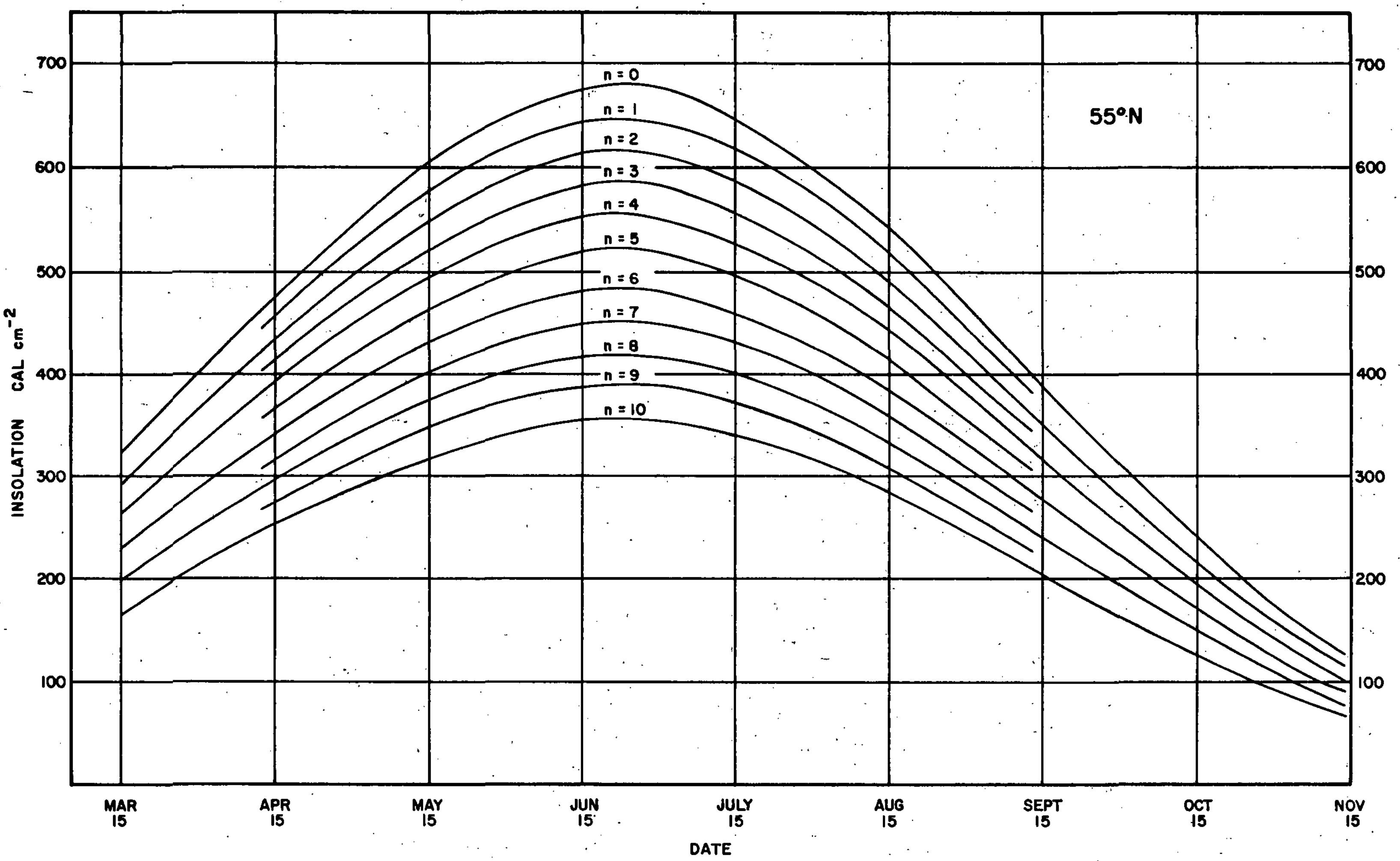

Figure 3C

Insolation Values at 55°N. Latitude for Different Cloud Amounts "n"

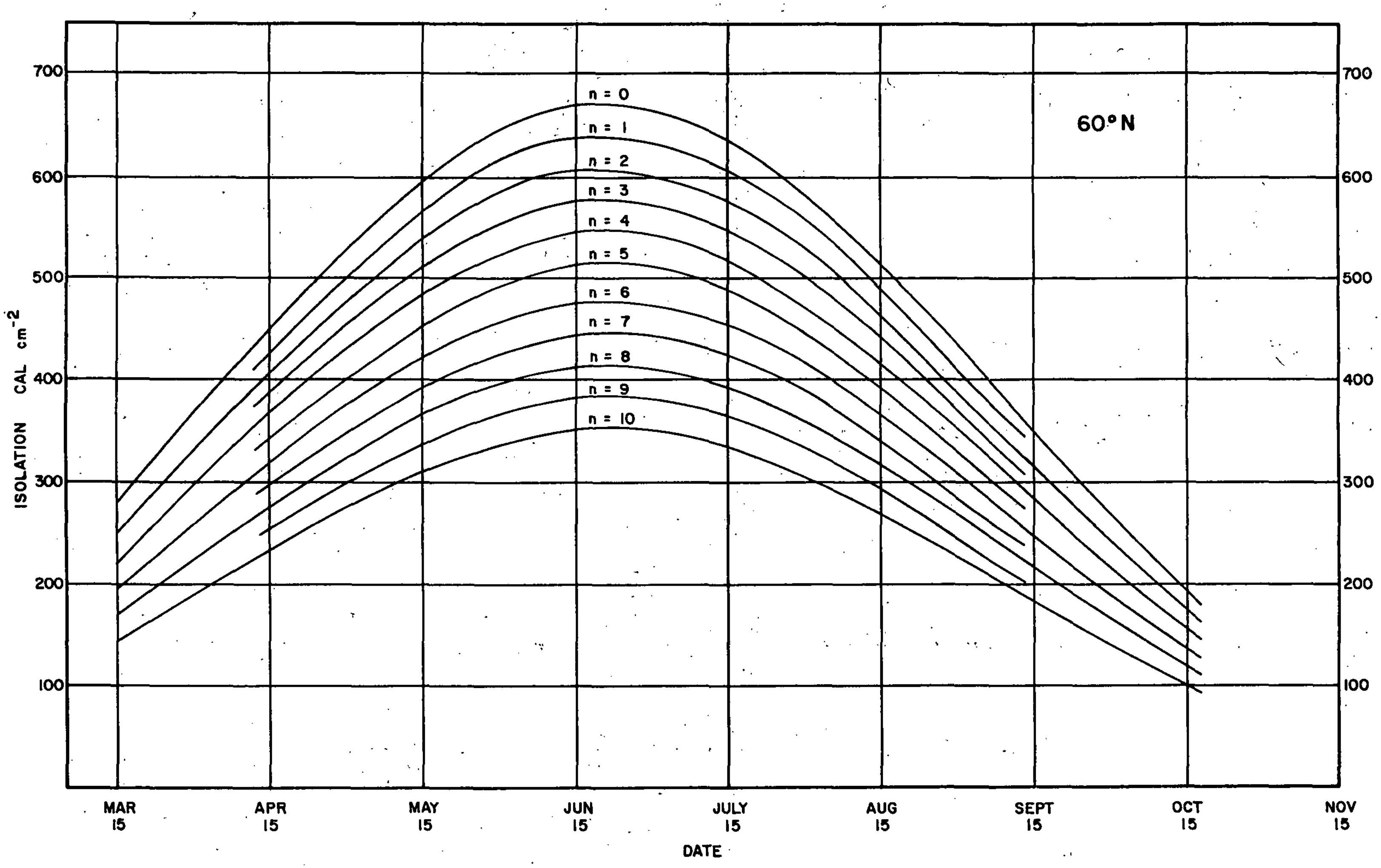

Figure 3D

Insolation Values at 60°N. Latitude for Different Cloud Amounts "n"

CLOUD AMOUNT	ALBEDO %
0.0	14
0.1	18
0.2	22
0.3	26
0.4	30
0.5	34
0.6	39
0.7	43
0.8	47
0.9	51
1.0	55

TABLE 1: Albedo of Clouds & Atmosphere for different Cloud Amounts - After Williams (11)

TYPE OF SURFACE	ALBEDO %
Cultivated Soil and Vegetation	8
Bare Ground	14
Grass	20
Dry Sand	18
Wet Sand	9
Fresh Snow	85
Old Snow	55

TABLE 2: Values of Albedo for Different Types of Surfaces - After Dickey (1)

	Hours Between Sunrise & Max. Temp.				
Temp °F	8	9	10	11	12
10	63	71	79	86	94
20	69	77	86	94	103
30	75	85	94	104	113
40	81	91	101	111	121
50	87	98	109	120	131
60	96	108	120	132	144
70	103	116	128	141	154
80	111	125	139	152	166

TABLE 3: Net Loss of Long-Wave Terrestrial Radiation in Cal/cm^{-2} for clear skies and for various lengths of time. (Based on Hewson & Longley's Formula

$S_o = 2.85 \times 10^{-11}\ T^4$ cal cm^{-2} min^{-1})

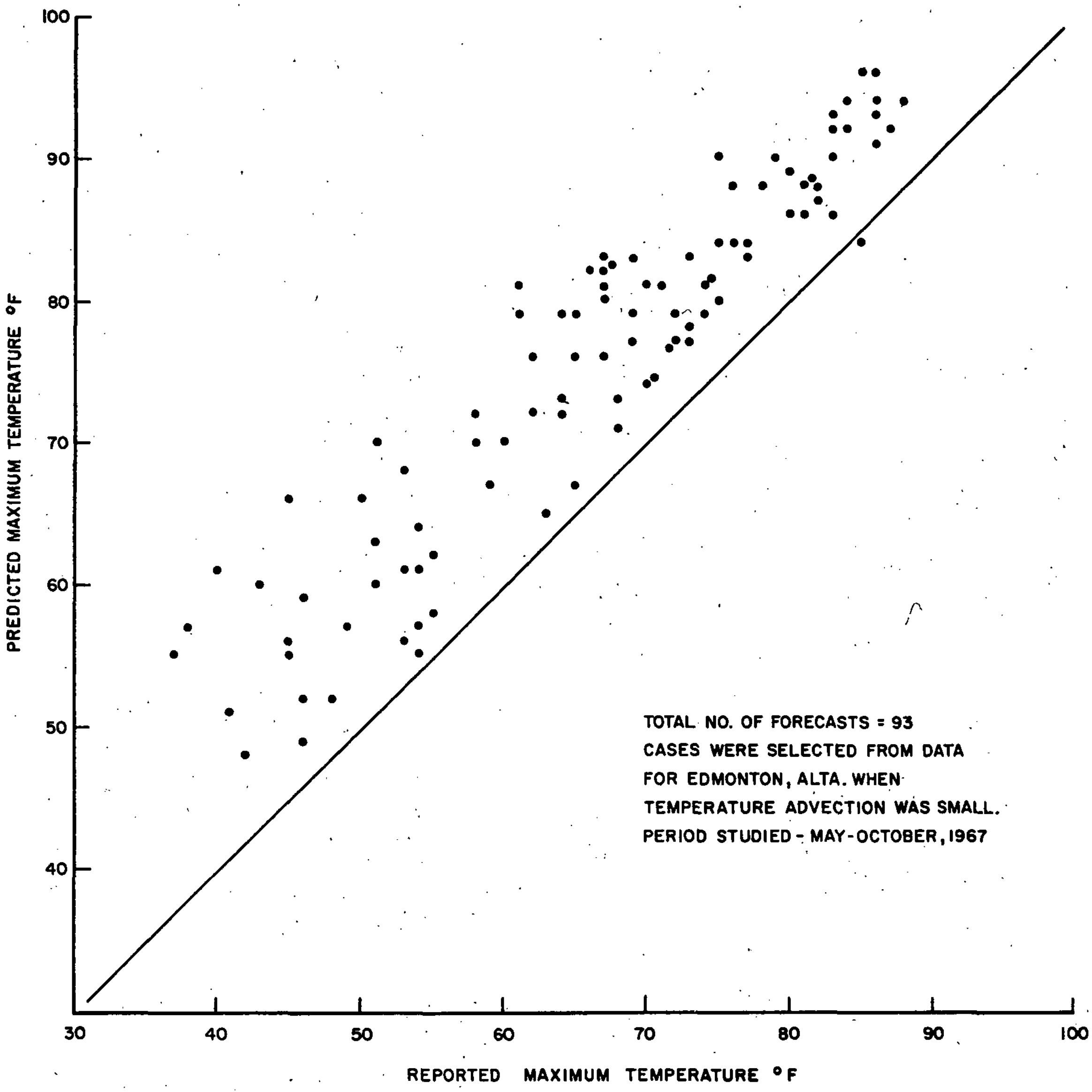

Figure 4

Plot of Predicted vs Reported Maximum Temperature at Edmonton Alta. Maximum Temperatures were Forecast with a Tephigram Overlay Assuming the Energy Available for Raising the Air Temperature was Equal to the Clear Sky Insolation Amounts Given in Figure 3 Heat Loss by Reflection and Absorption by the Ground and Long-Wave Terrestrial Radiation was Ignored

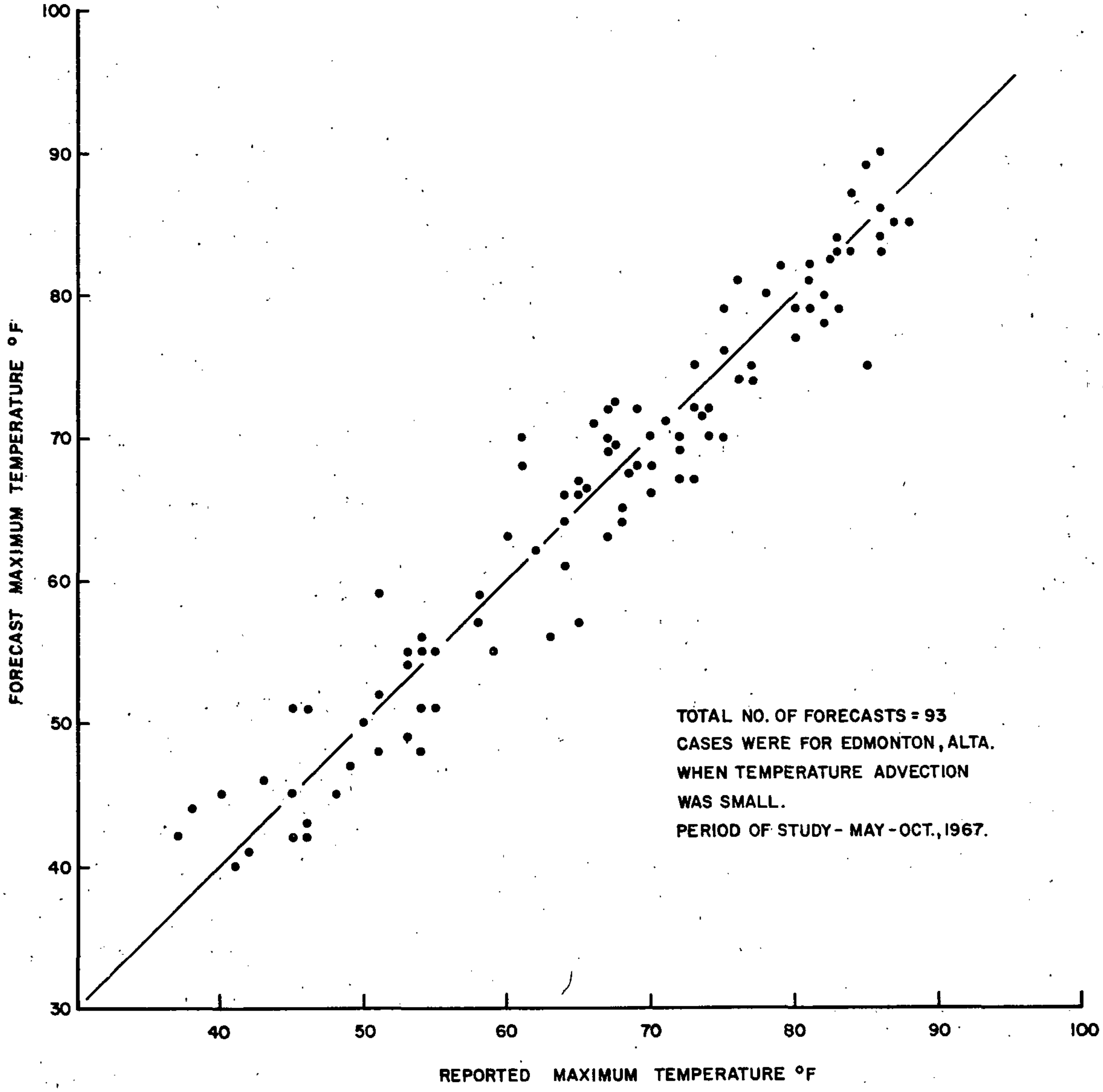

Figure 5

Plot of Predicted vs Reported Maximum Temperature at Edmonton Alta. Maximum Temperatures were Forecast Using a Tephigram Overlay Assuming Depletion of Solar Radiation by Reflection, Absorption and Long-Wave Terrestrial Radiation

WORK SHEET FOR FORECASTING MAXIMUM TEMPERATURES

REQUIRED DATA

Date ______________________

Station Latitude ______________________

Estimated Average Cloud Amount in Tenths
Between Sunrise and Maximum Temperature Time n = __________

Estimated Mean Temperature Between Sunrise
and Maximum Temperature Time ______________________

Time in Hours Between Sunrise and
Time of Maximum Temperature ______________________

PROCEDURE

1. Determine Insolation Received at Ground Taking Account of Reflection by Clouds and Sky

   Enter Figure 3 with the date, latitude and estimated amount of cloud cover.

   Insolation received at ground I_g = ______________ cal cm^{-2}

2. Deduct Energy Reflected by Ground

   Enter Table 2 and determine the albedo of the ground surface.

   Albedo = ______________ %

   Energy reflected by ground = I_g x Albedo

   = ______________ x ______________ cal cm^{-2}

   Remaining energy = Ig - Energy Reflected by Ground

   = ______________ - ______________

   = ______________ cal cm^{-2}

3. Deduct Energy Absorbed by Ground

   Assume 20% of the energy remaining after Step 2 is absorbed by the ground.

   Energy absorbed by Ground = 0.20 x Remaining energy from Step 2

   = 0.20 x ______________

   = ______________ cal cm^{-2}

   Remaining Energy = Remaining Energy from Step 2 - Energy absorbed by Ground

   = ______________ - ______________

   = ______________ cal cm^{-2}

4. Deduct Energy Loss Due to Long-Wave Terrestrial Radiation

Enter Table 3 with (a) the estimated average temperature between sunrise and the time of maximum temperature and (b) the time in hours between sunrise and maximum temperature time. Obtain the net loss of long-wave terrestrial radiation under clear sky conditions.

S_o = ________________________ cal cm^{-2}

Compute the terrestrial heat loss $S_o(n)$ taking account of cloud cover.

For low clouds use k = 0.085

For middle clouds use k = 0.063

$S_o(n) = S_o(1 - kn)$

= ____________________ (1- ____________________ x ______________

= ____________________ cal cm^{-2}

Energy available for warming the lower atmosphere = Remaining Energy Computed in Step 3 - $S_o(n)$

= ________________ - ________________

= ________________ cal cm^{-2}

The Tephigram overlay can now be used to add this value of energy to a plot of the sunrise radiosonde ascent and to predict the maximum temperature.

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28 May 1968

CANADA

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