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TROPOSPHERIC HEATING AND COOLING FOR SELECTED DAYS AND LOCATIONS OVER THE UNITED STATES DURING WINTER 1960 AND SPRING 1962

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PHILIP F. CLAPP AND FRANCIS J. WINNINGHOFF

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TROPOSPHERIC HEATING AND COOLING FOR SELECTED DAYS AND LOCATIONS OVER THE UNITED STATES DURING WINTER 1960 AND SPRING 1962

Philip F. Clapp and Francis J. Winninghoff
Research Branch, Extended Forecast Division

1. INTRODUCTION

In a previous report (Clapp, Winninghoff and Fisher, [2]), tabulations were given of the principal components of heating and cooling in the troposphere for 12-hr. periods during the summer of 1961 at Washington, D. C. Since publication of that report, a computer program became available which permitted what was by far the most time-consuming and laborious part of the computations (heating or cooling of the atmosphere by radiation), to be carried out very rapidly and easily. This encouraged the authors to extend the earlier study to different localities and seasons; the subject of the present report.

For the objectives and background of this series of computations the reader is referred to [2] which in addition contains a more detailed explanation of procedures, here somewhat curtailed. Two series of calculations were undertaken. The first was designed to give the day-to-day variation of heating in time as in [2] but for winter, and with some information on differences of heating in space. Therefore three midwestern United States cities were selected about 350 mi. from each other (Peoria, Ill.; Columbia, Mo.; and Topeka, Kans.) where calculations were made for the 31-day period February 16 to March 15, 1960. The second series was designed to emphasize the variation of heating in space. For this purpose data were chosen for the 5-day period May 8-12, 1962, for 9 cities making a southeast to northwest cross section over the United States from Charleston, S. C. to Seattle, Wash.; and for 6 cities making a southwest to northeast cross section from Midland, Tex. to Sault Ste. Marie, Mich. These include the same three stations used in the winter study.

As in [2] it was decided to compute the components of the heat balance in the two deep layers 1000-600 and 600-200 mb. However, in order better to represent the synoptic scale of heating and to avoid problems of determining the diurnal variation of certain components, it was decided to increase the "space-time domain" of averaging to 24 hr. and to an area within a 40-mi. radius of the selected cities.

Estimates were made of the four major components: i.e., long and short-wave radiative flux-divergence, condensation, and turbulent exchange of sensible heat with the earth's surface. As in [2] the turbulent exchange of heat by sub-synoptic-scale eddies through the sides and top of the space-time domain was neglected; as was in addition the turbulent exchange between the two sub-layers.

All available sources of published and unpublished data were used which might assist in determining the needed parameters. Most of the information

was gleaned from the following U. S. Weather Bureau publications: Local Climatological Data (L.C.D.'s), including the Supplement; Daily Series, Synoptic Weather Maps, Part II: Northern Hemisphere Data Tabulations; and Monthly Climatological Data.

No attempt will be made to quantitatively assess the accuracy of the computations, simply because few reliable physical measurements are available with which the indirect computations used here may be checked. However, some qualitative remarks regarding limitations of accuracy will be made from time to time.

2. HEATING AT THREE STATIONS, FEBRUARY 15 TO MARCH 16, 1960

Since the three selected stations lay relatively close together in a single time zone, the 24-hr. period of averaging was chosen as midnight to midnight Central Standard Time for each of the dates indicated in tables 1 to 3. This corresponds to 0600 of the indicated date to 0600 of the following day GMT.

a. Distribution of Clouds

Since all of the heating components are strongly influenced by clouds, we will begin with a discussion of the determination of the cloud distribution. This was done essentially as in [2] except it was assumed that in winter all of the clouds are stratiform in character, so that only three "types" were permitted; low, middle, and high clouds.

The first step consisted of determining the total amount of clouds in each layer from the surface reports for each hour at the principal first order station in the area. Where middle or high clouds were obscured by lower clouds the amounts of the former were increased by using the "random" assumption as in [2]. Sometimes certain amounts of higher clouds were assigned even when the sky was 100 percent covered by low clouds, if this was supported by surface reports for adjacent hours or by pilot reports. The mean 24-hr. cloud amount was then obtained by averaging the adjusted hourly values. As in [2] it is assumed that this mean cloudiness is representative of the entire 40-mi. radius area.

In making the computations, and for insertion in the radiation code, the average layer cloudiness was carried out to hundredths of sky cover. Then the total sky cover was computed from the amounts for the three layers by again using the random assumption. These total amounts, rounded to the nearest 10th, are listed in columns 2 to 5 of table 2. As a check on the calculations, the mean total sky cover published in the LCD's is listed in column 6. The close agreement between this and the computed sky cover in column 5 suggests that few mistakes were made in spite of the rather complex adjustments of fractional amounts.

The determination of the mean height of the base and top of each layer was more difficult. First, all hourly observations of ceiling heights for a given layer were tabulated. In a very few cases these could be supplemented by pilot reports of bases or tops but in the many cases in which neither of

these sources was available subjective estimates were based on an empirical relation between upper-air humidity and cloudiness (Smagorinsky [11]). When none of these methods yielded meaningful results (especially in the case of the high clouds) an average, or climatological, base or top was assigned. Finally the high clouds were considered to be sheet clouds of negligible thickness. The average 24-hr. heights of bases and tops estimated in this way are listed (in hundreds of meters) in columns 7 to 11 of table 2.

b. Long- and Short-Wave Radiation

In computing the long- and short-wave radiative flux or flux-divergence we used a program designed for the IBM Stretch or 7090 series computers kindly furnished by Dr. Smagorinsky, Director of the U. S. Weather Bureau's Geophysical Fluid Dynamics Laboratory. This code was written as part of a theoretical study of the structure of planetary atmospheres and was not intended primarily for computing radiative heating or cooling from "real" data. Nevertheless we found it quite convenient for our purpose. A detailed account of the radiation model is contained in several published reports (Möller and Manabe [9]; Manabe and Möller [7]; Manabe and Strickler [8]). Here, only enough information will be given to assist in understanding the content of the present computations. The first two references deal with essentially the same model used by us, but for a cloud-free atmosphere. The last reference discusses the treatment of clouds but allows for greater resolution in the vertical as compared to the 11-level code we used.

The model allows for selective absorption and emission of short-wave solar and sky radiation and long-wave infrared radiation by water vapor, ozone, and carbon dioxide. It takes account of the re-absorption of short-wave radiation by a single reflection from cloud tops or from the ground, and the absorption of short-wave radiation by liquid droplets within the clouds.

In determining the effect of clouds on long-wave radiation, it is assumed that their bases and tops are perfect absorbers and emitters, except for the high clouds which are "half black"; therefore the amount of high clouds are reduced by half in computing the long-wave flux.

A practical limitation of the code is that the base and top of a given cloud must be "moved" up or down to coincide with one of the 11 input levels, and in such a way that the base of one layer must coincide with or be higher than the top of the next lower layer. If a cloud is moved up or down it is necessary to adjust the area (amount) at the base and top so as to disturb the radiative flux as little as possible. The authors took care of this by changing the amounts so that the upward and downward long-wave flux from the cloud top and base respectively (given by the Stefan-Boltzman constant times the cloud area and fourth power of temperature) remained unchanged. Changes in elevation and amount of the clouds were seldom large. For example, a typically large change was a shift in cloud top from 1.0 to 1.7 km., and an increase in amount from 67 to 74 percent. Considering the great uncertainties in determining the heights and amounts of the clouds, such changes seem quite tolerable. In addition, tests indicated that even if the amounts had not been changed, the results would have been very nearly the same.

The 11 input levels are based on a "sigma surface" as vertical coordinate. Since this coordinate is always 0 at the top of the atmosphere and 1 at the earth's surface, the corresponding 11 input pressure levels vary according to the height of the station above sea level. When the station is at sea level (1000 mb.) the pressure levels are as given in table 5 p. 530 of Manabe and Möller [7].

In addition to the adjusted cloud amounts and elevations the input data must include the reflectivity and liquid-droplet absorptivity of each of the three cloud layers; the reflectivity (albedo) of the earth's surface; the temperature and the water vapor, carbon-dioxide and ozone concentration at each of the 11 input levels. We used constant values of cloud reflectivity and absorptivity for each of the three cloud layers, as listed in table 6. (Liquid droplet absorptivity is therefore independent of cloud thickness.) For surface albedo we used the values listed in column 7 of table 3. For fresh snow we assumed an albedo of 80 percent; for snow-free ground, 8 percent; and for a trace of snow, 13 percent. The intermediate values listed correspond to varying "age" of the snow cover, or to melting snow. Recent studies of surface albedo by Posey and Clapp [10] and by Kung et al. [6] show that the assumed albedo for fresh snow (80 percent) is much too large, especially for large areas with varied surface characteristics, as near cities; and the albedo assumed for snow-free areas (8 percent) is somewhat too small. More correct values, based on these two studies are listed in column 8 of table 3. Our use of the incorrect values caused small errors in short-wave absorption, especially in the air layers near the ground. However, tests in extreme cases suggest that this resulted in a maximum error of 6 percent in the 1000-600-mb. layer. No correction has been made in table 1 (row marked R_s).

The mean temperature and moisture at upper levels for each 24-hr. time interval and 40-mi. radius area was approximated by the average of the two soundings, 1200 GMT of a given date and 0000 GMT of the following day. Moisture at high levels was estimated as in [2]; i.e. extrapolation from the level of "motor-boating" to the tropopause and constant precipitable water in the stratosphere. However, unlike in [2] use of the labor saving radiation program allowed us to use a different sounding for each 24 hr. We assumed the temperature of the clouds and ground to be the same as that of the surrounding or overlying air.

Standard, middle-latitude values of ozone and carbon-dioxide mixing ratios were used which were held constant from day-to-day (Manabe and Strickler [8]).

Our consistent use of mean 24-hr. cloudiness is correct as far as long-wave radiation is concerned, but in computing short-wave absorption we should have used the mean cloudiness for daylight hours only. However, a test for a case of large difference between 24-hr. and daytime cloudiness (86 percent vs 32 percent low cloud amount) suggests that this produces an extreme error of 5 percent in short-wave absorption. Such a small error is probably due to the fact that variations in absorption depend more on moisture content than on cloud amount. This weak dependence of absorption on cloud amount may also be seen in a plot of absorption (table 1) against total cloudiness (table 2).

Included in the data output of the program is the short- and long-wave radiative flux-divergence for each of the lower 9 of the 11 pressure levels, expressed as heating per unit mass in °C./day, and considered positive when warming occurs. The mean heating or cooling in the two layers surface-600, and 600-200 mb. is obtained from these as a weighted mean (table 1, rows marked R_L and R_S).

The heating is "reduced" to 1000 mb. simply by assuming that the fictitious heating per unit mass in the layer from the surface down to 1000 mb. is the same as that in the layer surface to 600 mb. The mean heating in the layer 1000 to 200 mb. (not listed) is then simply the average of those in the two sub-layers.

The heating values in table 1 have been tabulated to the nearest hundredth of a degree Celsius per day. This was done only for the sake of completeness and does not reflect the assumed computational accuracy, which cannot be less than 1/10 °C./day.

Three other products of the radiation program are listed in table 3. They are the short-wave solar and sky radiation absorbed by the ground (R'_{SG}, column 2), the net long-wave flux at the ground (R_{LG}, column 4) and at the top of the atmosphere (R_{LT}, column 6); all expressed in ly/day (cal.cm.$^{-2}$ day^{-1}) and considered positive when directed downward.

c. Condensation and Evaporation in the Air

As in [2] it was assumed that the net condensation and evaporation within a unit-area column of the atmosphere is given by the average precipitation falling over the 40-mi. radius area. The precipitation at each of the stations with recording rain gages in the area (1 to several) was obtained simply by summing the hourly or 6-hourly amounts from midnight to midnight. The amount at the main Weather Bureau station is listed in table 2, column 12 (F, in inches x 100). The precipitation at the many cooperative stations within or near the chosen area could not be obtained directly because measurements were made for 24-hr. periods usually not ending at midnight. For these stations the fraction of the recorded precipitation which fell within the chosen time interval was determined from synoptic evidence. All adjusted precipitation values were then plotted on a large-scale map of the area, isolines drawn, and the average precipitation for the entire area determined with the aid of a planimeter. The results are listed in table 2, column 13 ($\overline{F}$).

Assuming that no condensation occurred above 200 mb. the average precipitation, $\overline{F}$, was converted to average heating per unit mass in the layer 1000-200 mb. from the known mass of the layer together with a constant latent heat of condensation (600 cal. gr.$^{-1}$). The net heating was partitioned between the two sublayers in a manner somewhat different from that used in [2]. The fraction of the total heat released in each layer was taken as proportional to the product of the cloud amount and the average thickness of clouds in that layer. This involves the assumption that the product of upward motion times moisture gradient is the same in the two layers. Since cirrus were assumed to be "sheet" clouds, they were ignored in the computations. The mean heating per unit mass (either positive or zero) is listed for each layer in the rows marked "C" in table 1.

d. Sensible Heating at the Ground

The heat gained or lost by the air through turbulent exchange with the ground cannot be determined satisfactorily with readily available data during winter because of large day-to-day changes in the heat stored in the ground as a result of melting and freezing of snow, ice, and ground water. Rather than completely ignore this component of atmospheric heating, we decided to obtain a rough substitute which might at least serve as a measure of its relative importance. This was done using an empirical formula worked up as part of another project (Clapp et al. [3]), relating sensible heat exchange (H_G) and the excess of radiation at the ground (E_s). The formula is:

$$H_G = 0.32\ E_s - 13.1 \qquad (1)$$

Here, H_G and E_s are both expressed in ly./day. Formula (1) applies to moist-temperate climates. E_s conforms to the sign convention (positive downward) but H_G is considered positive when directed upward.

This formula was obtained by plotting careful measurements of the components of the surface heat balance for individual months given by Frankenburger [4, 5] and for "normal" months, (long-period averages for each month) given by Russian meteorologists (Budyko [1]). Since all 12 months were used, the relationship presumably includes the effect of average changes in surface heat storage during winter, but it cannot represent the often large irregular day-to-day changes in this quantity.

The excess of radiation (E_s) is the sum of the short-wave radiation absorbed by the ground and the net flux of long-wave radiation at the ground. The latter quantity was obtained directly from the radiation program and is listed as R_{LG} in column 4 of table 3. Unfortunately, it was not possible to use the short-wave term obtained from the program (R'_{SG}) listed in column 2, table 3, for two reasons: The albedo values used in the code are erroneous, as indicated earlier; and for reasons that will be discussed below the values of solar and sky radiation reaching the ground, as computed by the code, are about 35 percent smaller than instrumental values from an Eppley pyrheliometer (available only for Columbia).

When the short-wave radiation reaching the ground for each day as computed by the code was plotted against the pyrheliometer values (graph not shown), a large scatter of the points was revealed which is understandably due to the many errors in estimating the cloud and other upper-air parameters (including the use of 24-hr. rather than daytime cloudiness). The reason for the systematic difference (shown by a curve of best fit) is not obvious, but this could be due to overestimates of the reflectivity and absorptivity of the clouds or to a systematic difference between 24-hr. and daytime cloudiness. The latter possibility is supported by the cloud data for Columbia, where the mean 24-hr. cloud amount in the lowest cloud layer (where the reflectivity and absorptivity are largest) exceeds the mean daytime amount on 15 of the 31 days, with the reverse occurring on only 9 days. This is only partially counteracted by the fact that the middle and high daytime cloudiness exceeds the corresponding 24-hr. amounts on a slight plurality of the days. In any case we have

assumed that the pyrheliometric observations are the more correct of the two and that the curve of best fit for Columbia may also be used for the other two stations. Therefore this curve of best fit was used to "correct" the incoming radiation at the ground computed by the code, and the adjusted value was multiplied by one minus the new albedo (column 8, table 3) to obtain an adjusted estimate of short-wave absorption (R_{SG}, column 3, table 3).

The sensible heat exchange (H_G, column 5, table 3) is then obtained from Formula (1) using the sum of columns 3 and 4 as the excess of radiation (E_S). Finally, it is assumed that in any given day all the sensible heat picked up from the ground is absorbed in the layer 1000 to 600 mb. The heating per unit mass in that layer is listed in the row marked P_G in table 1. Since sensible heating is zero in the layer 600-200 mb., the heating per unit mass in the 1000-200-mb. layer (not shown) is simply half that in the lower sub-layer.

e. Total Diabatic Heating and Thickness

An estimate of total diabatic heating per unit mass may be obtained by summing the four components. This total heating is not shown in the table. The thickness of each layer is obtained from the average of the two soundings (row marked h, values expressed in decameters).

3. HEATING FOR CROSS-SECTION STATIONS, MAY 8-12, 1962

Computations of the heating components for the cross-section stations were similar to those for the three stations discussed previously. Only differences in the procedures will be outlined here.

The results are tabulated in tables 4 and 5. Table 4 contains the same components as table 1, but the other table has a different format largely because much of the basic data were lost after the processing had been completed. For example, none of the information on individual cloud layers could be recovered, so that the only cloud information shown is the total sky cover obtained from the LCD's (N_o, column 6). Spaces left blank in table 5 mean data are missing, except for $\hat{F}$ and $\overline{F}$ (columns 7 and 8) where a blank means no measurable precipitation.

Since the stations making up the cross sections lie in four different time zones, we chose the 24-hr. time interval to be 1800 of the previous day to 1800 GMT of each indicated date. Each mean upper-air sounding was therefore the average of the 0000 and 1200 GMT soundings of the indicated dates, and the 24-hr. means of all other data used in the calculations were adjusted or weighted to correspond to GMT time.

Since general rain, showers, or thunderstorms occurred occasionally, a nimbus (Ns) or cumulonimbus (Cb) cloud type was added to the three layer types used previously. It was assumed that the top of the Cb coincided with the cirrus level while the base was determined from observations or from the soundings. The adopted values of reflectivity and absorptivity for these two types are included in table 6. Since the radiation code cannot handle overlapping cloud types, such as the Ns or Cb which penetrated the levels occupied by the other types, it was necessary to run the code twice; once with Ns or Cb alone,

assuming this type covered the entire sky, and again with all other types, which together also covered the entire sky. The two separate values of radiational heating and cooling for each of the two layers were then combined as a weighted mean, using as weights the relative amounts of Ns or Cb and all other types.

The albedo of the ground was taken as 8 percent, which while almost half the preferred value of 14 percent, leads to a very small percentage error in the direction of too little short-wave absorption in the layer 1000-600 mb., and to an error of only about 7 percent in the direction of too much short-wave radiation absorbed by the ground. No attempt was made to correct these errors. It should be noted that the heating by long- and short-wave radiation for Seattle and Columbia were computed by "hand" with the aid of an Elsasser diagram and an empirical formula respectively (see [2]), while for all other stations the radiative components were computed using the radiation code.

In determining the vertical distribution of condensation heating we reverted to the procedure used in [2], except that low and middle clouds were combined into a single layer-type cloud. This procedure ignores the relative amounts of the clouds in the two layers. Instead, it computes the relative rate of condensation as a function of the vertical wind velocity multiplied by the lapse rate of mixing ratio within the cloud layer. Only the shape of the vertical velocity profile is needed. This is assumed to be parabolic (zero at the ground and at the top of the middle cloud layer) for the layer-type clouds and non-parabolic, with a peak in the upper layers, for the Cb clouds.

The transfer of sensible heat from the ground (H_G, column 5 of table 5) is determined by the same heat-balance method used in [2], except that storage of heat in the soil is assumed to be negligible because it was found in [2] and from the computations of Frankenburger [4, 5] that it is small compared to the other terms, except in winter, and because it is impossible to estimate it accurately without soil temperature measurements.

Therefore the exchange of sensible heat is equal to the excess of radiation at the ground (sum of R_{LG} and R_{SG}, columns 2 and 3) minus the heat of evaporation (LE, column 4). The latter quantity is determined from the evapotranspiration, which is obtained independently by the same accounting procedure used in [2]. The solar and sky radiation absorbed by the ground (R_{SG}, column 3) is interpolated from the Eppley pyrheliometer values at the stations having these instruments (Charleston, Oklahoma City, Nashville, Rapid City, Great Falls, Spokane, Midland, Seattle, Columbia). At the other stations it is taken from the unaltered values of the radiation program.

The vertical penetration of heat picked up from the ground and the heating per unit mass in the two layers (P_G in table 4) is handled exactly the same as in [2].

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Table 1. - Winter 1960: Heating per unit mass (°C./day x 100) due to each of four components in the layers 1000-600 and 600-200 mb. for 24 hr. midnight to midnight CST of indicated date. Heating by each component in the 1000-200-mb. layer (not shown) may be obtained by averaging those for the two layers. Total heating in each layer (not shown) may be obtained by summing the four individual components. Symbols: R_L, long-wave radiational heating; R_S, absorption of short-wave radiation; P_G, heating by transfer of sensible heat from the ground; C, heating on condensation in clouds (all considered positive when air is warmed); and h, thickness of each layer in decameters.

Peoria, Illinois, Feb. 15 to Mar. 16, 1960

	1000 600 / 600 200	1000 600 / 600 200	1000 600 / 600 200	1000 600 / 600 200	1000 600 / 600 200	1000 600 / 600 200	1000 600 / 600 200
	Feb 15	Feb 20	Feb 25	Mar 1	Mar 6	Mar 11	Mar 16
R_L	-187 -142	-134 -187	-159 -175	-102 -170	-137 -153	-229 -138	-223 -153
R_S	31 29	27 35	33 36	24 36	29 36	42 36	47 41
P_G	27	47	-4	47	44	17	7
C		229	370		70	282	827
h	393 743	392 745	389 746	387 748	386 739	386 744	392 752
	Feb 16	Feb 21	Feb 26	Mar 2	Mar 7	Mar 12	
R_L	-213 -129	-190 -141	-159 -113	-103 -159	-144 -119	-121 -141	
R_S	35 29	31 30	36 30	25 32	33 32	38 34	
P_G	44	15	16	20	21	30	
C		510		131 28	70		
h	395 740	388 754	384 740	390 750	386 743	386 741	
	Feb 17	Feb 22	Feb 27	Mar 3	Mar 8	Mar 13	
R_L	-257 -103	-257 -129	-130 -150	-138 -143	-154 -195	-94 -168	
R_S	37 25	37 28	27 32	34 33	27 40	39 34	
P_G	28	20	33	14	38	36	
C			38 15	264			
h	389 740	390 746	386 741	381 740	391 747	386 741	
	Feb 18	Feb 23	Feb 28	Mar 4	Mar 9	Mar 14	
R_L	-211 -101	-154 -173	-151 -150	-128 -108	-241 -137	-116 -170	
R_S	33 24	29 32	32 30	34 25	36 35	28 39	
P_G	49	8	6	21	17	51	
C		95 46	97 26		528		
h	386 742	391 745	383 743	374 744	391 750	392 737	
	Feb 19	Feb 24	Feb 29	Mar 5	Mar 10	Mar 15	
R_L	-106 -119	-252 -140	-86 -119	-96 -120	-132 -179	-119 -197	
R_S	25 25	40 29	26 30	28 27	39 34	28 46	
P_G	59	9	24	33	34	42	
C		326 26				246	
h	378 747	389 747	380 746	380 737	392 746	394 748	

Columbia, Missouri, Feb. 15 to Mar. 16, 1960

	1000 600 / 600 200	1000 600 / 600 200	1000 600 / 600 200	1000 600 / 600 200	1000 600 / 600 200	1000 600 / 600 200	1000 600 / 600 200
	Feb 15	Feb 20	Feb 25	Mar 1	Mar 6	Mar 11	Mar 16
R_L	-161 -154	-156 -190	-204 -133	-96 -211	-181 -167	-244 -58	-201 -144
R_S	30 32	30 37	33 35	27 39	33 39	47 31	40 40
P_G	30	16	8	41	42	21	16
C		158	246		123		53
h	395 743	395 748	387 748	385 753	391 743	390 746	391 751
	Feb 16	Feb 21	Feb 26	Mar 2	Mar 7	Mar 12	
R_L	-222 -110	-253 -133	-187 -114	-197 -165	-185 -128	-134 -171	
R_S	43 28	37 31	41 26	35 43	42 38	31 35	
P_G	62	37	21	8	22	40	
C		282		634		35	
h	399 743	393 754	384 741	392 752	394 747	392 747	
	Feb 17	Feb 22	Feb 27	Mar 3	Mar 8	Mar 13	
R_L	-225 -106	-116 -163	-146 -142	-154 -128	-197 -187	-139 -122	
R_S	37 26	30 34	32 35	39 31	36 46	35 37	
P_G	43	44	28	27	20	40	
C			352		581		
h	391 740	392 746	389 750	383 750	399 754	392 744	
	Feb 18	Feb 23	Feb 28	Mar 4	Mar 9	Mar 14	
R_L	-111 -107	-181 -163	-154 -134	-94 -124	-250 -109	-126 -154	
R_S	33 25	37 33	41 32	27 34	49 36	36 39	
P_G	54	27	22	28	12	23	
C		370	158		106	155 3	
h	387 744	393 746	386 747	381 745	397 755	395 750	
	Feb 19	Feb 24	Feb 29	Mar 5	Mar 10	Mar 15	
R_L	-105 -129	-237 -142	-75 -149	-102 -141	-220 -171	-233 -146	
R_S	24 30	40 32	28 33	33 31	45 43	42 41	
P_G	54	8	28	50	14	14	
C					264	827	
h	389 747	390 748	385 750	383 739	397 747	398 752	

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Table 1. - Continued.

	Topeka, Kansas, Feb. 15 to Mar. 16, 1960													
	1000 600		1000 600		1000 600		1000 600		1000 600		1000 600		1000 600	
	600 200		600 200		600 200		600 200		600 200		600 200		600 200	
	Feb 15		Feb 20		Feb 25		Mar 1		Mar 6		Mar 11		Mar 16	
R_L	-175	-157	-201	-156	-121	-148	-162	-180	-189	-191	-175	-124	-170	-145
R_S	35	33	32	34	29	35	33	40	38	42	43	34	45	38
P_G	25		40		29		34		30		27		19	
C	14	14	792				18							
h	396	744	396	748	384	743	390	753	395	750	391	749	389	745
	Feb 16		Feb 21		Feb 26		Mar 2		Mar 7		Mar 12			
R_L	-96	-131	-165	-96	-125	-110	-136	-180	-182	-147	-153	-168		
R_S	35	26	39	30	37	27	31	42	49	35	32	44		
P_G	59		22		35		25		26		50			
C			18				510							
h	398	740	389	751	384	739	388	745	398	752	393	747		
	Feb 17		Feb 22		Feb 27		Mar 3		Mar 8		Mar 13			
R_L	-182	-77	-147	-179	-174	-145	-109	-134	-183	-197	-172	-180		
R_S	33	24	28	33	28	31	34	34	36	49	36	42		
P_G	54		40		25		27		12		25			
C					255	98			282		18			
h	389	738	391	743	388	748	384	751	400	754	395	749		
	Feb 18		Feb 23		Feb 28		Mar 4		Mar 9		Mar 14			
R_L	-137	-86	-235	-143	-100	-119	-91	-161	-244	-169	-143	-167		
R_S	34	26	33	33	35	30	27	38	39	44	30	38		
P_G	61		8		24		40		11		16			
C			686		35						742	190		
h	387	743	389	746	384	744	384	744	400	755	398	753		
	Feb 19		Feb 24		Feb 29		Mar 5		Mar 10		Mar 15			
R_L	-132	-160	-121	-167	-104	-147	-252	-123	-179	-185	-206	-169		
R_S	26	32	34	32	24	32	33	33	36	46	40	46		
P_G	51		22		28		30		14		12			
C									457		950			
h	392	745	385	745	385	753	387	743	398	750	395	752		

Table 2. - Winter 1960: Average weather elements for 24-hr. periods midnight to midnight CST of indicated dates. Symbols: N, cloud amount in tenths; subscripts L, M, H refer to total amounts of low, middle, and high clouds respectively (not fraction visible from ground); no subscript, estimated total sky covered by clouds; subscript O, total sky cover from LCD; B and T, base and top of indicated cloud layers in hundreds of meters; F, precipitation in inches x 100 at principal Weather Bureau first-order station; $\bar{F}$, average precipitation within 40-mi. radius area surrounding principal station.

Peoria, Illinois

1	2	3	4	5	6	7	8	9	10	11	12	13
Date 1960	N_L	N_M	N_H	N	N_O	B_L	T_L	B_M	T_M	B_H	F	$\bar{F}$
Feb 15	7	3	3	8	9	10	19	36	49	61		
16	4	3	2	7	6	7	16	34	40	61		
17	8			8	8	7	14					
18	5			5	5	9	16					
19				0	0	6	21			67		
20	5		8	9	9	5	34	28	34	67	14	13
21	7		2	7	7	3	31			67	31	29
22	8		2	8	8	4	11			67		
23	8	7	5	10	10	6	18	41	49	61	5	8
24	10	3		10	10	3	25	41	49		12	20
25	9	8	7	10	10	5	23	25	27	64	14	21
26	3	2	1	5	4	14	20	27	31	61		
27	2	3	5	7	6	4	23	37	49	67	3	3
28	8	5	4	9	8	6	18	37	49	67	9	7
29			1	1	1					67		
Mar 1		3	4	6	6			32	40	67		
2	8		8	10	10	9	49			67	10	9
3	5	3	5	8	7	7	25	31	34	67	14	15
4	2		1	3	3	6	15	24	27	67		
5			1	1	2			46	47	61		
6	2	2	5	7	6	9	29	32	38	61	3	4
7	2	1		3	3	15	29	28	33		3	4
8		8	7	9	10			30	39	67		
9	9			9	9	3	26				28	30
10	1	1	5	6	7	4	10	30	37	61		
11	7	5	2	9	9	5	17	31	38	61	9	16
12	1		4	5	5	0	6	31	37	64		
13	2	1	9	10	9	9	18	40		64		
14		3	6	7	6			39	43	61		
15	2	6	9	10	9	4	34	31	37	61	13	14
16	10	5	4	10	10	3	22	24	34	64	26	47

Columbia, Missouri

1	2	3	4	5	6	7	8	9	10	11	12	13
Date 1960	N_L	N_M	N_H	N	N_O	B_L	T_L	B_M	T_M	B_H	F	$\bar{F}$
Feb 15	7	1	4	8	8	13	24	31	37	61		
16	3		1	4	4	4	6			61		
17	6			6	6	7	13	37	44	61		
18	5			5	5	8	18					
19	1	4	6	8	8	19	21	26	33	70		
20	7	9	8	10	10	7	23	24	31	67	10	9
21	6			6	6	4	27				14	16
22		2	5	6	5			30	34	67		
23	7	4	6	9	10	3	25	30	37	67	27	21
24	10		4	10	10	3	15			67		
25	10		2	10	10	5	34			67	14	14
26	4		3	6	7	9	15	43		61		
27	5	2	6	9	8	2	31	29	34	70	27	20
28	4		2	5	5	3	20	31	34	68	12	9
29	1		3	3	3	17	20			61		
Mar 1	1	5	10	10	9	7	37	27	37	67		
2	10		3	10	10	5	40			67	47	36
3	2	2	1	4	4	6	13	25	34	61		
4	2			2	2	6	11			61	1	
5		1	4	4	4			37		61		
6	4	5	6	9	8	4	29	32	33	61	7	7
7	5	4	1	7	7	3	15	34	40	61		
8	8	6	6	10	10	7	27	31	38	67	36	33
9	9	2	1	9	10	7	18	24	29	61	6	6
10	10	4	7	10	10	3	18	27	34	67	17	15
11	6			6	6	5	19				3	2
12		4	5	7	6			43	46	70		
13	3	5	7	9	10	9	26	37	40	70		
14	7	4	8	10	9	7	33	37	43	73	14	9
15	10		3	10	10	7	31	37	38	73	64	47
16	9		3	9	10	4	37			61	4	3

Topeka, Kansas

1	2	3	4	5	6	7	8	9	10	11	12	13
Date 1960	N_L	N_M	N_H	N	N_O	B_L	T_L	B_M	T_M	B_H	F	$\bar{F}$
Feb 15	7	4	3	9	7	7	10	37	43	61	1	1
16		1	4	4	4	11	17	39	43	63		
17	4			4	5	7	9	24	27			
18	3			3	3	7	21					
19	4	4	5	8	10	14	27	38	44	64		
20	6	3	5	9	10	3	35	34	37	67	41	45
21	3			3	3	4	9	39	43	61		1
22		7	8	9	8			31	41	61		
23	10		3	10	10	5	39			64	41	39
24	5		7	8	10	5	20			64		
25	5		7	8	8	5	26			61		
26	3		4	6	7	10	14			61		
27	5	8	7	10	9	3	34	36	52	61	18	20
28	1	2	1	4	4	7	21	32	38	61	5	2
29		3	3	5	5			32	43	61		
Mar 1	3	8	5	9	10	8	34	24	34	61	2	1
2	7		7	9	8	4	29	26	34	67	28	29
3		1	1	2	2			37	43	61		
4		2	4	5	5			30	40	67		
5		9	1	9	9			18	27	61		
6	6	8	4	9	9	5	18	32	43	67		
7	6	1	1	7	9	6	13	24	31	61	1	
8	10		8	10	10	3	26			67	15	16
9	10		3	10	10	4	15	46	49	67		
10	10		7	10	10	3	32			67	20	26
11	3			3	3	6	9					
12		6	4	7	7	0	2	29	37	61		
13		9	5	9	9			17	33	61	2	1
14	10		6	10	10	3	52			67	56	53
15	10		6	10	10	2	40			67	52	54
16	7	3	2	8	8	4	15	37	46	61		

Table 3. - Winter 1960: Parameters of heat balance for 24 hr. midnight to midnight local time. Symbols: R'_{SG}, computed solar and sky radiation absorbed by ground; R_{SG}, adjusted solar and sky radiation absorbed by ground; R_{LG}, net flux of infrared radiation at the ground; H_G, flux of sensible heat from the surface; R_{LT}, infrared radiation at top of atmosphere: A', surface albedo used in radiation code; A, adjusted surface albedo. Heat fluxes expressed in ly./day; albedo, in percent. All fluxes except H_G considered positive when directed downward.

Peoria, Illinois

1	2	3	4	5	6	7	8
Date 1960	R'_{SG}	R_{SG}	R_{LG}	H_G	R_{LT}	A'	A
Feb 15	143	182	- 57	27	-431	13	20
16	190	246	- 69	44	-451	13	20
17	145	184	- 57	28	-455	13	20
18	229	299	-105	49	-455	8	14
19	349	410	-186	59	-451	13	20
20	132	233	- 44	47	-410	40	25
21	41	145	- 56	15	-426	80	50
22	36	126	- 24	20	-448	80	50
23	29	83	- 17	8	-389	75	45
24	25	72	- 4	9	-433	75	45
25	15	48	- 19	-4	-400	80	50
26	59	203	-112	16	-428	80	50
27	74	224	- 80	33	-405	75	45
28	30	103	- 44	6	-389	80	50
29	113	303	-186	24	-433	75	45
Mar 1	113	296	-110	47	-426	70	40
2	46	141	- 39	20	-351	73	40
3	47	165	- 80	14	-406	80	50
4	78	253	-145	21	-425	80	50
5	115	306	-163	33	-421	75	45
6	80	239	- 78	44	-411	75	45
7	75	246	-140	21	-446	80	50
8	69	211	- 51	38	-425	75	45
9	35	122	- 28	17	-445	80	50
10	57	198	-103	34	-451	80	50
11	38	132	- 38	17	-445	78	45
12	86	268	-133	30	-438	80	50
13	86	254	-109	36	-441	75	45
14	118	305	-105	51	-436	70	40
15	73	227	- 56	42	-421	73	40
16	21	71	- 8	7	-428	80	50

Columbia, Missouri

1	2	3	4	5	6	7	8
Date 1960	R'_{SG}	R_{SG}	R_{LG}	H_G	R_{LT}	A'	A
Feb 15	163	208	- 73	30	-432	13	20
16	277	354	-119	62	-490	8	14
17	206	272	- 94	43	-322	8	14
18	258	334	-130	54	-459	8	14
19	253	320	-110	54	-390	13	20
20	95	114	- 24	16	-390	13	20
21	50	175	- 20	37	-446	80	50
22	94	271	- 94	44	-419	75	45
23	84	163	- 39	27	-426	50	30
24	23	75	- 9	8	-431	80	50
25	30	87	- 21	8	-405	75	45
26	59	203	- 97	21	-405	80	50
27	55	184	- 56	28	-392	77	45
28	65	221	-113	22	-392	80	50
29	109	297	-170	28	-438	75	45
Mar 1	87	239	- 70	41	-421	70	40
2	25	83	- 17	8	-426	80	50
3	75	246	-121	27	-426	80	50
4	107	293	-162	28	-426	75	45
5	135	330	-132	50	-418	70	40
6	83	199	- 28	42	-421	65	40
7	49	172	- 63	22	-421	80	50
8	38	110	- 6	20	-433	72	40
9	33	114	- 36	12	-433	80	50
10	25	83	0	14	-433	78	45
11	58	200	- 93	21	-433	80	50
12	72	219	-107	40	-453	75	45
13	103	244	- 81	39	-393	65	40
14	53	149	- 36	23	-367	70	40
15	28	95	- 12	14	-432	80	50
16	35	122	- 30	16	-421	80	50

Topeka, Kansas

1	2	3	4	5	6	7	8
Date 1960	R'_{SG}	R_{SG}	R_{LG}	H_G	R_{LT}	A'	A
Feb 15	136	172	- 52	25	-428	13	20
16	318	386	-160	59	-428	13	20
17	262	340	-130	54	-428	8	14
18	314	394	-163	61	-428	8	14
19	205	270	- 70	51	-406	8	14
20	111	193	- 26	40	-425	40	25
21	68	229	-120	22	-425	80	50
22	66	204	- 39	40	-409	75	45
23	29	84	- 19	8	-412	75	45
24	53	186	- 78	22	-412	80	50
25	69	212	- 82	29	-399	75	45
26	100	270	-121	35	-399	70	40
27	45	138	- 19	25	-386	73	40
28	73	241	-124	24	-386	80	50
29	97	277	-148	28	-441	75	45
Mar 1	67	189	- 43	34	-429	70	40
2	54	170	- 51	25	-415	73	40
3	88	272	-146	27	-433	80	50
4	104	288	-122	40	-419	75	45
5	51	141	- 8	30	-419	70	40
6	47	129	+ 5	30	-419	70	40
7	56	173	- 51	26	-419	75	45
8	24	80	- 2	12	-429	80	50
9	29	84	- 8	11	-461	75	45
10	31	91	- 7	14	-416	75	45
11	79	255	-131	27	-468	80	50
12	86	254	- 57	50	-423	75	45
13	55	153	- 34	25	-426	70	40
14	32	94	- 3	16	-364	75	45
15	26	87	- 8	12	-428	80	50
16	47	165	- 66	19	-425	80	50

Table 4. - May 1962: Heating per unit mass (°C./day x 100) due to each of four components in the layers 1000-600 and 600-200 mb. for 24 hr. 1800 GMT previous day to 1800 GMT of indicated date. See legend to table 1 for explanation.

	Charleston, S.C. 1000 600 / 600 200	Athens, Ga. 1000 600 / 600 200	Oklahoma City, Okla. 1000 600 / 600 200	Topeka, Kans. 1000 600 / 600 200	Peoria, Ill. 1000 600 / 600 200
	May 8, 1962	May 8, 1962	May 8, 1962	May 8, 1962	May 8, 1962
R_L	-219 -164	-111 -123	-216 -131	-165 -114	-124 -169
R_S	78 56	32 102	67 52	60 56	45 54
P_G	161 1	213 2	187 0	187 0	203 0
C		6 9		7 9	1101 1015
h	423 775	423 770	430 774	427 774	421 772
	May 9, 1962	May 9, 1962	May 9, 1962	May 9, 1962	May 9, 1962
R_L	-218 -160	-220 -132	-190 -130	-208 -143	-179 -162
R_S	78 56	75 49	65 55	64 62	57 50
P_G	152 0	179 1	151 0	205 0	174 0
C				30 33	
h	425 777	425 773	430 777	424 772	416 770
	May 10, 1962	May 10, 1962	May 10, 1962	May 10, 1962	May 10, 1962
R_L	-215 -147	-205 -160	-182 -151	-235 -152	-228 -152
R_S	69 57	68 68	66 58	74 58	75 58
P_G	174 2	164 0	116 0	151 0	148 0
C	333 430	20 28			
h	420 777	424 777	430 778	427 779	418 774
	May 11, 1962	May 11, 1962	May 11, 1962	May 11, 1962	May 11, 1962
R_L	-272 -168	-287 -167	-195 -144	-215 -130	-153 -187
R_S	83 57	91 60	62 59	66 55	52 55
P_G	181 0	225 0	148 0	156 0	152 0
C					436 198
h	420 778	422 778	431 780	429 776	421 775
	May 12, 1962	May 12, 1962	May 12, 1962	May 12, 1962	May 12, 1962
R_L	-204 -148	-213 -157	-228 -163	-219 -134	-156 -156
R_S	70 58	76 59	74 56	75 52	47 63
P_G	196 0	186 1	188 0	191 0	140 0
C	16 15				122 79
h	423 779	424 777	431 781	431 780	423 775

	Green Bay, Wis. 1000 600 / 600 200	Sault St. Marie, Mich. 1000 600 / 600 200	Seattle, Wash. 1000 600 / 600 200	Columbia, Mo. 1000 600 / 600 200	Nashville, Tenn. 1000 600 / 600 200
	May 8, 1962	May 8, 1962	May 8, 1962	May 8, 1962	May 8, 1962
R_L	-229 -167	-124 -140	- 54 -158	- 88 - 87	-156 -197
R_S	54 63	39 54	47 53	51 61	66 60
P_G	139 0	228 0	217 0	162 0	227 1
C	637	79	74 35	4 105	
h	406 763	398 755	407 754	427 774	424 773
	May 9, 1962	May 9, 1962	May 9, 1962	May 9, 1962	May 9, 1962
R_L	-225 -179	-209 -127	-196 -155	-222 -149	- 95 -255
R_S	53 55	56 45	64 48	58 66	61 56
P_G	148 0	284 2	112 0	267 0	130 0
C		61	614 38	1 30	111 31
h	404 760	393 750	405 757	422 773	424 776
	May 10, 1962	May 10, 1962	May 10, 1962	May 10, 1962	May 10, 1962
R_L	-174 -159	-102 -107	- 96 -141	-200 -155	-175 -161
R_S	51 56	38 41	52 51	95 59	68 58
P_G	153 0	272 0	202 0	170 0	105 1
C	184 79		118 38		
h	406 766	400 756	402 754	425 778	422 778
	May 11, 1962	May 11, 1962	May 11, 1962	May 11, 1962	May 11, 1962
R_L	-256 -151	-130 -137	- 90 -128	-140 -130	-157 -164
R_S	65 57	42 47	52 43	77 68	58 58
P_G	180 0	265 1	267 4	202 0	149 1
C			28 4		
h	411 766	404 760	400 752	426 777	425 777
	May 12, 1962	May 12, 1962	May 12, 1962	May 12, 1962	May 12, 1962
R_L	-160 -154	-138 -136	-210 -112	-167 -100	-191 -130
R_S	49 56	45 47	61 42	85 54	67 51
P_G	233 0	269 1	274 4	206 0	142 1
C	565 256		47 0		
h	414 772	408 764	399 755	429 780	424 776

Table 4. - Continued.

	Omaha, Nebr.		Rapid City, So. Dak.		Great Falls, Mont.		Spokane, Wash.		Midland, Tex.	
	1000	600	1000	600	1000	600	1000	600	1000	600
	600	200	600	200	600	200	600	200	600	200
	May 8, 1962		May 8, 1962		May 8, 1962		May 8, 1962		May 8, 1962	
R_L	-173	-136	-131	- 84	-201	-128	-119	-185	-167	- 93
R_S	65	54	49	47	59	55	48	59	51	56
P_G	214	3	363	1	279	2	213	0	354	0
C	124	132	14	21	14	5	18	3		
h	425	766	418	763	405	755	408	759	433	776
	May 9, 1962		May 9, 1962		May 9, 1962		May 9, 1962		May 9, 1962	
R_L	-140	-166	-146	- 91	-154	-112	-116	-188	-157	-131
R_S	59	57	52	48	55	43	41	53	53	56
P_G	136	0	391	0	430	1	204	0	365	0
C	10	6	8	11	37	34	543	110		
h	419	769	424	770	417	762	409	759	433	780
	May 10, 1962		May 10, 1962		May 10, 1962		May 10, 1962		May 10, 1962	
R_L	-298	-100	-118	-154	-152	- 92	-209	-193	-189	-165
R_S	86	46	51	51	51	43	52	52	66	61
P_G	174	0	410	2	300	0	299	0	341	0
C							218	0		
h	426	774	426	771	416	761	407	758	434	781
	May 11, 1962		May 11, 1962		May 11, 1962		May 11, 1962		May 11, 1962	
R_L	-188	- 91	-164	-157	-136	- 90	-205	-137	-191	-150
R_S	68	44	56	55	47	45	60	49	60	60
P_G	258	0	287	2	76	0	335	0	313	0
C					53	56	12	6		
h	428	774	427	768	414	758	406	757	435	783
	May 12, 1962		May 12, 1962		May 12, 1962		May 12, 1962		May 12, 1962	
R_L	-127	- 69	-119	- 91	-144	-157	-179	-151	-187	-154
R_S	59	48	35	52	45	44	47	49	62	62
P_G	230	0	346	0	291	2	350	0	323	0
C					86	32				
h	431	778	426	770	409	759	405	755	437	786

Table 5. - May 1962: Surface weather and heating elements for 24-hr. 1800 GMT previous day to 1800 GMT indicated date. Symbols: R_{SG} is either solar and sky radiation absorbed by ground as computed by the radiation code (Athens, Topeka, Peoria, Green Bay, Sault Ste. Marie, and Omaha), or same quantity computed using albedo and Eppley pyrheliometer measurements (all other stations); LE, latent heat of evaporation (considered positive when directed downward). Units and other symbols explained in legends to tables 2 and 3.

1 May 1962	2 R_{LG}	3 R_{SG}	4 LE	5 H_G	6 N_O	7 F	8 $\bar{F}$
Charleston, South Carolina							
8		617			2		
9		592			2		
10		391			9	80	50
11		456			7		
12		612			6		2
Athens, Georgia							
8		555			5	2	1
9		575			4		3
10		469			6		
11		483			8		
12		587			1		
Oklahoma City, Oklahoma							
8		590			4		
9		549			5		
10		548			3		
11		590			2		
12		613			1		
Topeka, Kansas							
8		513			7		1
9		471			9	2	4
10		489			2		
11		529			4		
12		600			4		
Peoria, Illinois							
8	- 40	362	-124	198	10	123	136
9	- 21	285	- 93	171	10		
10	- 33	292	-115	144	10		
11	- 14	261	- 98	149	10	67	41
12	- 30	263	- 96	137	10	11	13

1 May 1962	2 R_{LG}	3 R_{SG}	4 LE	5 H_G	6 N_O	7 F	8 $\bar{F}$
Green Bay, Wisconsin							
8	- 16	222	-.69	137	10	40	41
9	- 52	284	- 87	145	9		
10	- 40	284	- 94	150	10	7	17
11	- 42	331	-112	177	9		
12	- 55	433	-150	228	10	46	53
Sault Ste. Marie, Michigan							
8	- 76	380	- 80	224	10	12	5
9	- 72	443	- 90	281	6	10	4
10	-169	554	-118	267	8		
11	-143	541	-137	261	9		
12	-171	606	-171	264	4		
Nashville, Tennessee							
8		584			5		
9		419			9		9
10		422			3		
11		522			5		
12		547			2		
Omaha, Nebraska							
8		497			8	4	16
9		334			7		1
10		363			9		
11		547			7		
12		577			9		
Rapid City, South Dakota							
8		440			8		2
9		487			6	1	1
10		472			8		
11		406			9		
12		403			9		

1 May 1962	2 R_{LG}	3 R_{SG}	4 LE	5 H_G	6 N_O	7 F	8 $\bar{F}$
Great Falls, Montana							
8		316			10		1
9		521			7	1	4
10		442			5		
11		244			8		6
12		328			6	9	6
Spokane, Washington							
8		363			9		1
9		301			10	26	38
10		361			9	6	12
11		475			7		1
12		497			7		
Midland, Texas							
8		568			5		
9		581			3		
10		561			1		
11		536			1		
12		543			2		
Seattle, Washington							
8	- 64	432	-106	262	10	1	7
9	- 52	237	- 73	112	9	34	42
10	- 72	397	- 97	228	9	1	10
11	-100	481	-103	278	9		2
12	- 97	522	-114	311	7		3
Columbia, Missouri							
8	-145	457	-185	127	8	7	7
9	- 36	367	-132	199	9	2	2
10	-176	498	-187	135	1		
11	-170	587	-252	165	4		
12	-195	599	-246	158	4		

Table 6. - Assumed reflectivity (percent) and absorptivity (percent of penetrating radiation absorbed by water droplets) for different cloud layers.

	Low	Middle	High	N_s or C_b
Reflectivity	69	48	21	70
Absorptivity	3.5	2.0	0.5	3.5

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