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THE NOCTURNAL MAXIMUM OCCURRENCE OF THUNDERSTORMS IN THE MIDWESTERN STATES

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ABSTRACT

A nocturnal maximum occurrence of thunderstorms is found in certain geographical regions.

Airway hourly observation data for Omaha show that the month of maximum occurrence of nocturnal thunderstorms falls later in the year than the month of maximum occurrence of daytime thunderstorms at Omaha. July and August are important months for the occurrence of nocturnal thunderstorms. The average duration of nocturnal thunderstorms at Omaha is greater than the average duration of daytime thunderstorms.

Factors bearing a causal relationship to the nocturnal maximum should (1) have a geographical distribution similar to that of the nocturnal thunderstorm maximum, (2) show a diurnal variation with a nocturnal maximum in the region of the nocturnal thunderstorm maximum, and (3) be sufficiently persistent to be consistent with the longer average duration of nocturnal thunderstorms.

In the study of individual occurrences at Omaha (airport elevation, 996 feet above M.S.L.) for 1941, using radiosonde data and hodograph analysis of pilot-balloon data, the principal factor contributing to instability for the formation of thunderstorms was found to be advection of warmer air in the lower layers of the atmosphere (2,000-8,000 feet above M.S.L.). Thunderstorms that occurred with advective warming in these lower layers occurred both day and night but were more frequently nocturnal.

This factor was therefore examined with regard to the above requirements with the following results:

1. Data for the 1,500-m level show a geographical area of maximum occurrence of apparent warm-air advection corresponding to the general region of nocturnal maximum occurrence of thunderstorms, while at the 3,000-m level the warm-air advective component is less.

2. The diurnal wind variations for summer months at Omaha as described by A. Wagner show stronger winds at night for the levels from 750 to 2,000 m. These winds have an average direction from regions which are warmer in the mean. Mean temperature gradients for these levels show small variations from day to night in the Middle West, with possibly slightly greater temperature gradients occurring at night.

3. Instances have been found where persistent advection of warmer

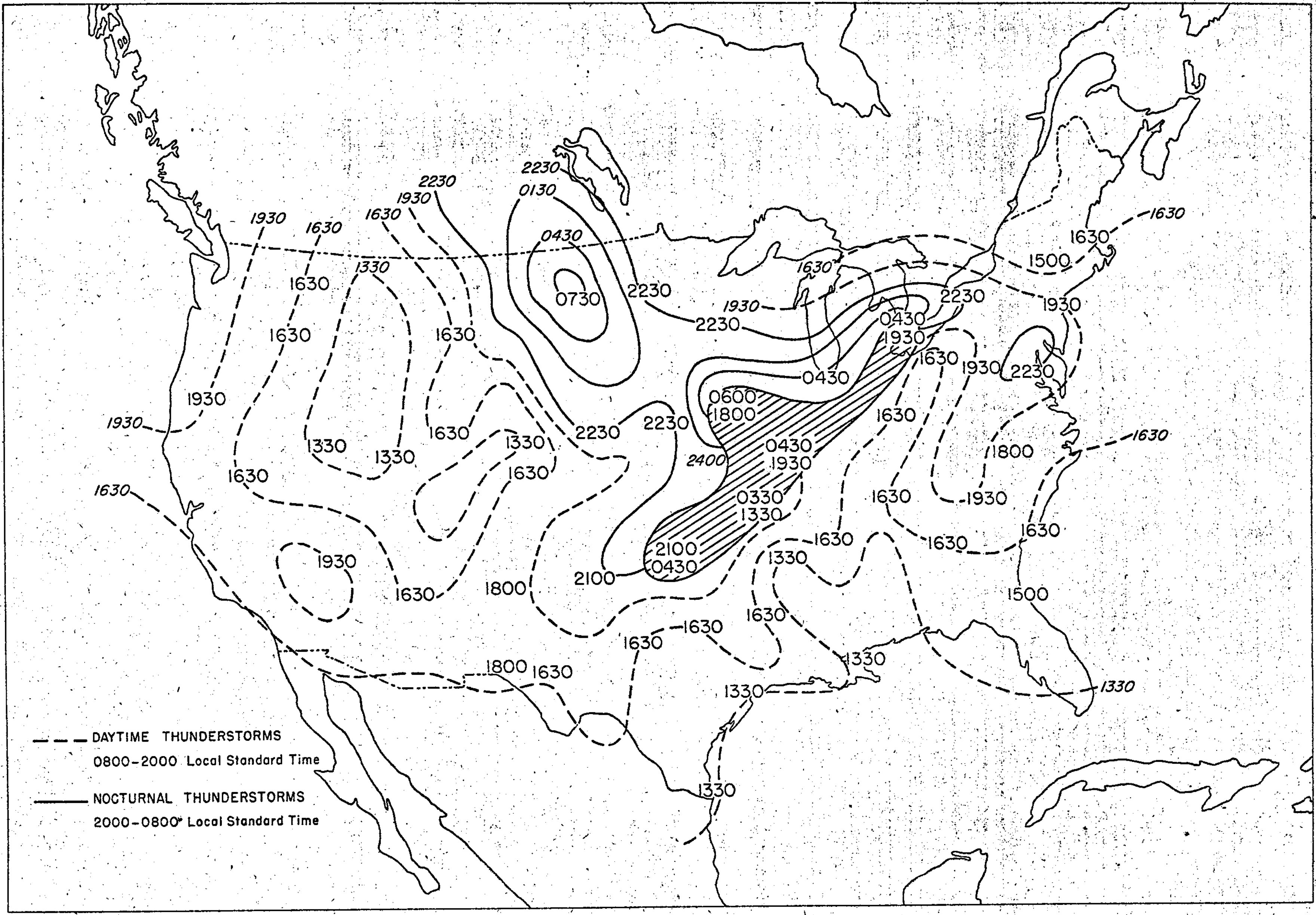

FIG. 1.—Time of maximum frequency of thunderstorm occurrence (local standard time). The hatching covers a region in which nearly equal maxima are found at two different periods (data from United States Weather Bureau, *Airway Meteorological Atlas*).

air in the lower layers at night has contributed to the maintenance of instability and thunderstorm activity at Omaha for more than 4 hours at a time.

These data show that the advection of warmer air in the lower layers of the atmosphere is a consistent factor as related to the nocturnal maximum occurrence of thunderstorms in the Middle West.

INTRODUCTION

The geographical distribution of the time of maximum occurrence of thunderstorms in July is given in Figure 1. The shaded area represents that portion of the United States where similar maxima are found both in the afternoon and at night. (In this report a nocturnal thunderstorm is defined as one that occurs between the hours of 8:00 P.M. and 8:00 A.M., local standard time; a daytime thunderstorm, as one that occurs between 8:00 A.M. and 8:00 P.M., local standard time). A nocturnal maximum is found at Omaha, North Platte, Kansas City, Bismarck, Minneapolis, Chicago, and also at Buffalo and Washington (data from Airway Meteorological Atlas for the United States). The most important general regions of occurrence of nocturnal thunderstorms are the Missouri River Valley and the valley of the upper Mississippi. Areas having a maximum occurrence of thunderstorms during the day are the Gulf states, most of the Atlantic states, the mountain and plateau regions of the West, and the Pacific Coast area.

The predominance of nocturnal thunderstorms in the center of the United States seems paradoxical, since many publications have for years ascribed the occurrence of summer precipitation to instability showers formed by the steepening of the lapse rate due to the surface heating of land areas by the intense insolation during spring and summer months. Daytime thunderstorms constitute one important factor in summer precipitation. However, for nocturnal thunderstorms a cause other than instability through surface heating must be found.

PURPOSE

The purpose of this paper is to present data and conclusions regarding nocturnal thunderstorms and factors bearing a causal relationship to the occurrence of a nocturnal maximum of thunderstorms at Omaha and in the surrounding regions.

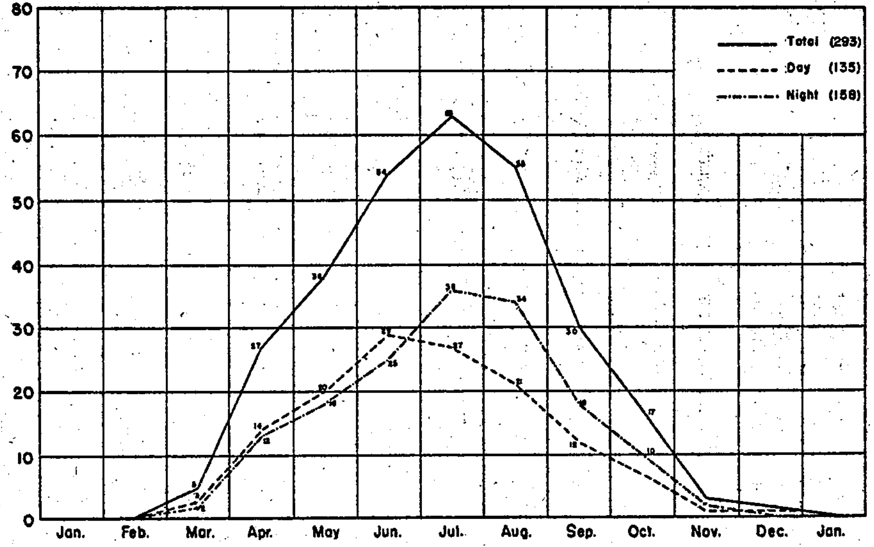

FIG. 2.—Annual distribution of number of thunderstorm occurrences at Omaha (1937-41 inclusive).

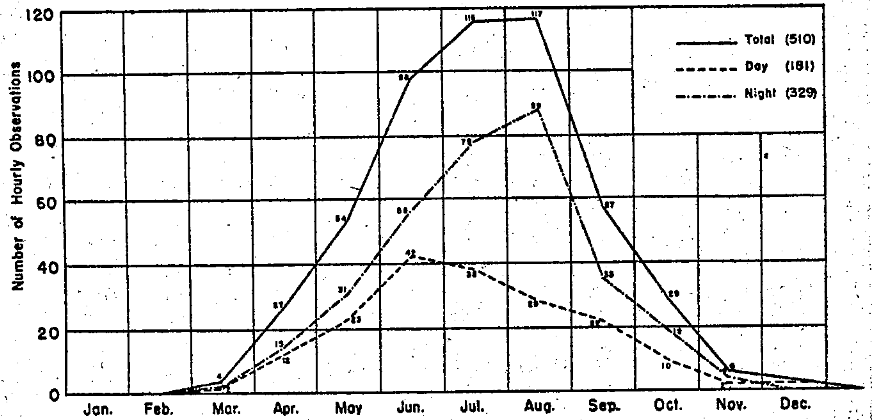

FIG. 4.—Annual distribution of number of hourly observations with thunderstorms at Omaha (1937-41 inclusive).

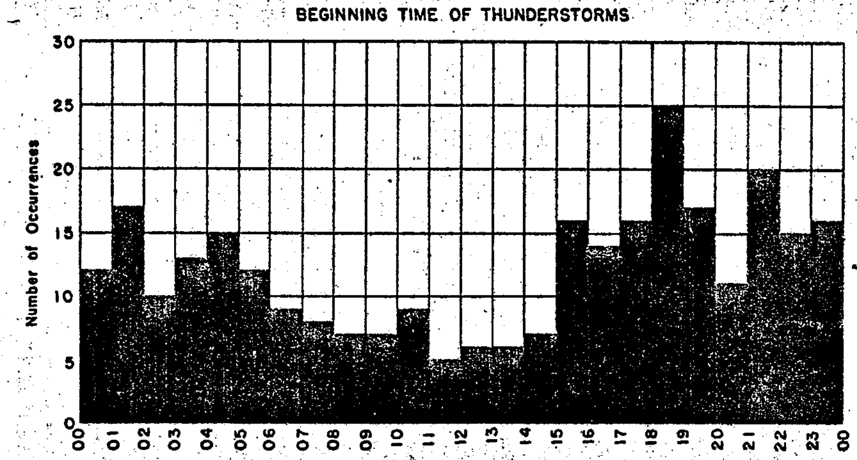

FIG. 3.—Diurnal distribution of number of thunderstorms beginning in a given hour at Omaha (1937-41 inclusive).

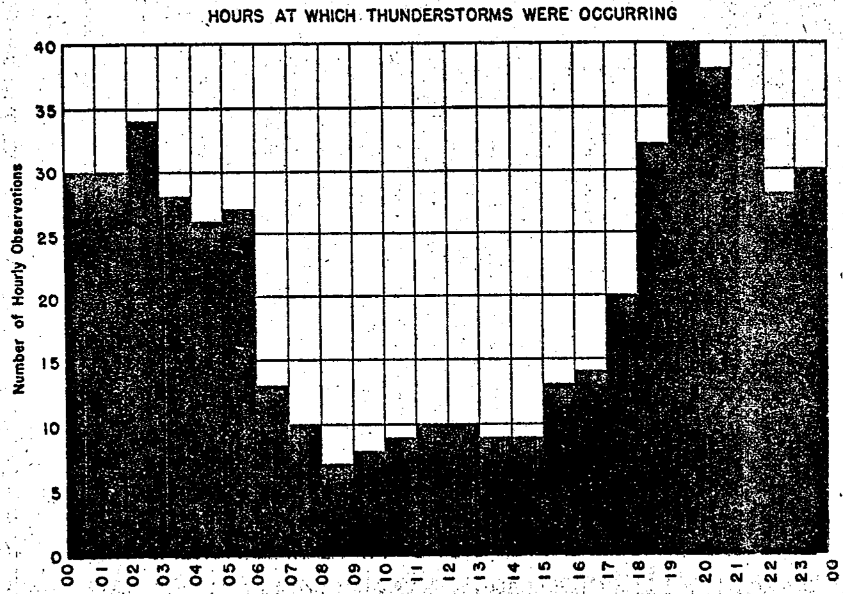

FIG. 5.—Diurnal distribution of number of hourly observations with thunderstorms at Omaha (1937-41 inclusive).

PART I

THE OCCURRENCE OF NOCTURNAL THUNDERSTORMS

1. Summary of Data

Omaha was chosen as a representative station for a detailed investigation because it is well located with reference to the area of general occurrence of nocturnal thunderstorms and because radiosonde and upper-air wind data are available for that station.

Data examined include 5 years (1937-41) of hourly airway observations, as recorded on Weather Bureau Form 1130, and one year (1941) of upper-air wind and radiosonde data.

The annual distribution of daytime and nocturnal thunderstorms is given in Figure 2. It is apparent that more nocturnal thunderstorms than daytime thunderstorms occur at Omaha and that the time of maximum occurrence of the nocturnal thunderstorms falls later in the year. July and August are the important months for the occurrence of nocturnal thunderstorms at Omaha. The June maximum for daytime thunderstorms may be explained, since in that month the air masses crossing Omaha have not attained a temperature as high as is reached in July and August, while the long days and relatively intense insolation contribute a large amount of surface heating with a marked steepening of lapse rates in the lower layers of the atmosphere by midafternoon.

In Figure 3 a diurnal distribution of the beginning time of thunderstorms is given. In these data the hours of maximum occurrence of the beginning time of thunderstorms are between 6:00 P.M. and 7:00 P.M. and between 9:00 P.M. and 10:00 P.M. (local standard time). If a smooth curve were drawn for the data, a nocturnal maximum would be shown.

An annual distribution of the number of hourly observations at which thunderstorms were occurring is given in Figure 4. Here the duration of the thunderstorms is taken into account. The month having the greatest number of hourly observations with nocturnal thunderstorms is August.

Figure 5 shows the distribution for the 24 hours of the day of the hourly observations at which thunderstorms were occurring. Comparison of Figures 3 and 5 demonstrates that nocturnal thunderstorms last longer than daytime thunderstorms. These data show the average duration of daytime thunderstorms at Omaha to be 95 minutes; the average duration for nocturnal thunderstorms is 118 minutes.

Any proposed solution of the cause of nocturnal thunderstorms must be consistent with the descriptive facts thus far presented. These facts in outline are as follows:

a) Since the nocturnal maximum of thunderstorms occurs in certain geographical regions, factors having a causal relationship should show a similar geographical distribution.

b) Since nocturnal thunderstorms occur more frequently than daytime thunderstorms at Omaha and in a large surrounding area, the causal factors should show a diurnal variation with a nocturnal maximum for that area.

c) Nocturnal thunderstorms last longer than daytime thunderstorms. Therefore, a dynamic factor must be discovered which provides sufficient energy for continuous overturning over a longer period of time than that required for the overturning of a layer of air heated from below, such as occurs in surface-heating type thunderstorms.

2. Current Theories

Several theories have been advanced to explain the nocturnal maximum occurrence of thunderstorms. Those referred to most commonly are perhaps (1) radiational cooling at the top of a cloud layer and (2) advection of cold air aloft. Another theory based on advection of warmer air in lower layers is considered in this report.

Ordinarily over land a stabilizing effect due to radiational cooling is expected, since the surface of the earth usually cools more rapidly than the air aloft. Radiational cooling of the free atmosphere does occur, but with clear conditions the order of magnitude of differences in temperature changes between two levels due to this cause is small, being about 1° C or 2° C for a 12-hour period.

Perhaps the most marked effect of radiation would be noted with a cloud layer aloft. Net radiational cooling at the top of the cloud would occur at night, since a cloud radiates approximately as a black body. The base of the cloud, on the other hand, would be absorbing quantities of heat that are radiated from the surface of the earth and from the water vapor in the atmosphere between the earth's surface and the base of the cloud. With a steep lapse rate above the cloud, vertical accelerations might possibly carry air parcels aloft, which, with the condensation of moisture, would release latent heat for continued upward acceleration, giving sufficient energy for the formation of a thunderstorm. However, some observers have pointed out that an inversion or stable layer would probably be formed just above the top of the cloud due to radiational cooling, or any stable layer or inversion that had been present would be intensified so that vertical motions from within the cloud to a region above the cloud would be suppressed.[1] Also, any temperature changes that might be expected with the addition or loss of heat by radiation to the base of the cloud or from the top of the cloud would be retarded to some degree by the release of latent heat with cooling and condensation and by the absorption of latent heat with heating and evaporation.

No evidence has been offered to show that such a radiation effect has a geographical distribution corresponding to the area in which nocturnal thunderstorms occur. Data on the mean distribution of clouds for the season June to August do not show such a geographical effect. Also, there is no immediately apparent reason that raditional cooling aloft would produce thunderstorms of longer duration than those due to surface heating.

The largest temperature changes per unit time at a fixed point in the free atmosphere are due to advection. Advection of colder air aloft therefore has been offered as an explanation of nighttime instability. Winds-aloft data might seem to support this theory. Frequently before the occurrence of a nocturnal thunderstorm the winds at the ground have a southerly direction, turning in a clockwise direction with height as viewed from above, so that at a level of 7,000 or 8,000 feet above M.S.L. the wind may have a slight component from the north. Near the surface of the earth southerly winds are usually warm and northerly winds are usually cold. However, a northerly wind aloft does not necessarily bring in colder air. As is pointed out in several texts dealing with dynamic meteorology,[2] the clockwise turning of wind with height usually implies advection of warmer air in the layer in which this occurs (in the Northern Hemisphere). No evidence has been offered to show that advection of colder air aloft has a nocturnal maximum nor that it would occur more frequently or to a greater degree in the area of frequent occurrence of nocturnal thunderstorms. It is probable that advective effects, either the advection of colder air aloft or the advection of warmer air in lower layers, could contribute continued instability over a period of time longer than that required for the overturning of a heated layer of air near the ground.

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[1] This is an opinion privately communicated to the author by Major Harry Wexler, U.S.A.A.F.

[2] Cf. B. Haurwitz, Dynamic Meteorology (New York: McGraw-Hill Book Co., 1941), p. 150.

PART II

INSTABILITY DUE TO ADVECTION OF WARMER AIR

3. Summary of a Year's Occurrences at Omaha

In the examination of data for 1941 at Omaha, radiosonde data were plotted on pseudo-adiabatic charts for the periods before and after the occurrence of each thunderstorm. Hourly airway observation data including three-hourly cloud and pressure-change data for periods before, during, and after each thunderstorm were obtained from Weather Bureau Forms 1130-Aer. Hodographs of pilot-balloon observation data before and after thunderstorms were prepared. Of a total of 69 thunderstorms at Omaha in 1941, sufficient relevant data were found to classify 51 of the occurrences as to the principal factor contributing to instability for the formation of the thunderstorm. A summary of this classification follows:

	No. of Cases
ADVECTIVE WARMING IN LOWER LAYERS (Usually at elevations between 2,000 and 8,000 feet above M.S.L.)	28
ADVECTIVE COOLING ALOFT (Usually more than 8,000 feet above M.S.L.)	5
INSTABILITY AND CONVECTION FROM THE GROUND (Surface heating or turbulence, or both)	8
CONVECTIVE INSTABILITY (Release through frontal lifting directly with passage of cold front or instability from lifting of air up warm-front surface)	4
INSTABILITY OF SATURATED AIR WITH RESPECT TO THE PSEUDO-ADIABAT (Where long-continued precipitation was an important factor in supplying moisture for saturation of an air mass through which precipitation was falling)	6

The thunderstorms that occurred with advective warming in the lower layers were more frequently of the nocturnal type. The greater number of them occurred during the latter part of the thunderstorm season, that is, from July through October.

4. General Discussion of Instability Due to Advection of Warmer Air

Examination of radiosonde data for a number of cases with thunderstorms of this type shows a relatively stable layer of air from the ground to the gradient wind level or just above the gradient wind level. The stability of this layer may be due to radiational cooling or may result from the presence of a frontal inversion at the top of the layer.

In the case of a frontal inversion frequently no increase in moisture with height through the inversion is found, although from the surface map it is quite apparent that a frontal surface extends over the station. Above the stable layer next to the ground the air is conditionally unstable.

Frontal situations that are favorable for the formation of thunderstorms due to warm-air advection are: (a) a slow-moving cold front that has a NE-SW orientation, with the development of frontal waves southwest of the area in which thunderstorms occur; (b) a slow-moving cold front or occlusion in an elongated N-S trough to the west of the region in which the thunderstorms occur; and (c) the warm sector of a wave.

In (a) an appreciable influx of overrunning warm air to the north of the wave may contribute instability through the advection of warmer air just above the frontal surface, even though no overrunning type clouds (M1 or M2) are produced. If clouds were produced at the frontal boundary, the thunderstorms might be due primarily to convective instability. More frequently the air above the frontal inversion at Omaha is not saturated but has a relative humidity nearer to 50 per cent, with a convective condensation level near 10,000 feet above M.S.L., or higher.

Most thunderstorms occur with a frontal system within 250 miles of Omaha. Namias has shown that the occurrence of thunderstorms is related to the presence of moist tongues aloft as indicated by isentropic charts.[3] Moist tongues aloft are closely related to the presence of fronts and surface troughs of low pressure.

In a case where the thunderstorm is due to advection of warmer air in the lower layers the plot of the upper-air wind vectors on a polar diagram (hodograph) will show a pattern similar to that shown in Figure 6a prior to the thunderstorm. Hodographs of this type are found more frequently at the 2300 and 0500 pilot-balloon observations than at the 1100 and 1700

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[3] Namias, Introduction to Air Mass and Isentropic Analysis (New York: American Meteorological Society, 1940).