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AIR MASS CLIMATOLOGY OF THE
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Jay R. Harman
Major professor

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# AIR MASS CLIMATOLOGY OF THE NORTH CENTRAL UNITED STATES

By

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## ABSTRACT

## AIR MASS CLIMATOLOGY OF THE NORTH CENTRAL UNITED STATES

By

Mark Donald Schwartz

This study is concerned with the geographic distribution of the major air masses that affected the North Central United States from 1970-1979. These air masses, and the transition zones between them, were delimited through map analysis of 850mb air and surface dewpoint temperatures. The results show that Continental air was dominant in all seasons in the north but was less influential in the south, whereas Pacific air was prominent in the west. Also, Dilute Tropical/Tropical air was important in the southeast, and Dry Tropical air was primarily a summer season phenomenon, influential only in the western portions of the study area. Furthermore, the occurrence of each air mass in the study area appears to be associated with a particular 500mb pattern. These flows may be helpful in explaining the mean and modal patterns of the various seasons.

## ACKNOWLEDGMENTS

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# CHAPTER I

# INTRODUCTION

North American weather patterns are difficult to generalize because they are produced by an extremely complicated system. However, generalization is necessary in climatology in order to begin to understand how the different components of a weather-producing mechanism create the specific combination of environmental conditions on the earth's surface known as climate. Usually the main variables examined are the characteristics and movements of air at the earth's surface and at higher altitudes, and how often different types of air occur in the area being studied.

## The Problem

Different types of air with relatively uniform characteristics are usually referred to as "air masses", and are a convenient way of analyzing, describing, and thereby understanding the variability of weather from day to day. Unfortunately, there is no widely accepted method of classifying air masses. Many systems exist that group air mass types on the basis of their upper air characteristics (Godson 1950), region of origin (Brunnschweiler 1952,1957; Bryson 1966, 1981), or both (Showalter 1939; Willett 1940), without giving special attention to the range of surface conditions associated with each air mass type. Developing a reliable quantitative air mass classification scheme is not a simple task because extensive mixing occurs, making the boundaries between air masses difficult to locate. Also, individual air masses are modified by contact with the earth's surface as they move outward from their source regions.

My intent in this study is to examine the geographic distribution of the major air masses that affect the North Central United States by delimiting these air masses using 850mb air and surface dewpoint temperatures. The validity of these limits will be assessed by analyzing the upper air pattern associated with each delimited air mass type. Because of the overlapping characteristics of some air masses, the boundaries between them are often not sharp lines but gradual transition zones, complicating recognition of the boundaries and reducing the confidence with which they can be drawn. Therefore, I will examine only the Continental, Pacific, Tropical, and Dry Tropical air masses because these are relatively discrete types, and will not attempt to analyze the many sub-classes and combinations associated with each major air mass. I will examine the distribution of these air masses in each of the four seasons (using January, April, July, and October to represent their respective seasons) and also identify the changes in their numerical limits during different seasons. The validity of my "limits" procedure as a method of air mass classification will be addressed by comparing the results of this study to previous research.

Using the number of commonly recognized major air mass types in my study area as a reference, I also intend to employ a statistical classification procedure on the data from one station. A comparison of the class limits from this statistical grouping with the numerical limits I find through map analysis will help to determine how well the statistical groupings appear to agree with physical reality. If the results from these two methods compare well, the statistical method of classification may have a future as a refinement of the necessary subjectivity present in standard climatological air mass research at this time.

This problem has broad implications for many aspects of climatological research. If a quantitative classification system could be devised, it would increase our empirical understanding of climate. The quantitative system would allow air masses to be defined by a definite range of temperature and moisture conditions, and the air mass climatology of a region could be analyzed using daily surface and upper air information. If a relationship between upper air patterns and specific numerical distributions of air masses in a given geographical location is demonstrable, a more detailed description of expected temperature and moisture conditions could accompany an upper air pattern forecast. Such forecasting is not now routine in part because of the lack of an adequate description of the range of surface conditions associated with individual air masses in specific geographical locations. I believe that this study could be part of the effort to develop the "better quantitative models" that will be necessary in order to develop reliable long range weather and climate predictions (Mather et al. 1980).

## CHAPTER II

## REVIEW OF THE LITERATURE

North America and its sub-regions have been the subject of several air mass studies (Burke 1945, Burbidge 1951, Harley 1962, Henry 1979, McIntyre 1950, Miller 1953, Weedfall 1970) and studies of other regions can be found in European meteorological/geographical literature as well (Belasso 1952, Craddock 1951, Crowe 1965, Frisby and Green 1949, Geb 1975, James 1969;1970, McDonald 1975, Myachkova 1979, Soronking 1976, Stessel and Van Isacker 1975, Stopa 1970). Burke (1945) studied the modification of continental polar air over a water surface, and Burbidge (1951) complemented that study with an examination of the modification of continental polar air over Hudson Bay. Henry (1979) studied the problem of separating tropical air from return flow polar air. Miller (1953) wrote a general reference article concerning air mass climatology, and Weedfall (1970) examined applications of air mass classification to West Virginia climatology.

European air mass literature has placed a greater emphasis on the quantification of air masses. McDonald (1975) used eigenvector analysis as an aid to air mass recognition, and Stopa (1970) studied the probability of extreme temperatures and definite diurnal amplitudes in various air masses. These studies are typical of most of the air mass literature. In general, research has been directed toward detailed studies of one or two air masses in a specific area, a general examination of all air masses in a review fashion, or the use of commonly recognized air masses in an attempt to better understand some aspect of local or regional climate. Few have attempted to devise new methods for separating air masses, and an even smaller number have tried new methods to describe the complete air mass climatology of a region. The remainder of my review will be devoted to those articles that have contributed to this last area of air mass research.

Dodd (1965, pp. 113-122) produced average dewpoint maps for the contiguous United States for each month of the year based on an average of ten years of record for each of the approximately 200 stations that have psychrometric data available. The author also presented standard deviation patterns for each of the months, and suggested that frequency of air mass change, diurnal range of temperatures, and the relationship between the absolute atmospheric water content and temperature should be considered when interpreting these patterns. Harman and Harrington (1978, pp. 402-413) addressed the problem of identifying tropical air in the summertime. They concluded that a dewpoint of 65°F (18°C) at the surface is the lower threshold of maritime tropical air in the upper Midwest (p. 404).

Wendland and Bryson (1981) identified "near surface airstream regions" in the Northern Hemisphere using 16-year mean resultant winds from 3° latitude by 3° longitude grids. The authors proposed 19 different sources during the various seasons of the year and determined the period of time each was present over the Northern Hemisphere. Favored areas for frontal development (those areas subject to incursions by the most air streams) were described, and they revealed several north-south bands that represent "the mean leading edge of continental air masses" (p. 225). Wendland and Bryson postulated that mean dew-points "demonstrate the character of the moisture discontinuity across several mean frontal boundaries."

In an earlier study Bryson (1966) analyzed July air mass frequencies from 1945-1951 and 1954-1956 using daily computation of trajectories back to source regions. He compared these results to an independent analysis of the July air mass frequency distribution during 1948-1957 obtained by resolution of the daily maximum temperature frequency distribution into partial collectives, i.e., component normal distributions. Bryson concluded that these two methods produced similar results, and performed a final analysis using monthly resultant wind stream lines (produced from ten year mean geostrophic winds over North America) near the surface which indicated that "mean airstreams and confluences between airstreams define climatic regions with a distinctive annual march of airstream and air mass dominance" (p. 228). The final conclusion of the study was that the analyses "strongly suggest that the boreal forest occupies the region between mean or modal southern boundaries of Arctic air in winter and summer," and that a "distinctive cornbelt climate" existed which "coincides with the corn belt as defined by land use" (p. 257).

Barry (1967) used the 850mb level to determine the mean position of the Arctic front during each season of the year from 1961-1965. Air mass characteristics and boundaries were identified by analysis of aerological data in the form of tephigrams, hodographs, and vertical cross sections in order to determine the lines of intersection of frontal surfaces with pressure levels (pp. 19-80). In comparing his results with those of Bryson, Barry concluded that the position of the continental Arctic front in winter appeared to agree with Bryson's Arctic frontal zone, and in summer the agreement continued, with some problem areas developing east of 90°W longitude.

Willett (1940) is the author of one of the early studies of North American air masses. The major types of air masses were classified by the relative temperature (polar or tropical) and moisture content (continental or maritime) characteristics of their source regions. Processes of air mass modification, including surface contact, subsidence, and turbulence, were explained, and the average characteristics (temperature °C, absolute and relative humidity) of several of the major winter and summer air masses were presented. The author concluded that the investigation of the characteristics of the principal air mass types could be of great assistance to the synoptic meteorologist and forecaster (p. 73). Showalter (1939, pp. 204-218) covered similar topics and concluded that ten air mass types (Polar Continental, Polar Atlantic, Polar Pacific, Polar Moist, modified Polar Continental, modified Polar Pacific, modified Polar Moist, modified Polar Superior, Tropical Maritime, and Superior) were of practical synoptic significance for the United States during most of the year, with fewer types (modified Polar, modified Polar Moist, modified Polar Superior, Tropical Maritime, and Superior) in midsummer (p. 217).

Godson (1950) studied the relationship of air masses to frontal positions and concluded that "an air mass contiguous to a given front should be given the same designation at all points along the front regardless of the possible differences in trajectory which might exist" (p. 90). He noted that air masses that would be classed "maritime" from their trajectory can be relatively dry at higher levels, thereby suggesting that the trajectory method alone is not a satisfactory method for air mass classification. The author postulated that "the number of air masses in summer should be less than in winter" (p. 91) because of the disappearance of continental arctic air in the summertime. After a discussion of the typical temperatures at various upper levels in winter and summer air masses and the processes of upper level cold dome and warm pocket creation and destruction, he concluded by proposing that three-dimensional analysis be included in the preparation of forecast charts.

Two works by the same author have the closest relationship to my study. Brunnschweiler (1952) examined North American air masses and determined the actual daily position of each air mass boundary derived from daily weather maps (p. 42). The author investigated the three winter months (December, January, February) and the three summer months (June, July, August) for the period 1945-1949. Two final maps were drawn that indicated the average distribution and tendencies of expansion of various air masses (p. 42). Three zones were established: regions dominated by an air mass at least 80% of the days during the season concerned (source regions), regions in which the particular air mass prevailed 20-80% of the period (conflict regions), and regions invaded by a particular air mass only occasionally, i.e., less than 20% frequency (p. 42). Three types of air mass boundaries were recognized:

geographic, frontal, and transitional. The author found a "distinctive dominance of arctic and polar air masses ... in winter" (p. 48), and in summer "a less uniform air mass regime than that of winter" (p. 48). In a later study, Brunnschweiler (1957, pp. 167-195) applied the same air mass classification methods as above to the entire Northern Hemisphere, and suggested that his method, "aerosomatic", could be used to genetically classify climates, with air masses as "the major causative factors of the climatic differentiation of the Northern Hemisphere" (p. 195).

If air mass research is to be successfully integrated into the mainstream of modern climatological/meteorological research, it must become increasingly quantitative. This quantification is necessary if air masses are to be described precisely so that their frequencies can be compared to other meteorological variables. Air masses should be exactly delimited whenever possible. Nearly all of the aforementioned articles recognized air masses by their average conditions instead of the range of conditions associated with each type in a given geographical area. Those studies that did recognize air masses as a range of conditions did not include a quantitative indicator of moisture content along with their thermal criteria. Therefore, a study is needed that not only examines the complete air mass climatology of a region but also provides a workable method for recognizing the range of thermal and moisture characteristics associated with each air mass type. Further, the method should identify the transition zones that exist between air masses. Such a study would facilitate the quantification of air masses and might open possibilities for air mass research to improve the detail of long range weather and climate predictions.

# CHAPTER III

# METHODS

## Determination of the Study Area

The North Central United States (Figure 1) was chosen as my study area not only because I am familiar with the regional air masses, but also because the air mass contrasts are pronounced in this region. North America is the only continent extending from polar to tropical regions which does not present physical barriers to air mass movement in a north-south direction. This unique physiography, along with the central location of the study area on the landmass, allow easy movement of the air masses from four source regions into the study area. Further, other studies of this area have yielded results that do not always seem consistent with daily synoptic patterns. The study area was defined so as not to include the Rocky Mountains because of the complex air mass climatology of that region. The South and East were not added to the study because of the reduced air mass contrast of these areas. Since my study is concerned with both upper air and surface data, I determined which weather stations had these data available for the period 1970-1979. These stations are shown in Figure 1. One station, Monette, MO, had data from only 1971-1979; however, I considered this sufficient to be included.

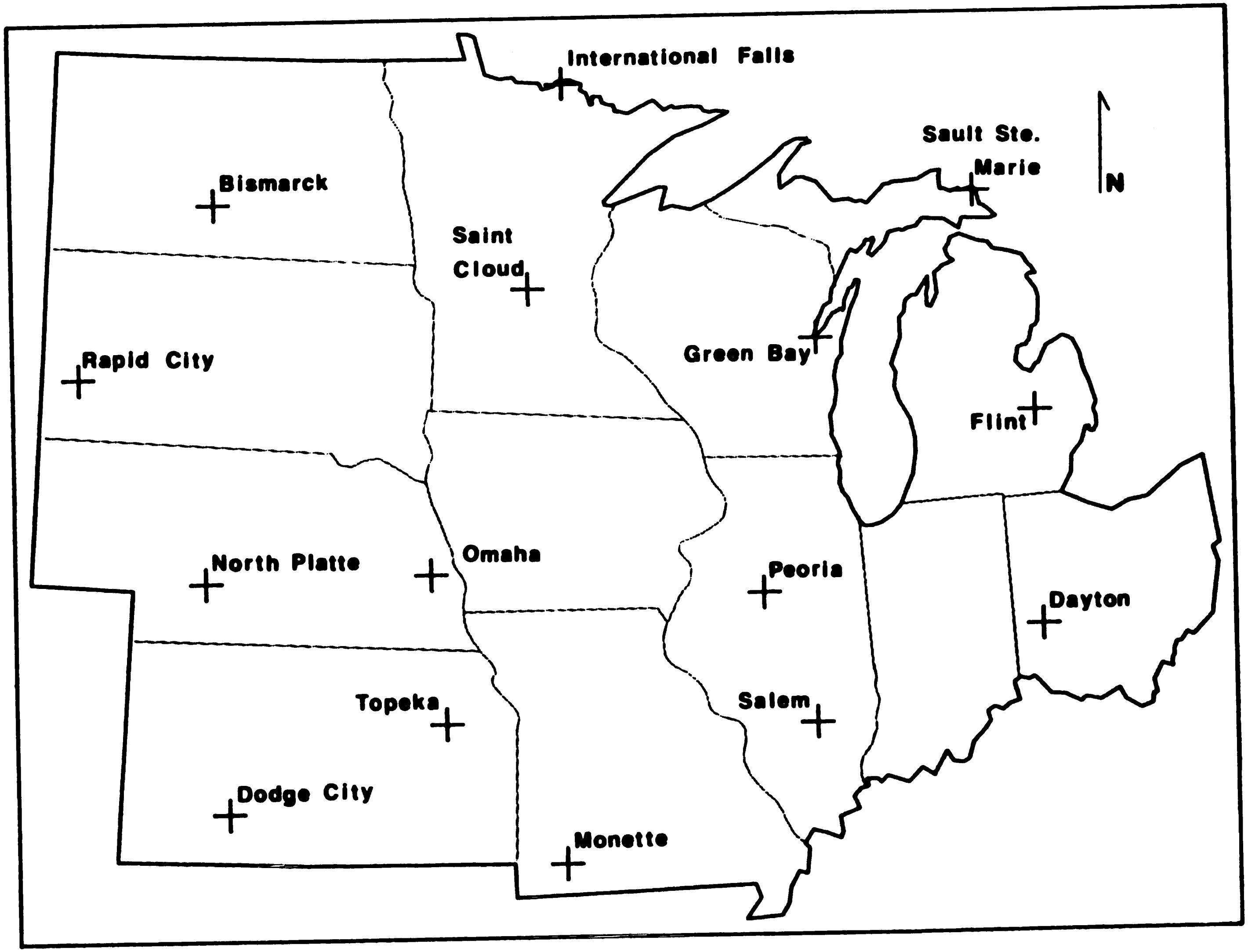


Figure 1. Station locations in the study area.

## Air Mass Names

In this study I am defining air masses using methods that are not directly comparable to other research, and, as previously mentioned, only a few relatively discrete types are being analyzed. Therefore, I decided to use generic names for the air masses that referred to their source region, conveying a general description of their relative characteristics without directly associating them with names used in previous research.

## Source Regions

### Fall, Winter, and Spring

Continental--Persistent upper level ridging in the western part of North America induces areas of subsidence on the east side of the ridge during passage of short wave troughs with their negative vorticity advection areas. This subsidence favors anticyclogenesis, particularly over north central Canada where cold surface conditions reinforce the dynamic anticyclones. Taking on the cold, dry characteristics of their source region, these high pressure air masses frequently travel southeastward along the mean flow lines behind moving troughs and affect the United States. Barry (1967) used the 850mb temperature to distinguish these air masses from warmer types of air.

Pacific--During periods of zonal flow, air from the north Pacific is advected landward behind moving troughs and forced to traverse the Rocky Mountains where its moisture content is reduced and temperature increased. This mild, relatively dry air can be distinguished from

Continental air by using Barry's (1967) 850mb temperature criteria, and from moister types by the surface dewpoint.

Tropical--Particularly during periods of mean upper level troughing in the western United States, tropical moisture is drawn northward into the central United States. Cyclogenesis under the modal positive vorticity advection area that would be located in the lee of the Rockies would produce storms that move northeastward ahead of short waves moving out of the mean trough. These storms bring with them a great amount of tropical moisture from the Gulf of Mexico into the central and eastern United States in the southerly low-level circulation on their eastern flanks. This warm moist air was distinguished by Harman and Harrington (1978) using the surface dewpoint temperature.

Dry Tropical--as described below.

Summer

Polar--As the northern regions of North America warm in summer and lose part of their snow cover, their temperature equals or surpasses that of nearby oceans. Air occupying the land assumes characteristics similar to air over the oceans. Therefore air from these two regions (the Continental and Pacific source regions) that moves into the North Central United States is indistinguishable during the summer. The name "Polar" was used to designate this cold, relatively dry mixture of Continental and Pacific air, which can be distinguished from Tropical air by Harman and Harrington's (1978) surface dewpoint criteria.

Tropical--During the summer, the strongest mean tropospheric winds withdraw to an average position north of the study area. This situation, coupled with the weak circulation over the Texas coast, allows tropical moisture originally directed northward by high pressure over the Caribbean Sea to move into the southern United States. The air is drawn farther north in the southwesterly flow preceding traveling short wave troughs and their associated cyclones crossing the midwest. As in other seasons, this air can be distinguished by the surface dewpoint.

Dry Tropical--During the warmer part of the year the vast continental area in northern Mexico and the southwest United States is heated to extreme temperatures by the plentiful solar radiation. Air in this region, also greatly heated, tends to be confined by the Rocky Mountains to the west and undergoes limited mixing with Tropical air to the east. Based on my preliminary analysis, this air can be distinguished from cooler and moister types by using the 850mb temperature and surface dewpoint.

## Assumptions

The sources of my assumptions are threefold: Barry (1967), which relates to 850mb limits; Harman and Harrington (1978), which addresses surface dewpoint limits, and my own preliminary observations.

1. "Transition conditions" exist between air masses and these account for a percentage of the total number of days in any season.

2. The months of January, April, July, and October in the years 1970-1979 inclusive provide a sufficient data base from which to determine the average frequencies of individual air masses in specific geographical regions.

3. January, April, July, and October represent the best meteorological characterizations of winter, spring, summer, and fall, respectively.

4. The ranges of temperature and moisture content used to identify the air masses have remained unchanged throughout the period of study.

5. The characteristics of an air mass from a given source region change as the air mass moves away from the source region. Therefore the limits defining an air mass may change as distance from the source region increases.

## Operational Definitions

1. Air mass--a body of air with a relatively uniform range of temperature and moisture characteristics observable at or near the surface of the earth. There are several types which originate from different source regions on the earth's surface.

2. Transition conditions--groups of days that have meteorological conditions which fall between air mass types and cannot be accurately classified. These conditions can occur during or just after the passage of a frontal zone through the station location. Since a front is a broad transition zone, it takes time for the atmosphere to assume the characteristics of the new air mass behind the front. Another source of transition conditions is air mass mixing; this occurs when two or more air masses are combined and modified before they reach the station.

3. Dilute Tropical--air that is clearly of tropical origin, but has had its moisture content reduced by mixing with other air masses. This can occur through both dilution and modification. Modification occurs in the cold months of the year when warm tropical moisture is advected northward in a thin band over cold land surfaces that have been recently occupied by Continental air. Dilution is produced when air

from a continental anticyclone is mixed with tropical moisture in the "return flow" on the west side of an eastward moving anticyclone. I will refer to both forms as Dilute Tropical.

4. Northern group--stations at Flint, Sault Ste. Marie, Green Bay, International Falls, Saint Cloud, Bismarck, and Rapid City.

5. Southwest group--stations at North Platte, Omaha, Dodge City, Topeka, and Monette.

6. Southeast group--stations at Peoria, Salem, and Dayton.

## Data Sources

The data required for this investigation were obtained from the National Weather Service's Daily Map Series. These maps were available to me:

1. on microfilm at the Michigan Office of Climatology (Michigan Weather Service), and

2. on themofax paper from 1972 to the present at the Department of Geography, Michigan State University.

## Data Analysis

Temperature data recorded at 1200Z were used in this study. Missing values were estimated from the surrounding stations. The limits were used by a computer program which assigned each day to either an air mass type or "transition conditions" and then tabulated totals and percentages for all types in each of the four seasons.

The above method is necessarily somewhat subjective, so the Jenks statistical classification procedure was used on one station (Flint) in order to determine whether the data distributions suggest limits which agree with those found through map analysis. This procedure classifies by maximizing inter-class variance and minimizing intra-class variance. Because of computer memory limitations I was able to use only seven of my ten years of data, but based on my preliminary examination this number is representative.

## Air Mass Criteria

The 850mb level is close enough to the surface (1200-1500 meters, or 4000-5000 feet) to reflect surface conditions, but enough removed so that it is not substantially influenced by diurnal changes in temperature. These qualities make it an ideal indicator of surface air mass temperature, and the 850mb temperature has been established as a reliable way to differentiate cold continental air from other types (Barry 1967). Likewise, the surface dewpoint temperature has been regarded as an acceptable way to distinguish tropical air (which can be recognized by moisture characteristics alone) from cooler and drier types (Harman and Harrington 1978). These two measures will be the criteria I will use to separate and delimit each season's air masses.

The limits (depicted in Figure 2) were determined through map analysis of air masses of known origin at the surface and 850mb level. For example, in establishing the upper Continental limit in January, I identified a number of Continental air masses over their source region, and then noted the temperatures associated with wind shifts and other

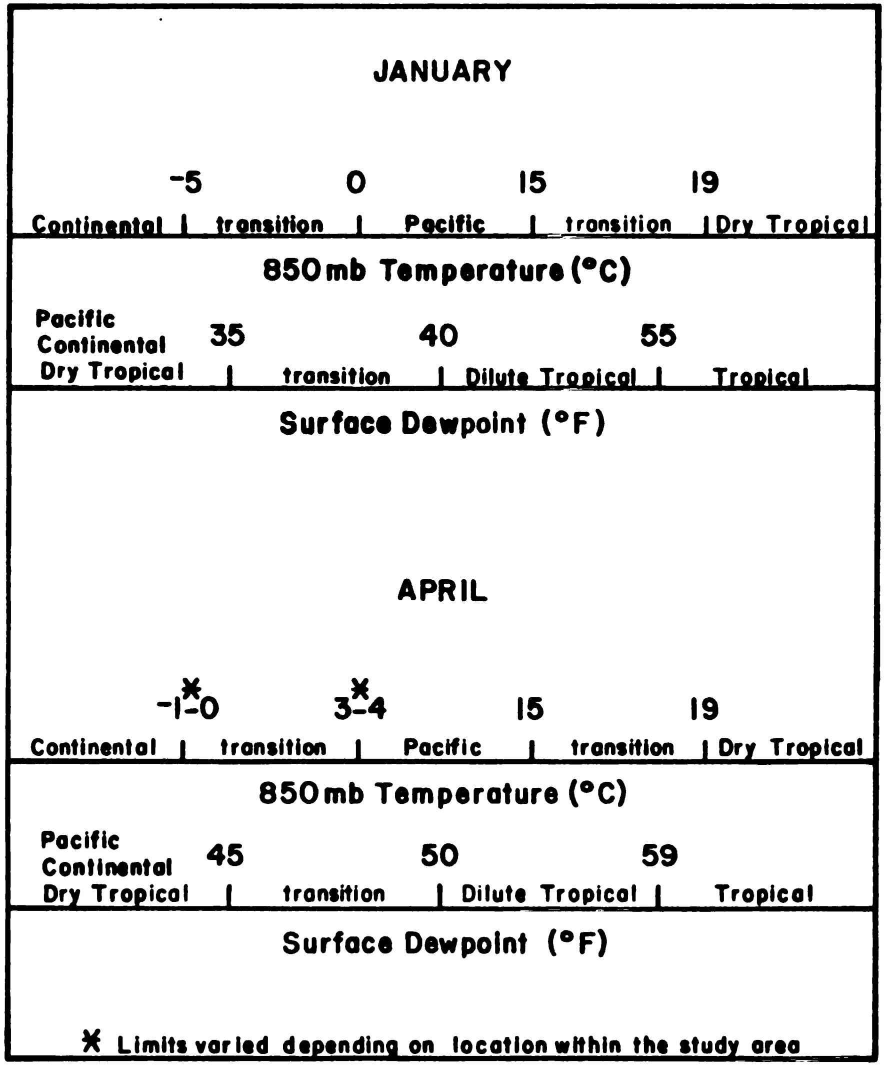


Figure 2a. Air mass limits in January and April.

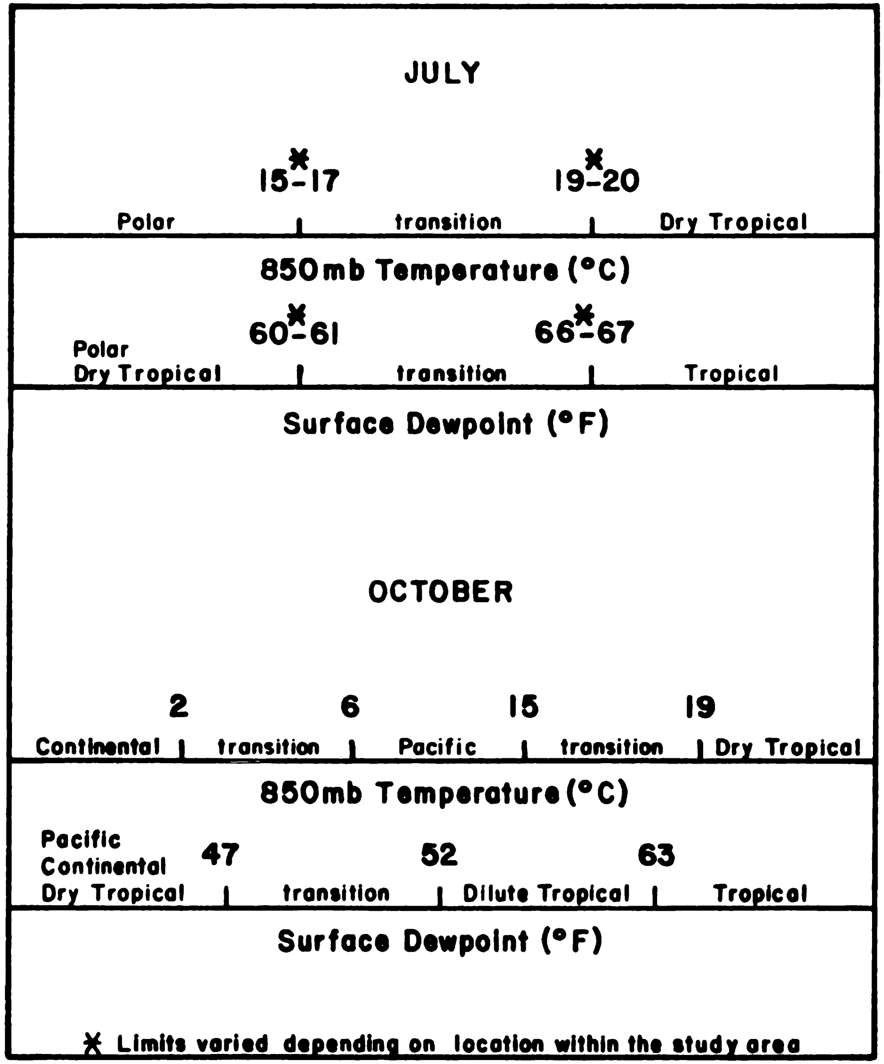


Figure 2b. Air mass limits in July and October.

discontinuities as they moved into and through my study area. After observing an increasing number of these air masses I became confident that specific numerical limits could be used to define each air mass. Essentially the same procedure was followed in defining limits for other air masses and seasons.

I realized that sharp boundaries may not exist between air masses; therefore, daily temperature observations that did not clearly fall into one air mass category or another were designated "transition conditions", and were not included in any air mass total. Even with these precautions, I suspect that in a few instances a mixture of different air masses could produce a temperature that would normally be assigned to an air mass category by my limits. The exact number has not been compiled, but these days probably account for less than five percent of the days in any category.

Differential limits dependent on season were established for the individual air masses because the characteristics of the source regions varied throughout the year. These changes affected the temperature and moisture content of air masses in the study area. For example, the temperature of Continental air increases in response to the shedding of ice cover over a large part of its northern source region and the development of longer days. Tropical air becomes warmer and more moist because of the warming of the Gulf of Mexico. In general the 850mb limits applied to the air masses were warmest in the summer, next warmest in fall, cooler in the spring, and coldest in the winter. The surface dewpoints were highest in summer, lower in fall, still lower in spring, and lowest in the winter.

Geographical location also affected the limits in several seasons. The characteristics of an air mass in one part of the study area did not necessarily hold throughout the entire region because in some cases the air masses were slightly modified as they traversed the study area. For example, in spring Continental air warmed as it moved southward, necessitating an upward adjustment in the 850mb limit from -1°C to 0°C. Differential limits were established by subdividing the study area into groups that were closer to particular source regions, and then observing the limits associated with each air mass type in these various sub-regions.

In light of these geographical differences the following adjustments in the limits were made.

Continental--In spring, differential limits were established because Continental air was consistently warmer in the southern part of the study area. Northern group--(850mb temperature $\leq$ -1°C, surface dewpoint $\leq$ 45°F), other stations--(850mb temperature $\leq$ 0°C, surface dewpoint $\leq$ 45°F).

Polar--In summer, the Continental and Pacific air masses became indistinguishable and are designated together as "Polar". Polar air was consistently warmer in the southwest portion, and moister in the southern portion of the study area.

Northern group--(850mb temperature $\leq$ 15°C, surface dewpoint $\leq$ 60°F).

Southwest group--(850mg temperature $\leq$ 17°C, surface dewpoint $\leq$ 61°F)

Southeast group--(850mb temperature $\leq$ 15°C, surface dewpoint $\leq$ 61°F).

Pacific--In spring differential limits were established because Pacific air was found to be warmer in the southern part of the study area.

Northern group--(3°C $\leq$ 850mb temperature $\leq$ 15°C, surface dewpoint $\leq$ 45°F)

Other stations--(4°C $\leq$ 850mb temperature $\leq$ 15°C, surface dewpoint $\leq$ 45°F)

Dilute Tropical--This air mass was not recognized as a separate category in summer because in my preliminary analysis I was not able to reliably separate days of this type from days of "transition conditions" in this season.

Tropical--In summer, Tropical air was found to have consistently higher dewpoints in the southeastern part of the study area.

Southeast group--(surface dewpoint $\geq$ 67°F)

Other stations--(surface dewpoint $\geq$ 66°F)

Dry Tropical--In summer, Dry Tropical air was found to be particularly warmer in the southwest, and moister in the southern part of the study area.

Northern group--(850mb temperature $\leq$ 19°C, surface dewpoint $\leq$ 60°F).

Southwest group--(850mb temperature $\leq$ 20°C, surface dewpoint $\leq$ 61°F).

Southeast group--(850mb temperature $\leq$ 19°C, surface dewpoint $\leq$ 61°F).

## Map Preparation

The Surface II computer mapping routine was used to prepare the isoline maps. The isoline interval was set so that the resulting maps would accurately portray the range of the data distributions. Air mass distributions with maximum values greater than 20% were assigned an interval of ten, and those between 10% and 20%, an interval of five. Likewise, distributions with maximum values between 8% and 10% were assigned an interval of 2.5, while those less than 8% were given an interval of one.

# CHAPTER IV

# RESULTS

## Outline of Presentation

In order to share my results in a systematic manner, air mass types will be described according to their relative importance in the study area, the most important air mass being presented first. Within each air mass discussion, the general distribution over the entire year will be addressed initially, followed by the specifics of the seasonal distributions in chronological order starting with winter.

## Air Mass Distributions

### Continental

This air mass was by far the most important in all seasons in the northern part of the study area, and it also exerted a marked influence in the southern region. Percentage occurrence was greatest in the northeast section and smallest in the southwest.

Winter--(Figure 3)--Most of the study area was occupied by the air mass fifty percent or more of the time. Importance of this air mass increased northward across the study area in general, except in the Dakotas where it was greater toward the east. The fact that the eighty-percent line included most of Minnesota, Wisconsin, and upper Michigan

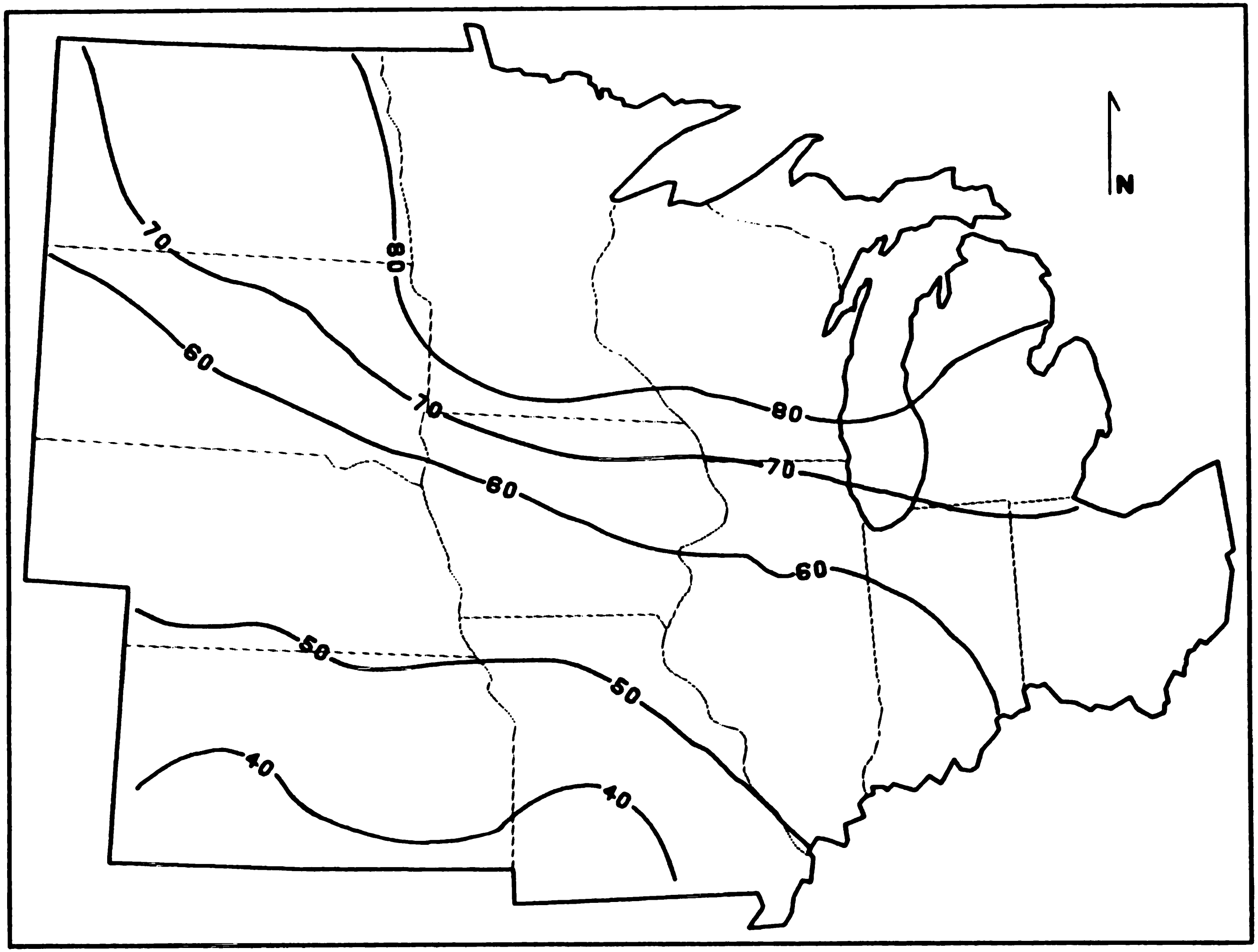


Figure 3. Percentage of Continental air in January, 1970-1979.

was interpreted to mean that these areas have conditions in winter similar to those of the Continental source region.

Spring--(Figure 4)--As in winter, the percentage occurrence was greater toward the north and, in the Dakotas, toward the northeast. The overall frequency was reduced approximately twenty to thirty percent from winter, which left the influence on the southern regions substantially weakened.

Summer--See Polar.

Fall--(Figure 5)--Although the autumn percentage contribution of Continental air was only slightly reduced from that of spring overall (approximately ten percent), the pattern was more erratic in the southern portion of the study area. Two areas of lessened frequency appeared in the eastern Nebraska/western Iowa area and in southern Indiana and Illinois.

## Polar

As previously mentioned, air masses designated "Polar" (Figure 6) in this study were recognized only in summer when air streams from the Continental and Pacific source regions were indistinguishable. Thus, "Polar" air may originate from one or both source areas and is the only cool summertime air mass recognized in this study. It was most important in the northeast section of the study area (Michigan, Ohio, Indiana, Illinois, Wisconsin, and Minnesota), where it had a frequency of fifty to seventy percent. Its impact on the southwest was substantially less (ten to thirty percent).

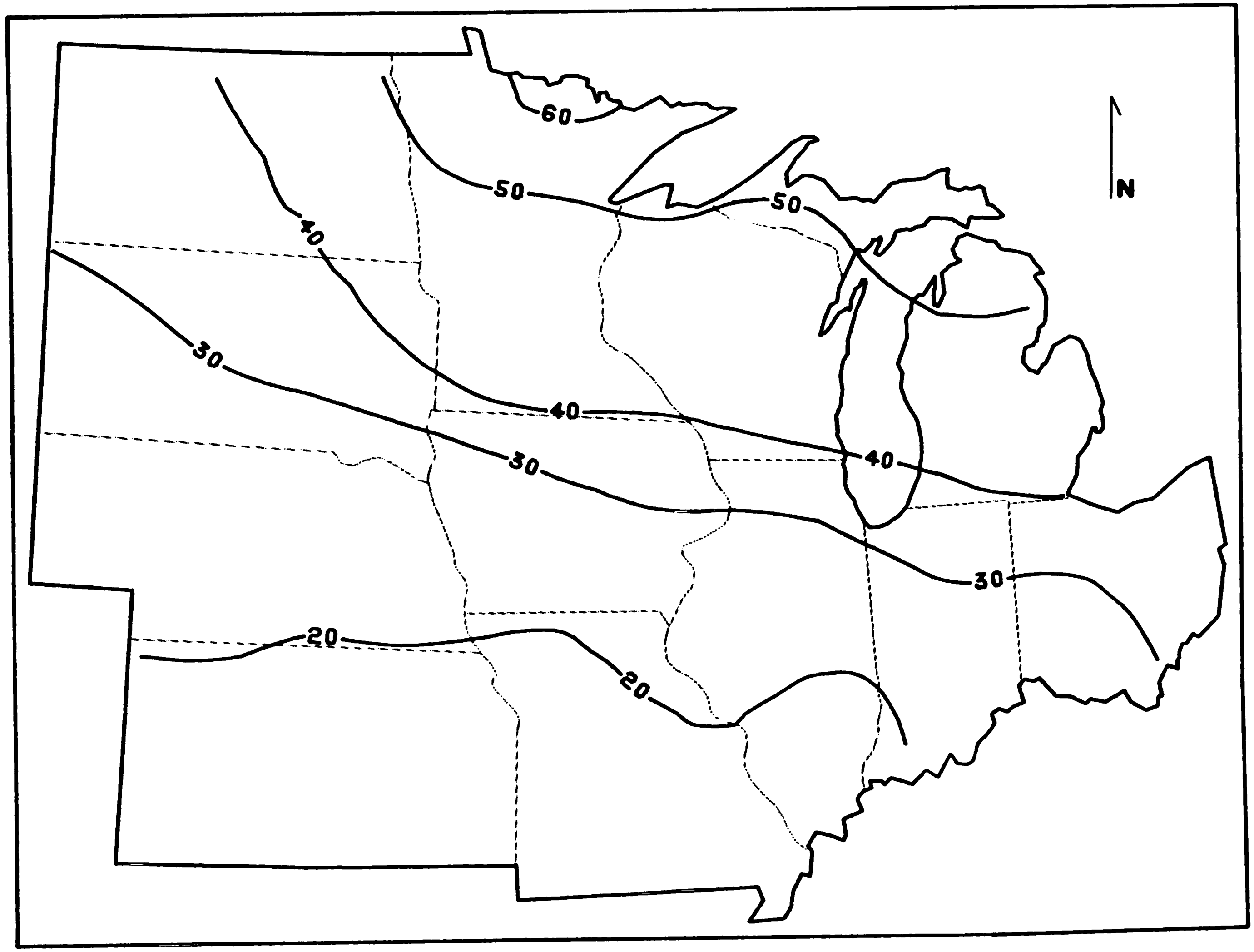


Figure 4. Percentage of Continental air in April, 1970-1979.

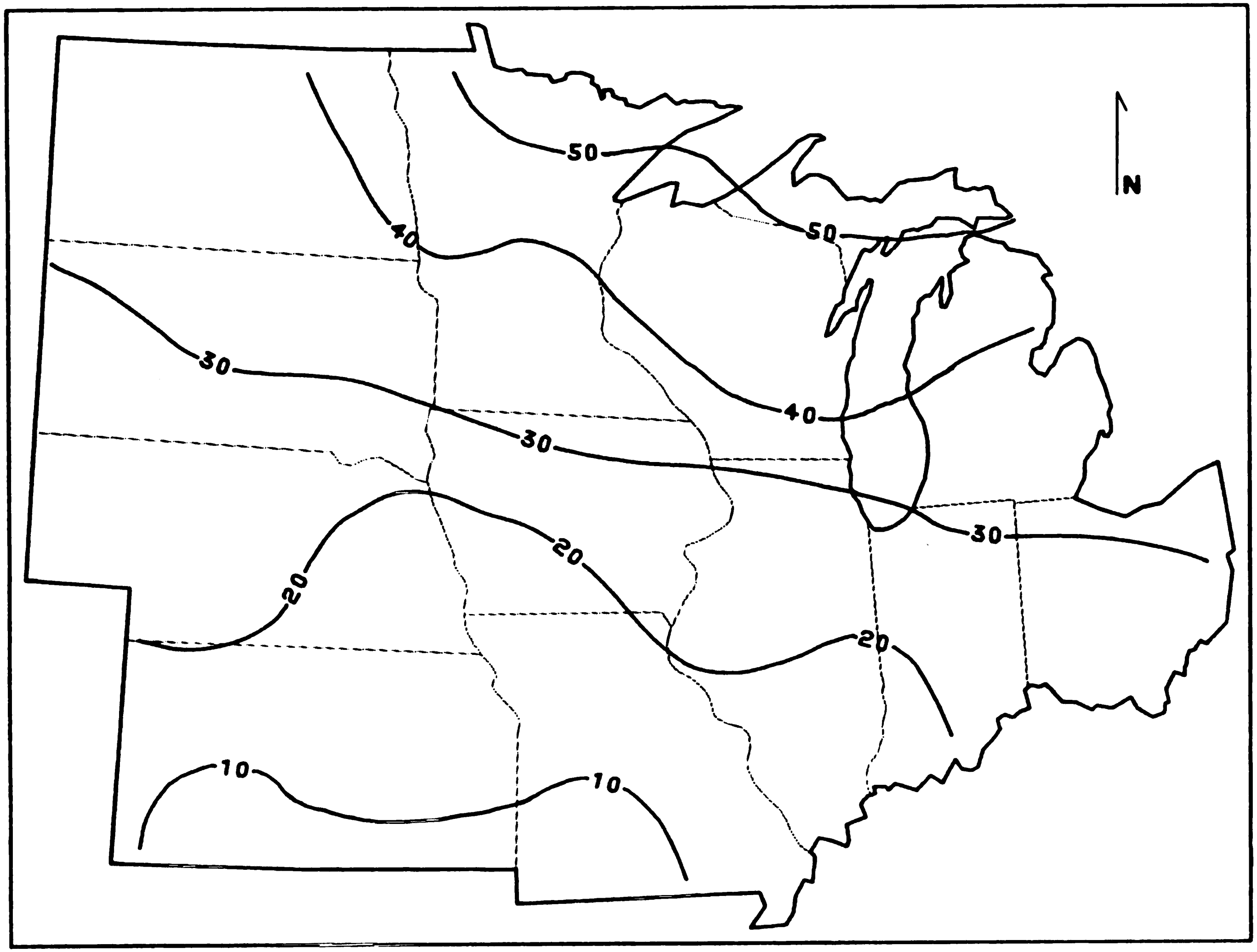


Figure 5. Percentage of Continental air in October, 1970-1979.

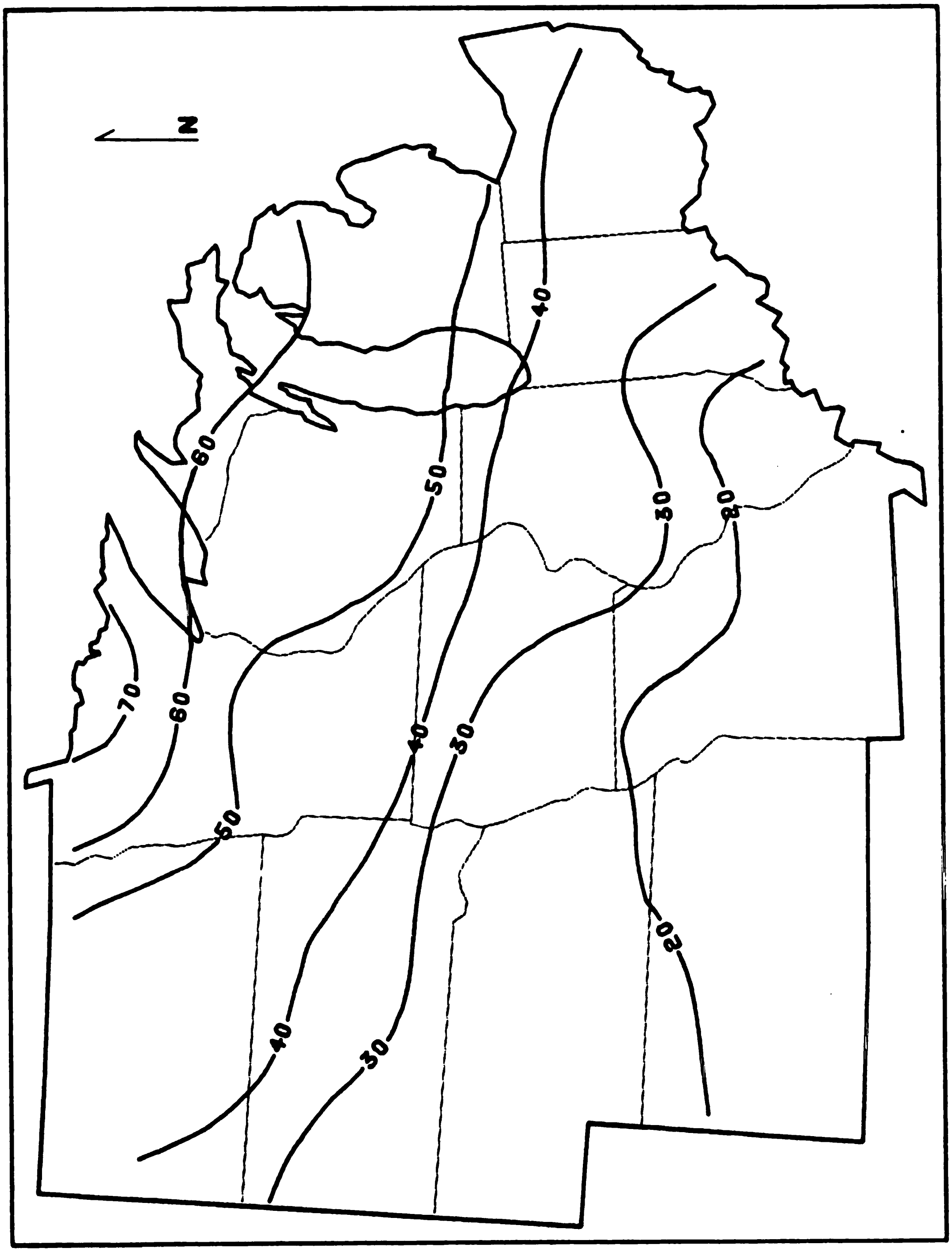


Figure 6. Percentage of Polar air in July, 1970-1979.

Pacific

The western part of the study area was influenced by this air mass throughout the year; however, it did not attain even here the degree of dominance exhibited by Continental air in the north during winter. In general, frequencies of the air mass lessened toward the east, and no contribution in any season was greater than fifty percent.

Winter--(Figure 7)--Highest frequencies were found in the southwest corner of Kansas (forty percent), with lower values toward the northeast from that point. The air mass was uncommon in most of Minnesota, Wisconsin, and Michigan, where it occurred less than ten percent of the time.

Spring--(Figure 8)--The range of percent occurrence across the region was only about twenty percentage points during this season, from the mid-forties in the southwest to the mid-twenties in the northeast. Overall the frequencies increased from winter and were spatially quite uniform, with only a gradual increase toward the southwest.

Summer--See Polar.

Fall--(Figure 9)--While this season was marked by about the same range of frequencies as was spring, the overall pattern of the distribution shifted to gradients in a more east-west orientation. In general, values are greatest in the western part of the study area and lessen toward the east. Also worth noting is the anomalous area of greater occurrence that was present in eastern Indiana and Ohio.

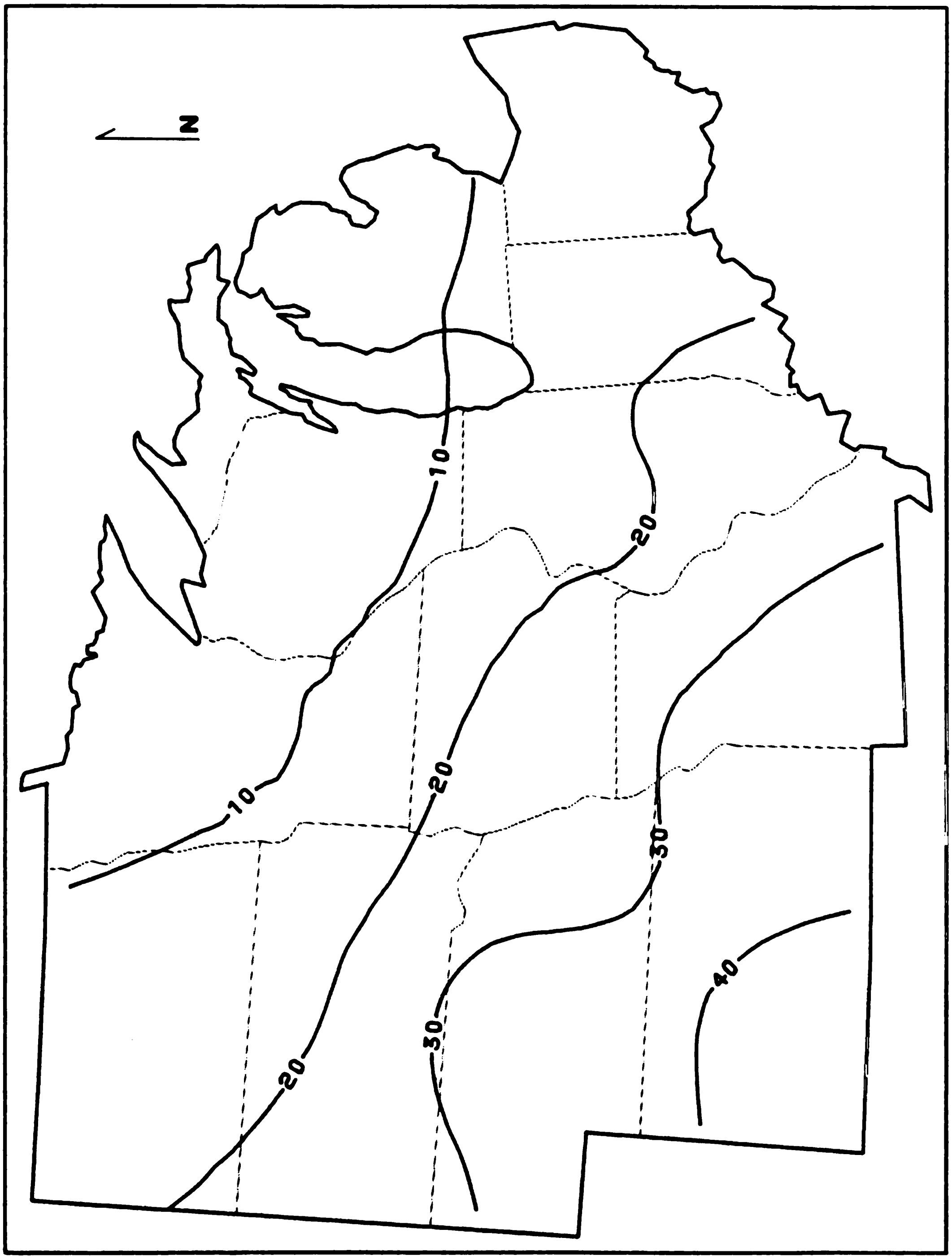


Figure 7. Percentage of Pacific air in January, 1970-1979.

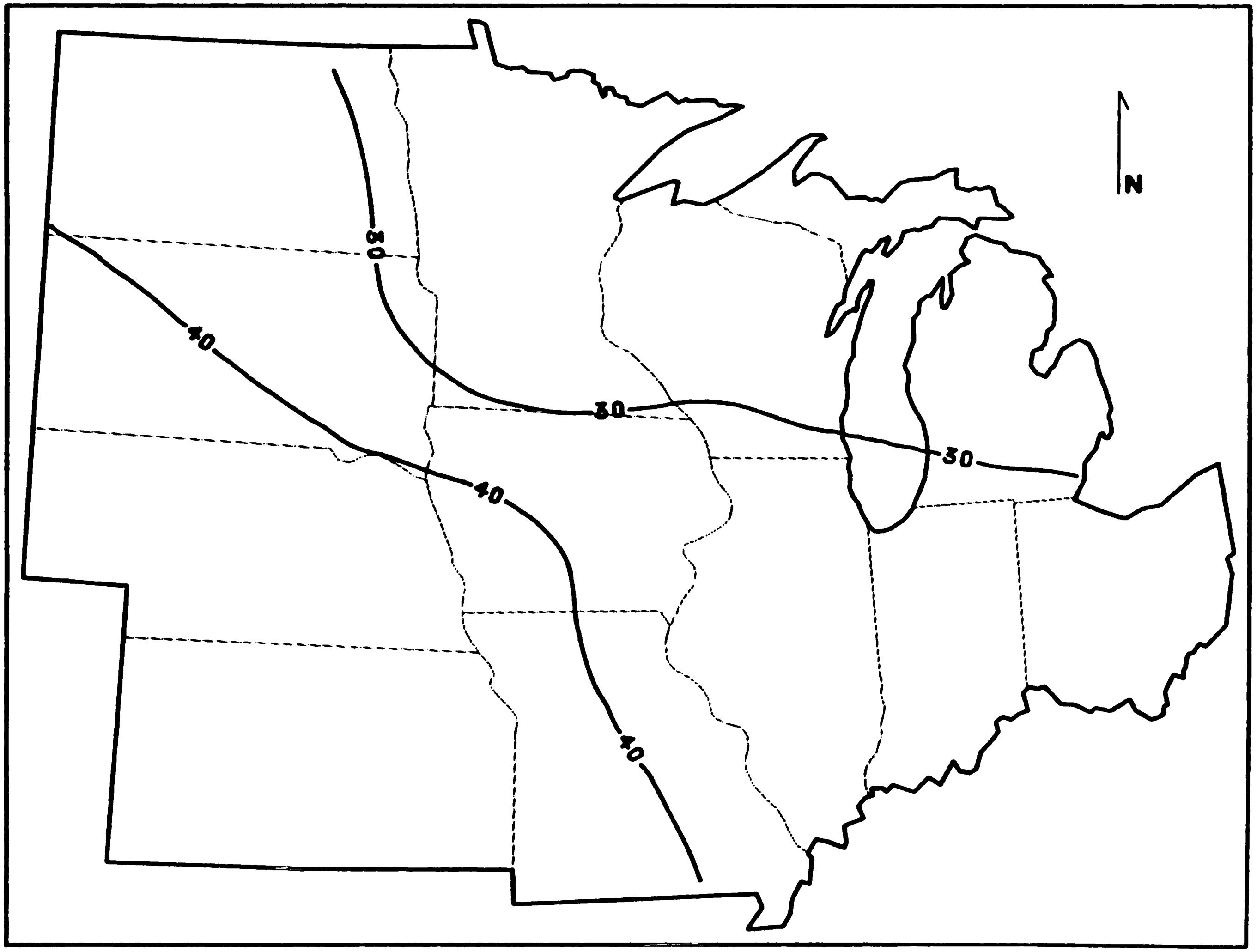


Figure 8. Percentage of Pacific air in April, 1970-1979.

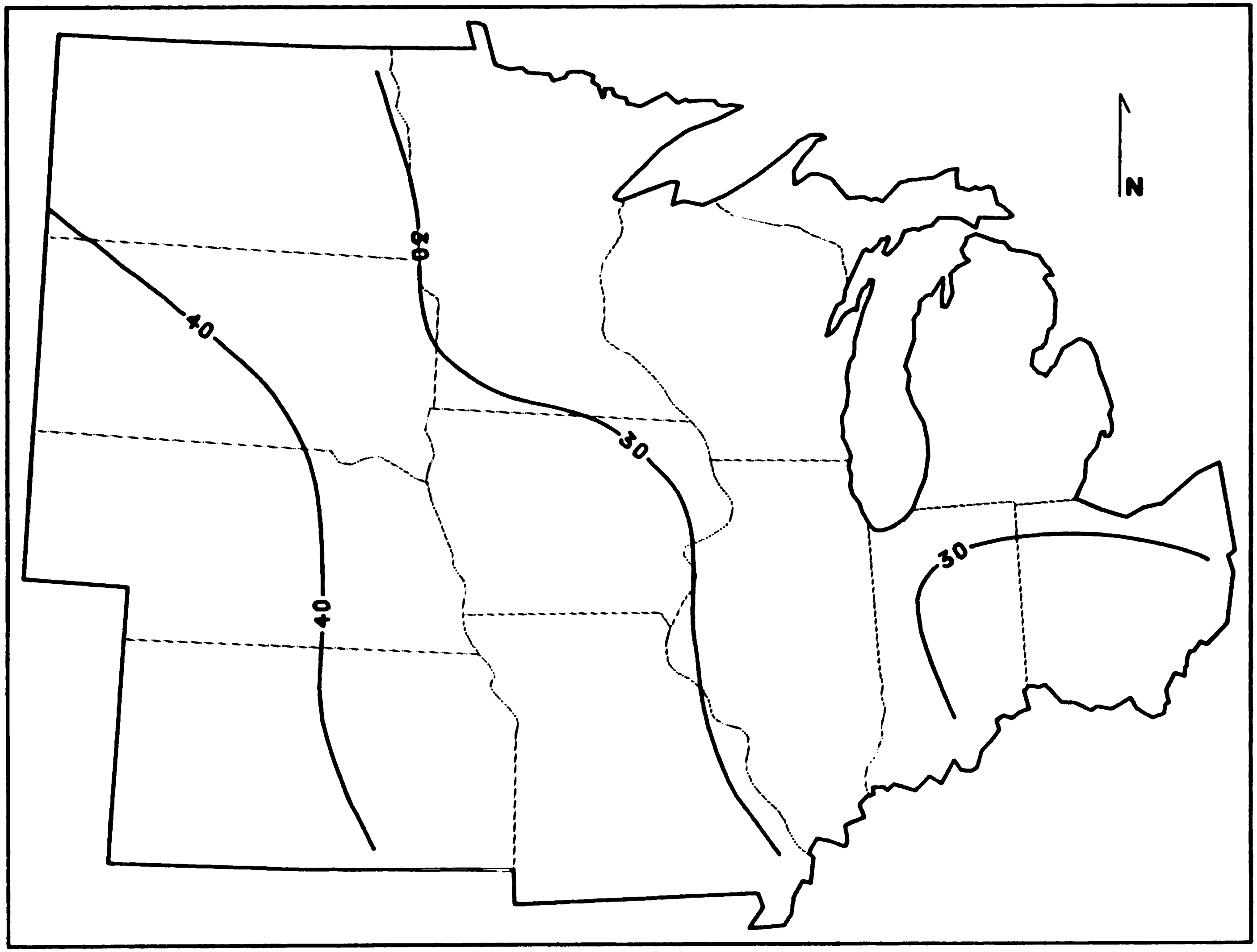


Figure 9. Percentage of Pacific air in October, 1970-1979.

Dilute Tropical/Tropical

As was previously discussed, both of these air types originate from the same source region; thus, Dilute Tropical is no more than a sub-class of Tropical. Throughout the year these air masses were important only in the south and east portions of the study area, and dominated (greater than fifty percent) even in summer in but a small portion of southern Illinois, Indiana, and eastern Missouri.

Winter--(Figures 10 and 11)--During January the dilute air mass was found only occasionally in the south and east portions of the study area (less than five percent of the time). True Tropical air was even rarer, and occurred with a frequency of slightly more than one-half percent in southern Illinois, Indiana, and southeastern Missouri. In the remaining portions of the study area, these air masses occurred less than one-half percent of the time during this season.

Spring--(Figures 12 and 13)--The dilute air mass influenced most of the southern study area at least ten percent of the time. Tropical air in this season was somewhat more common than in winter, but greatest frequencies (less than ten percent) were still found in the southeast portion of the study area. Across the remainder of the region these air masses had a smaller influence.

Summer--(Figure 14)--As indicated before, the dilute air mass was not recognized as a separate category in July. Even though the influence of Tropical air was much greater in summer than in any other season in parts of the southeast, the extreme west and northwest portions of the study area were affected to a much smaller degree (less than ten percent).

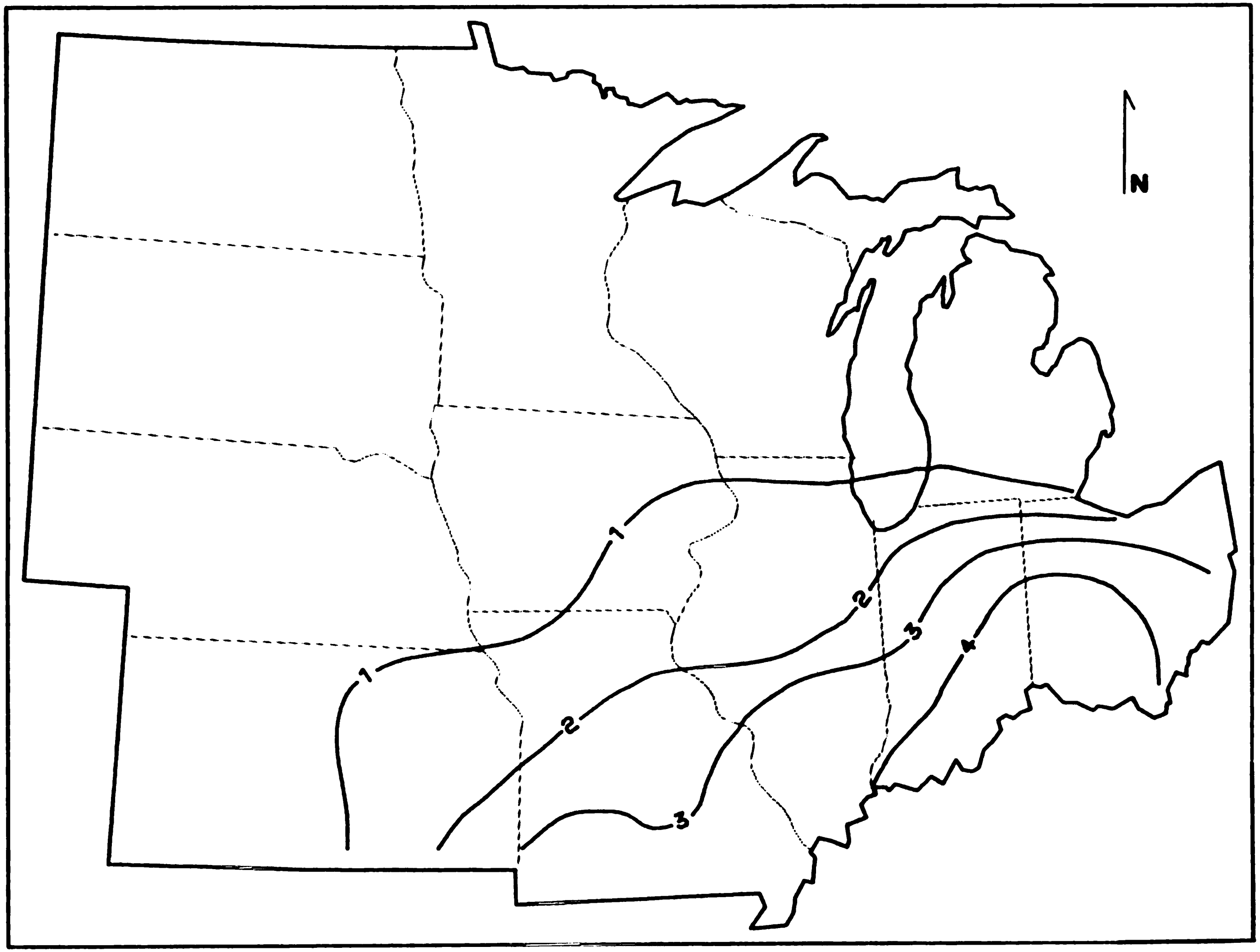


Figure 10. Percentage of Dilute Tropical air in January, 1970-1979.

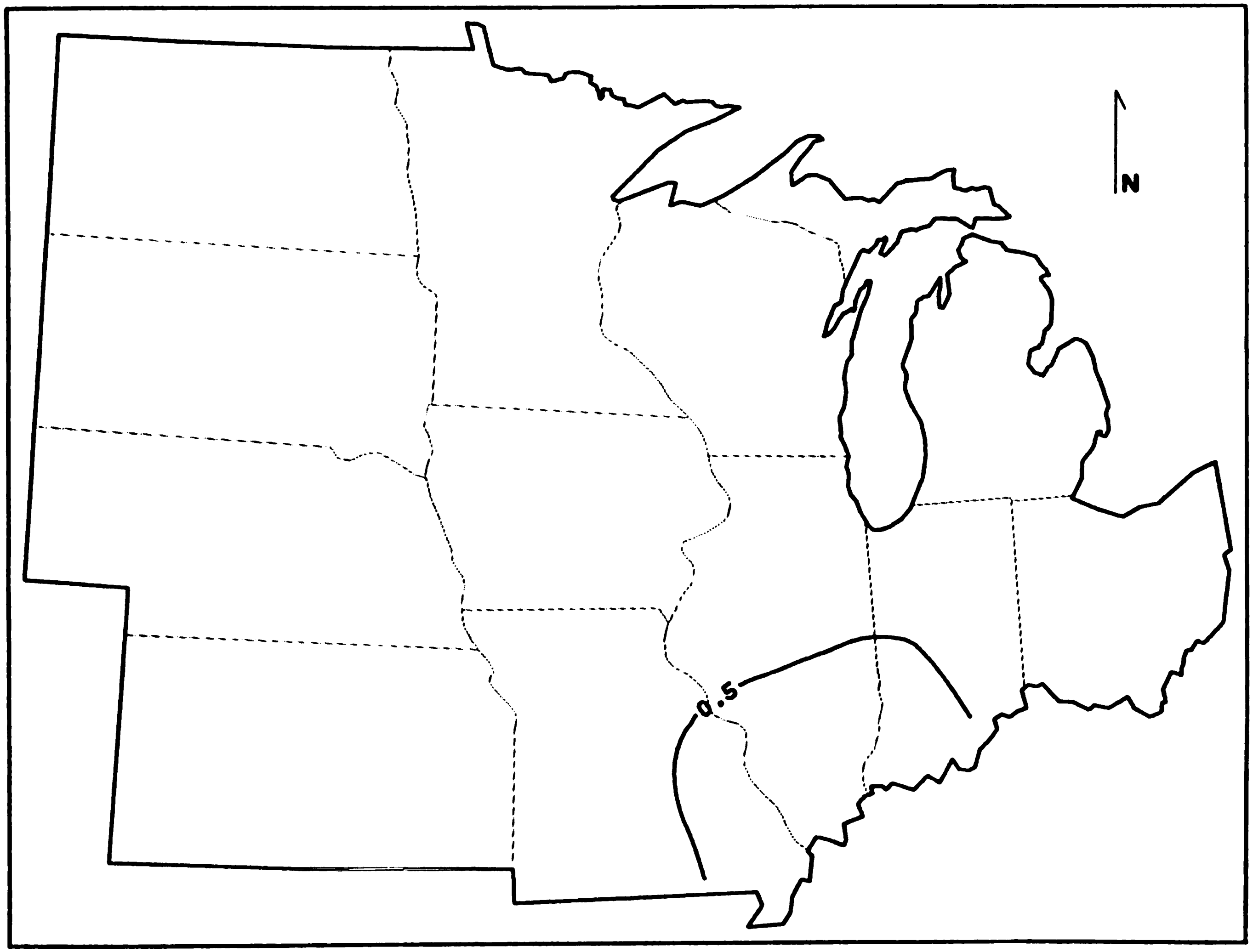


Figure 11. Percentage of Tropical air in January, 1970-1979.

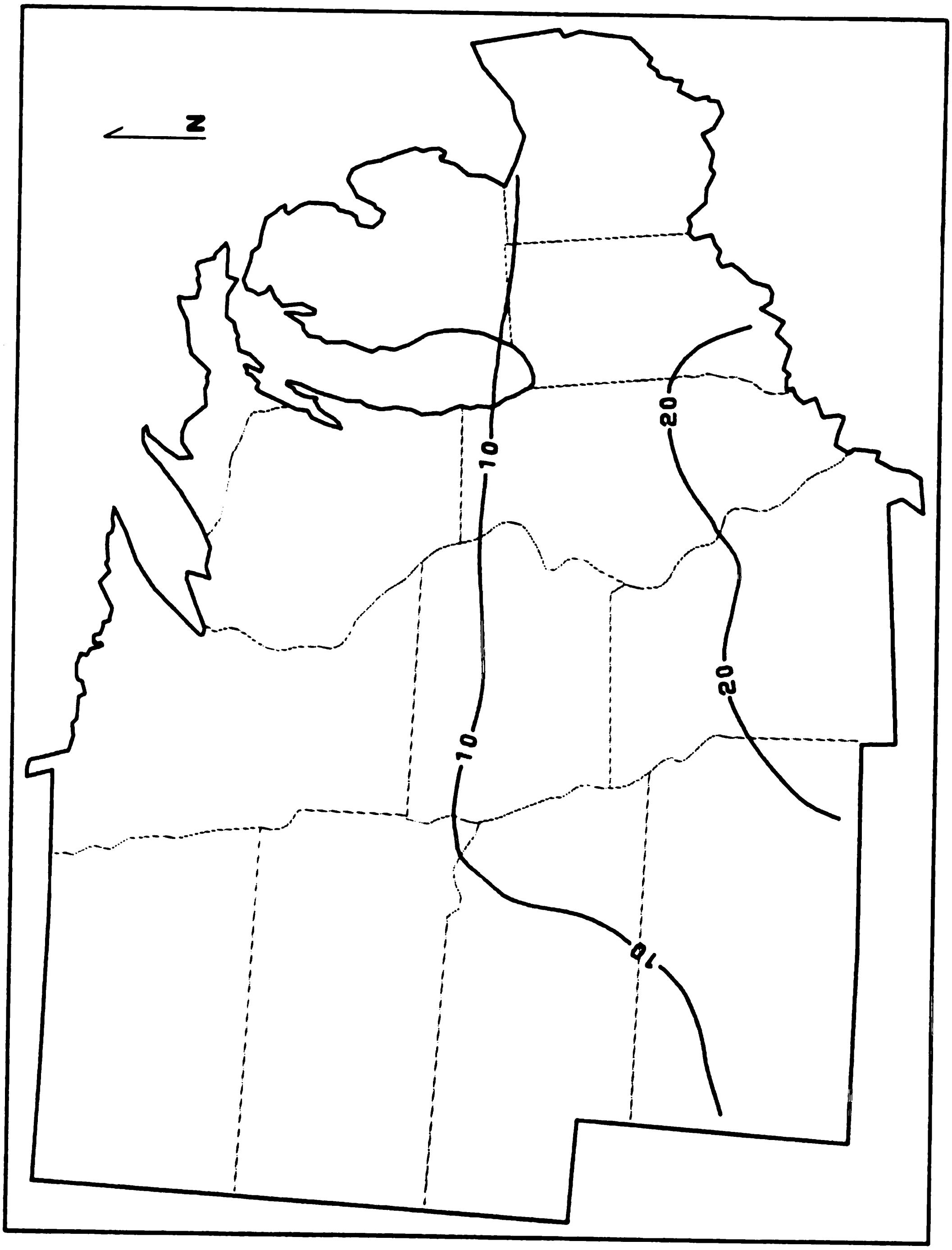


Figure 12. Percentage of Dilute Tropical air in April, 1970-1979.

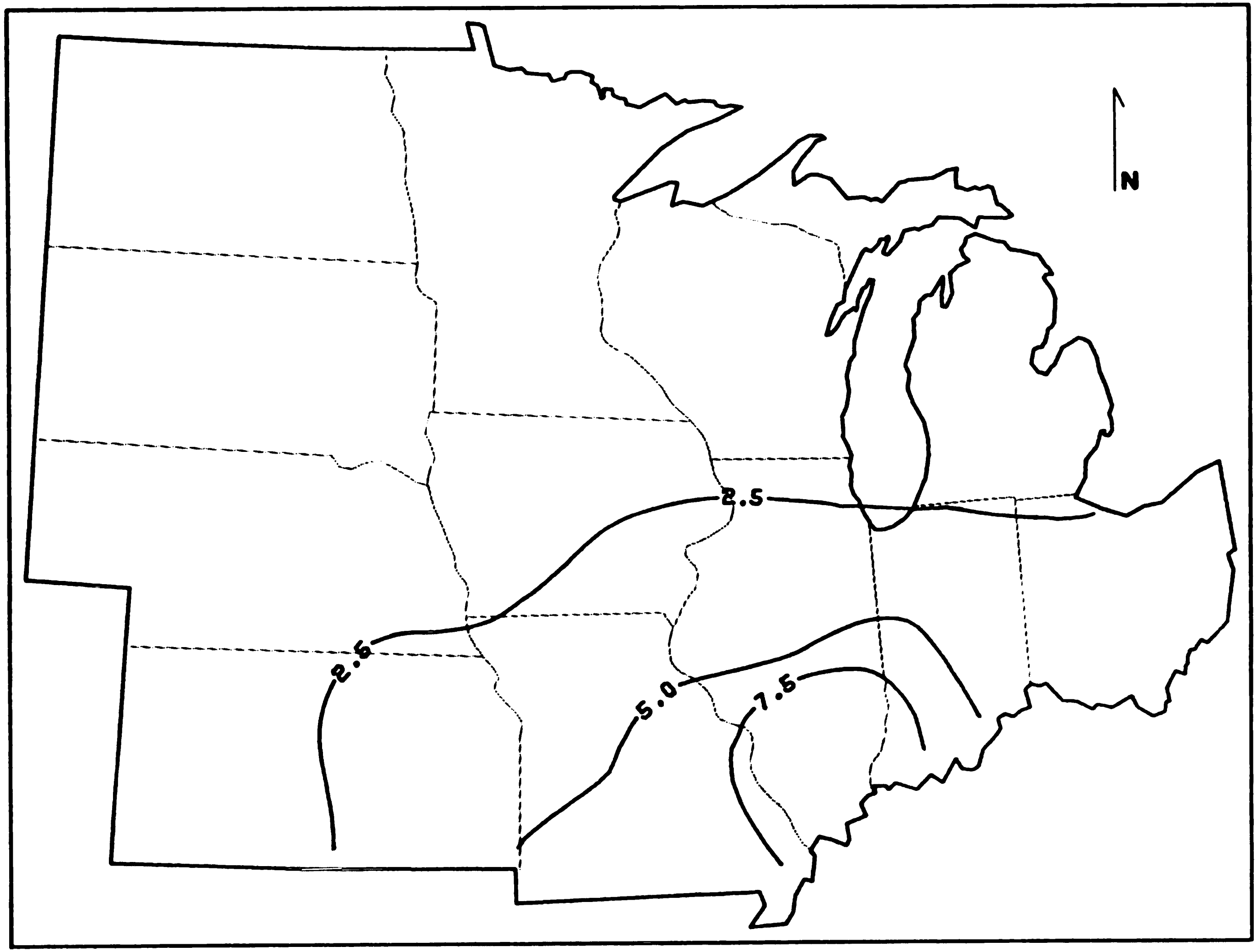


Figure 13. Percentage of Tropical air in April, 1970-1979.

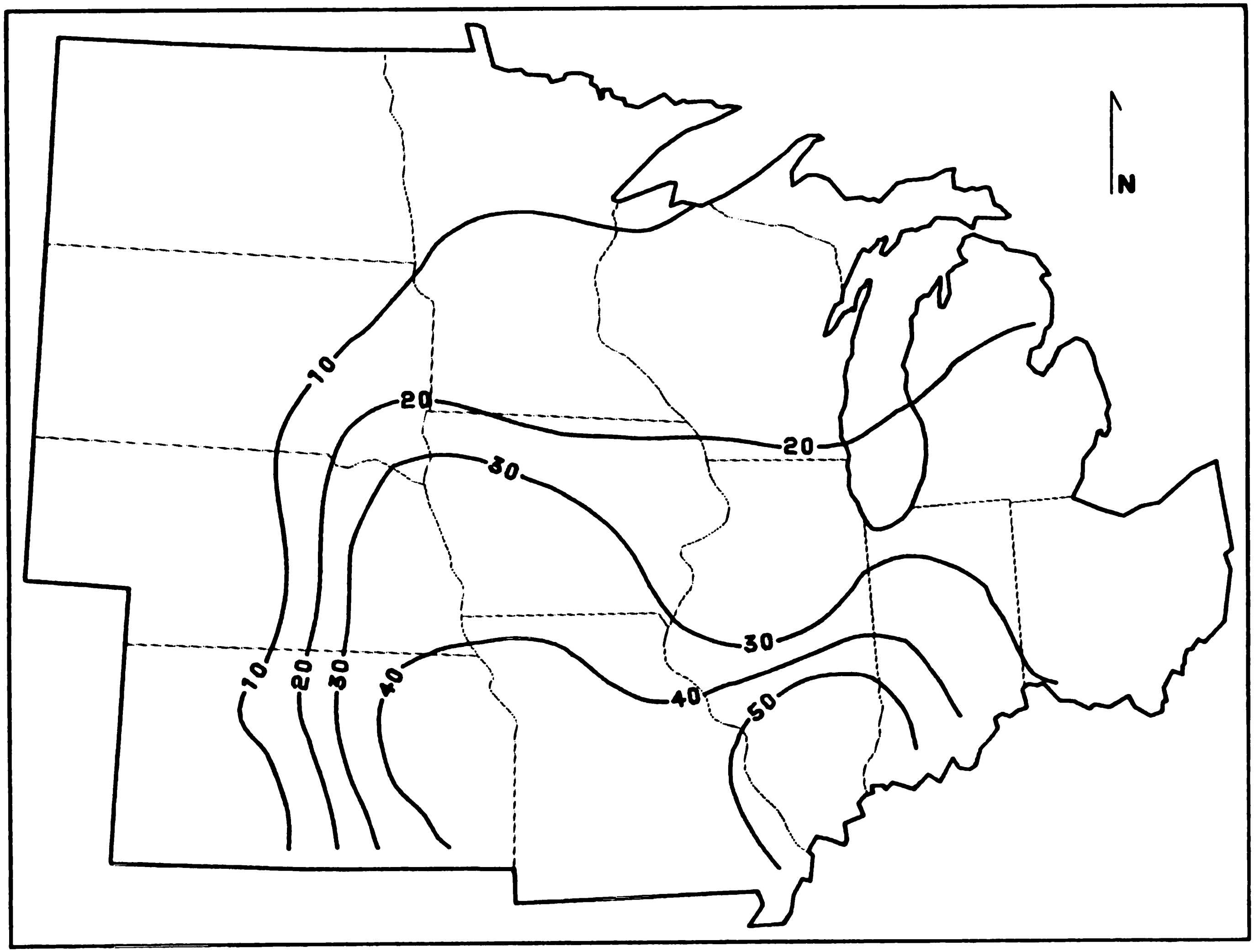


Figure 14. Percentage of Tropical air in July, 1970-1979.

This air mass dominated (more than fifty percent of the time) in only a small portion of the southeast during this season.

Fall--(Figures 15 and 16)--During the fall, Dilute Tropical air occurred throughout the study area ten percent or more of the time except in most of the Dakotas, Minnesota, and western Nebraska, where the frequency was less. Overall the number of Tropical air occurrences in this season was less than summer and comparable to spring, with the northeast portions of the study area being the least influenced by this air mass.

Dry Tropical

This air mass affected only slightly the portions of the study area east of the Mississippi River, and was most prominent in the states of North and South Dakota, Nebraska, and Kansas. Primarily a summer season phenomenon, it rarely occurred in the other seasons and was least evident in winter.

Winter--No parts of the study area were affected one-half percent or more of the time in this season by the air mass, so a map was not prepared.

Spring--(Figure 17)--Dry Tropical air did not occur in this season more than five percent of the time in any part of the study area, although it was more prominent than in winter. Kansas, Nebraska, and South Dakota were the states most affected.

Summer--(Figure 18)--Although the frequency of Dry Tropical air dramatically increased in summer, the distribution was essentially limited to the western four states (North and South Dakota, Nebraska, and

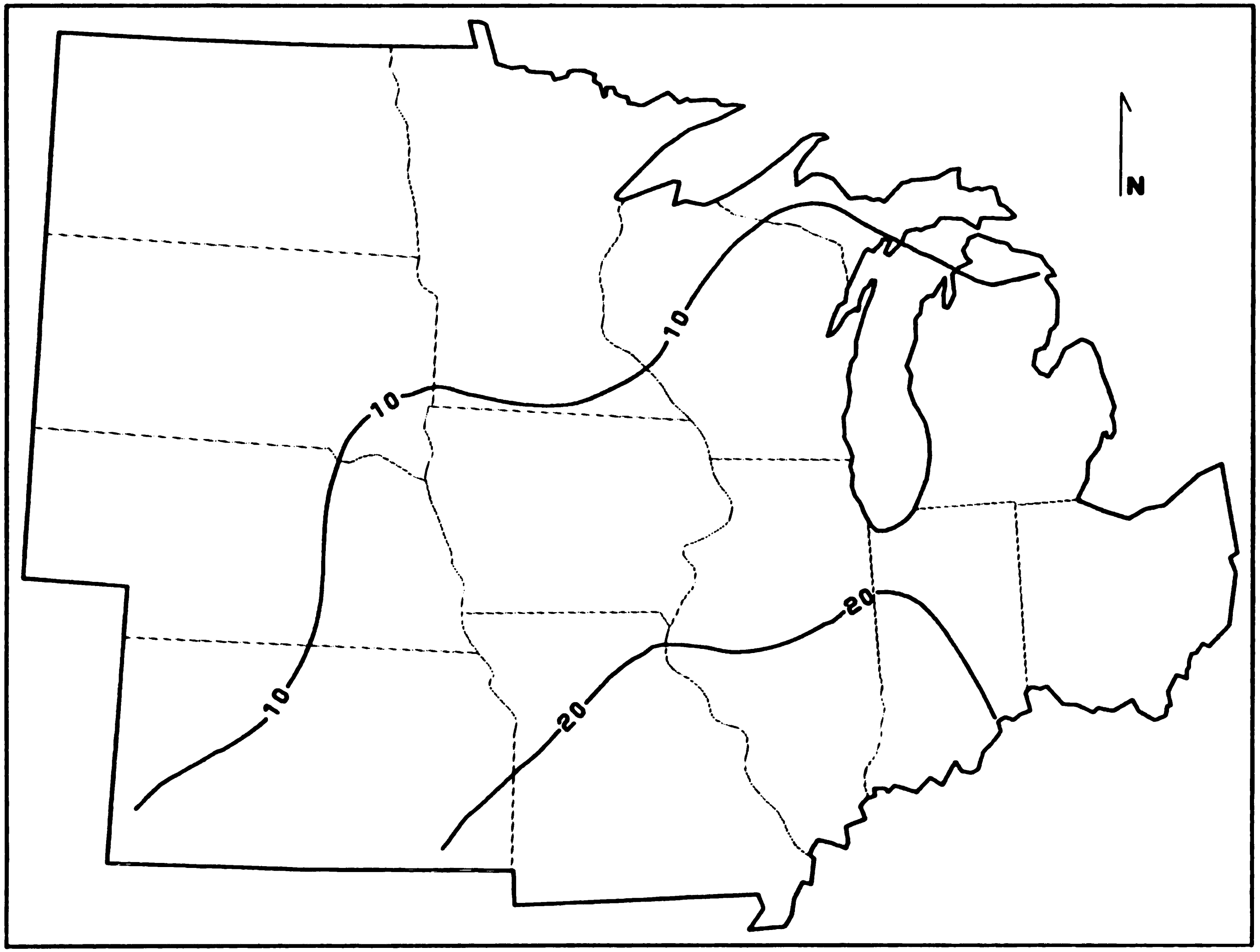


Figure 15. Percentage of Dilute Tropical air in October, 1970-1979.

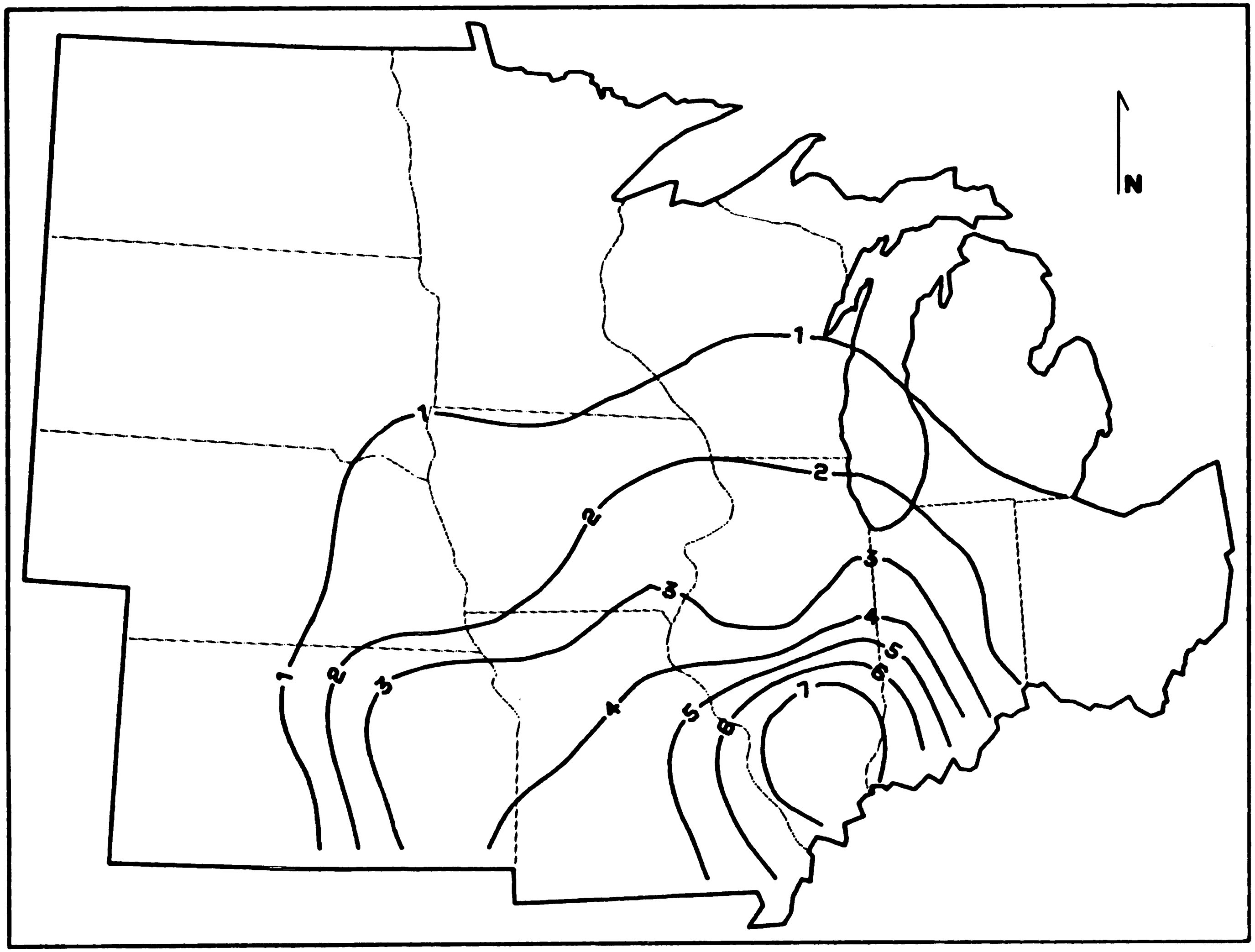


Figure 16. Percentage of Tropical air in October, 1970-1979.

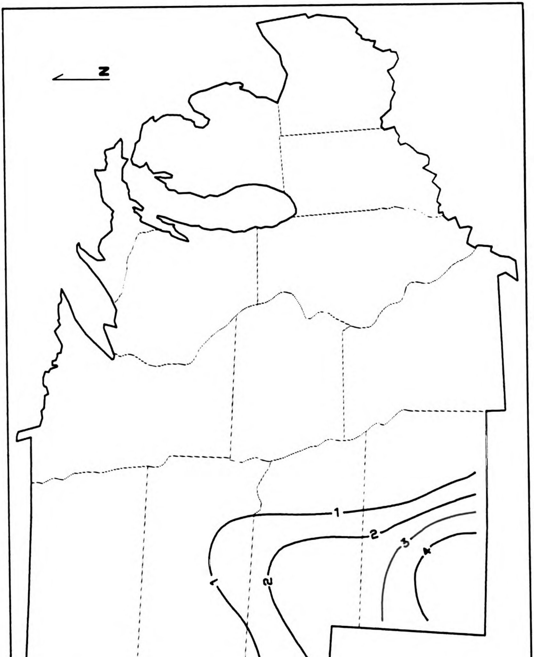


Figure 17. Percentage of Dry Tropical air in April, 1970-1979.

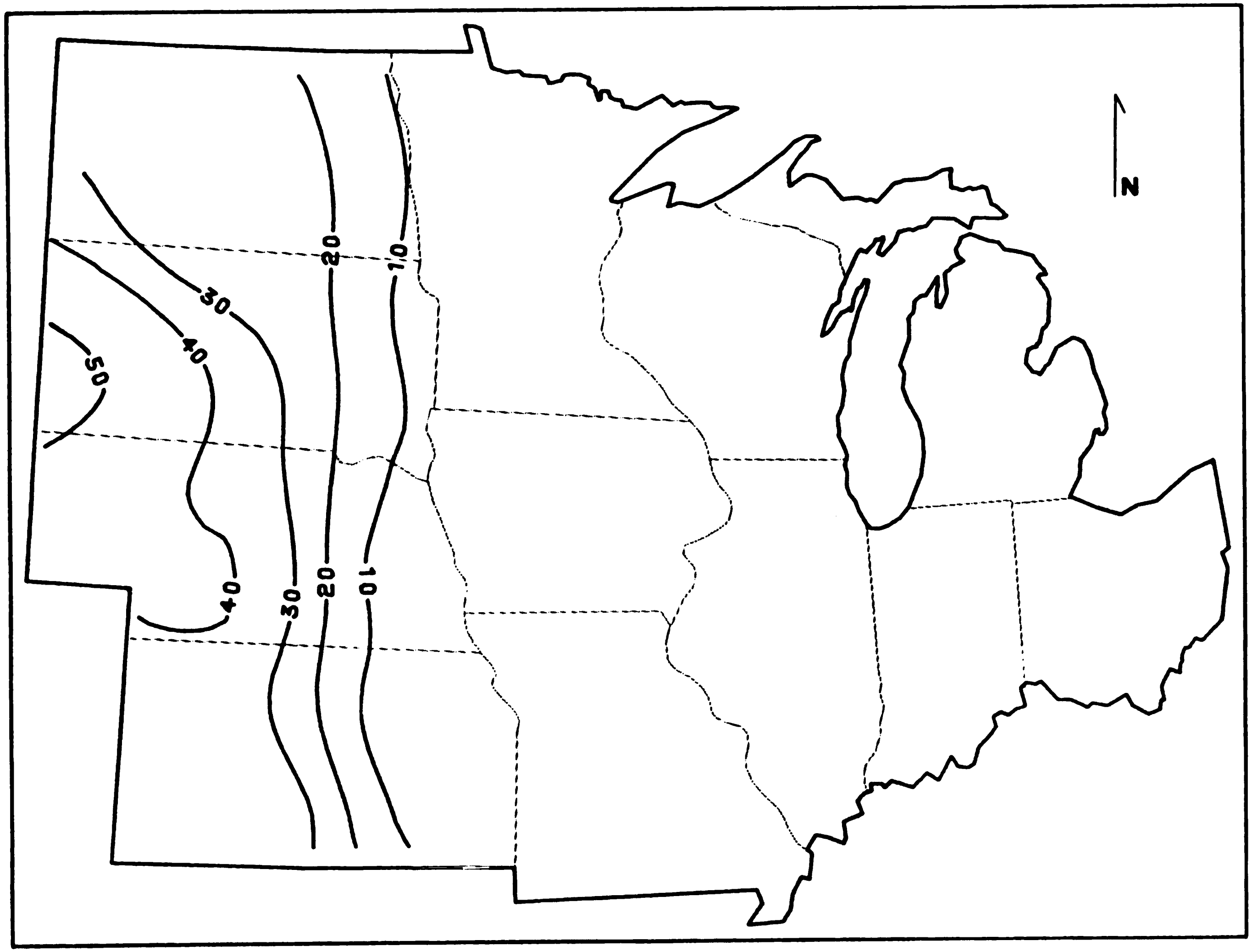


Figure 18. Percentage of Dry Tropical air in July, 1970-1979.

Kansas). Within these states, frequencies decreased rapidly to the east, and the air mass was dominant (greater than fifty percent) in only a small area of southwestern South Dakota.

Fall--(Figure 19)--Frequencies declined again in fall, with highest values approaching ten percent. Influence of the air mass was limited to the four western states, particularly western Kansas and Nebraska.

## Air Mass Distribution Summary by Season

Winter--The air mass of primary importance in this season across most of the study area was Continental. Pacific air was of equal importance to Continental air in only the extreme southwest. Dilute Tropical/Tropical air had a small influence on the southeastern portion of the study area, and Dry Tropical was unimportant anywhere.

Spring--The overall frequency of Continental air declined from the winter maximum, but the air mass remained dominant in the northeast. Pacific air became the most important air mass in the southwest, and the influence of Dilute Tropical/Tropical air increased from winter in the southwest. Dry Tropical air became recognizable in this season but had only a small impact in the extreme southwest.

Summer--During this season, Polar air (a mixture of Continental and Pacific) was dominant in the northeast. Tropical air increased in importance in the southeast, and even dominated a small portion of this area. The frequency of Dry Tropical air dramatically increased from spring, but this air mass was most important in only the extreme west.

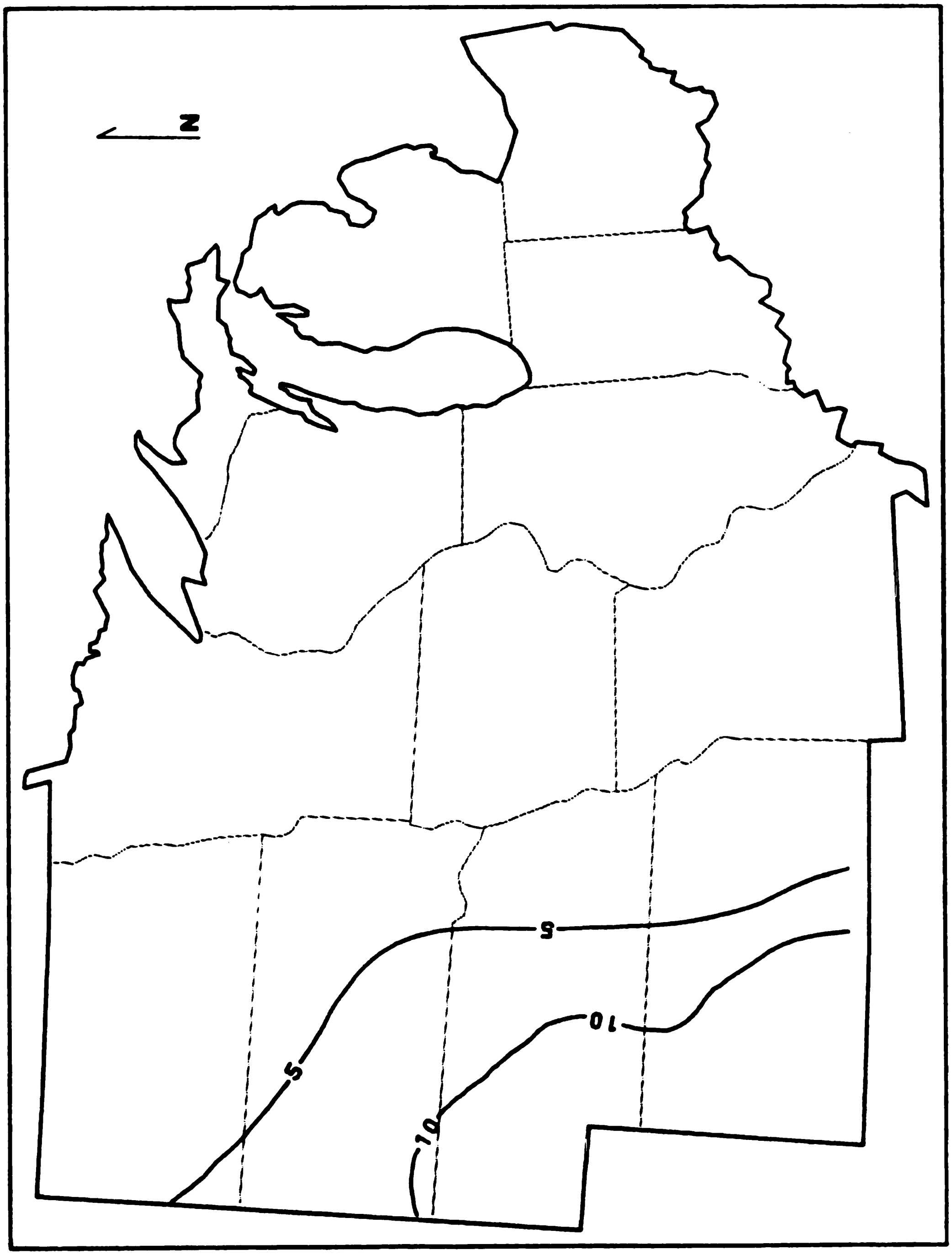


Figure 19. Percentage of Dry Tropical air in October, 1970-1979.

Fall--The frequency of Continental air returned to levels similar to those of spring in this season, and Pacific air became most important again in the west. The influence of Dilute Tropical/Tropical air on the southeast was reduced to spring-like levels, and the frequency of Dry Tropical air in the southwest decreased substantially from summer to levels slightly greater than those common in the spring.

## Jenks Classification Technique

Limits obtained by this method are compared to those found through map analysis. In the discussion below, the comparable map analysis limit appears in parentheses after each Jenks limit.

### Results from Flint Data

Winter--Surface dewpoint limits were underpredicted in this season in all cases; however, the 850mb temperature limits were quite similar to those found through map analysis. For example, the Dilute Tropical dewpoint limit was 30°F (40°F), while the lower Pacific 850mb limit was 0°C (0°C).

Spring--Dilute Tropical and Tropical dewpoint limits were predicted quite accurately; however, as in winter, those for the colder air masses were underpredicted. As examples, the Tropical dewpoint limit was 60°F (59°F), while the Continental/Pacific dewpoint limit was 37°F (45°F). The 850mb limits for this season were similar to the map analysis limits, but provided for a greater range of transition conditions between the Continental and Pacific air masses. For example, the upper

850mb limit for Continental air was -3°C (-1°C), and the lower limit for Pacific air was 6°C (3°C).

Summer--The limits produced by the technique for this season were in close agreement with those found by map analysis at both the 850mb and surface levels. As examples, the surface dewpoint limit for Tropical air was 60°F (60°F), and the 850mb limit for Dry Tropical air was 18°C (19°C).

Fall--As in spring, the dewpoint limits for Dilute Tropical and Tropical air were predicted with reasonable accuracy by the technique, but the cold air mass limits were still underpredicted. For example, the Tropical dewpoint limit was 64°F (63°F), while the Continental/Pacific dewpoint limit was 41°F (47°F). The 850mb limits in this season, as in spring, were similar to those obtained through map analysis, but provided for a greater range of transition conditions between the Continental and Pacific air masses. As example, the upper 850mb limit for Continental air was 3°C (2°C), and the lower limit for Pacific air was 9°C (6°C).

In summary, a number of the Jenks limits agreed quite well with those found through map analysis, although many were somewhat different. The technique predicted best the map analysis limits of summer, and was least accurate in winter. Also, the surface dewpoint limits were somewhat better predicted than the 850mb temperature limits.

# CHAPTER V

# DISCUSSION OF RESULTS

## Relationship Between Upper Air Flow Patterns and General Air Mass Climatology

To place these results in a broader climatological context, the percentage maps presented in the previous chapter will be considered in relation to monthly upper air circulations. Specifically, the results of the air mass classification were examined in order to determine a representative day or group of days for each air mass type in each month studied. The upper air pattern on one or more days was then extrapolated as an example of the mean flow associated with the appearance of the given air mass in the study area. Thus, I will demonstrate the different circulation patterns I found to be associated with each type. Also, mean and modal monthly patterns will be used in an attempt to explain the relative distribution of the air masses in each season.

Within the westerlies, the disposal of air masses from source regions is not random, and their trajectories can be related at least in part to the position of mean planetary waves. As planetary flow lines determine the path of traveling waves and surface pressure features, they also guide the movement of the associated air masses. In general, air movement in the upper atmosphere is parallel to the flow lines, and a geographic area must be "downstream" in the flow from a source region if it is to be affected to any degree by air masses from that source region (which move outward in association with traveling waves and pressure cells). Thus, particular flow patterns will facilitate the movement of specific air mass types into the study area.

## Modal Upper Air Patterns

If the daily 500mb pressure heights in the Northern Hemisphere are observed for an extended period, clear geographical preferences for some of the features will be noted. For example, a mean ridge position is common near the Rocky Mountains. This association of air flow with certain physical features is not random, and both mountain ranges (orographically) and oceans (thermally) influence the atmosphere by sustaining certain modal patterns in a given geographical location (Bolin 1950). Although the persistence of modal patterns is not difficult to explain, the causes of deviations from these preferred flows are more complex.

The westerlies are a continuous flow of air that encircles the Northern Hemisphere, and this arrangement allows "teleconnection" to occur. Changes of amplitude in one part of the flow can be transferred downstream to other areas. Thus, changes of amplitude in the upper air patterns over North America could be the result of events half-way or more around the world. The concept of the "Stationary wavelength" adds an additional dimension to the interdependency of the planetary wave train. The faster the air is moving within the westerlies, the more rapid the downstream movement of a short wave; however, longer wavelength can compensate for higher wind speed and slow wave migration. Therefore, for any given meridional thermal gradient and associated zonal index and mean wind speed, a stationary wavelength can be calculated that will balance the effects of wind speed and wavelength and allow long waves to remain "anchored" in favored positions determined by thermal and topographic factors with "resonant" waves spaced symmetrically downstream.

The stationary wavelength changes seasonally with wind speed and, further, is not often an integer, while the number of waves in the upper air circulation must be an integer because of the continuity of the flow. If the prescribed stationary wavelength is 3.5, for example, the hemispheric circulation may modulate between three and four planetary waves in an attempt to reach stability and thereby cause deviations from the modal flow. These deviations can cause realignment of all the mean wave positions, which can in turn change the relative frequency of different air masses in a given region. Beyond seasonal changes, teleconnection, and stationary wavelength considerations, Namias (1969) presented yet another possible mechanism to account for some deviations from the modal positions. He proposed that anomalous sea-surface temperatures in the central and northern Pacific were responsible for a variation of the upper air flow that in turn produced climatic fluctuations in North America.

In summary, modal patterns can conveniently explain much of the upper air circulation structure, but deviations from these most frequent features do occur, and are produced by a number of processes. Deviations are expressed as changes in the amplitude or location of the mean long waves, which can then alter the distribution and frequency of air masses in the study area.

## Relationship Between Upper Flows and Monthly Air Mass Percentages

Winter--The mean height of the 500mb surface in January (Figure 20) is an areal average of the component patterns of the month as well as a representation of the relative frequency of each pattern. This mean chart depicts a low amplitude ridge just off the west coast and a trough in the eastern United States. In review, Continental air was dominant in this season, with Pacific air second in importance and Tropical and Dry Tropical of only minor influence. Given that the occurrence of specific air mass types is related to certain upper level circulations, the statistical dominance by Continental air suggests that the upper air pattern associated with it throughout the study area would be the modal arrangement of winter, and consequently would most resemble the mean pattern in terms of long wave location. The pattern associated with a specific occurrence of Continental air (Figure 21) displays the same ridge-trough system as the mean map except that both features have higher amplitude. Amplification of a western ridge facilitates the movement of Continental air from the central Canadian source region into the study area. It accomplishes this by favoring anticyclogenesis under the negative vorticity advection area on the east side of the ridge, and then directing the resulting anticyclones southeastward into the study area, both in association with moving waves.

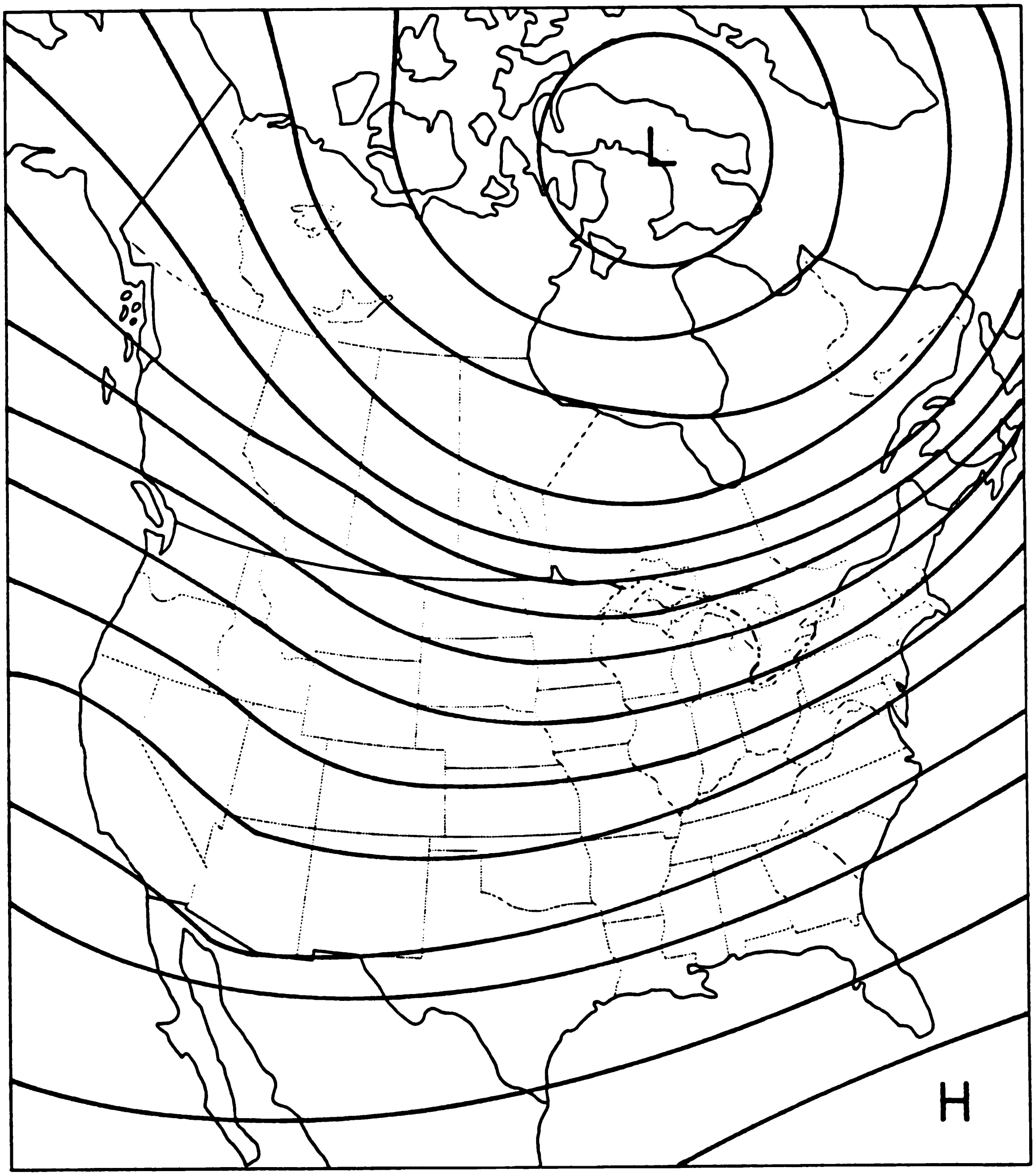


Figure 20. Mean configuration of the 500 mb surface in January (Showing areas of high (H) and low (L) pressure height). Source: Adapted from Lahey et al. (1958).

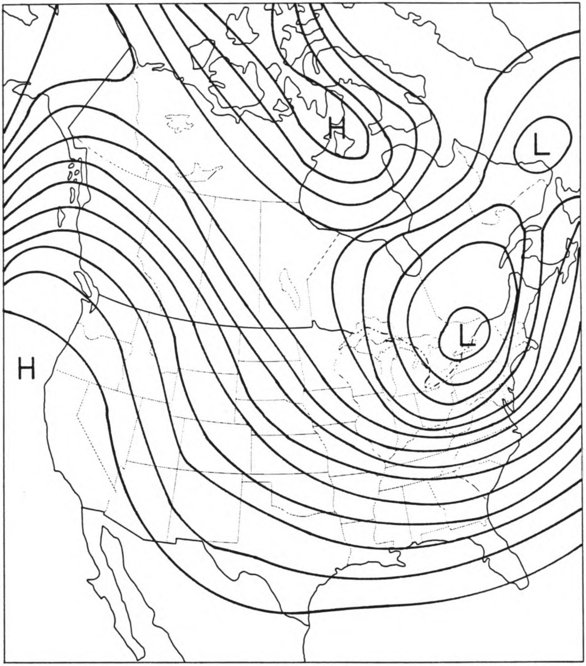


Figure 21. Configuration of the 500 mb surface for 00Z on Monday 17 January 1977 associated with a Continental air occurrence in the study area (showing areas of high (H) and low (L) pressure height).
Source: Adapted from National Meteorological Center facsimile product.

In contrast, the pattern of a single Pacific occurrence (Figure 22) is characterized by a low amplitude Gulf of Alaska trough coupled with a relative zonal flow across North America. This type of flow contains Continental air north of the study area and allows Pacific air to move into the region behind passing Alberta-track cyclones. A deep trough in the central United States is the distinguishing upper air characteristic of a single occurrence of Dilute Tropical/Tropical air (Figure 23). If a surface low was associated with this trough, it would most likely have formed in the Oklahoma panhandle region and then tracked northeastward following the moving vorticity maximum. The southerly surface winds associated with this cyclone would bring Tropical moisture into the southeast portion of the study area as the low moved northward.

Only one day in January during the study period was classified as Dry Tropical (Figure 24). The associated pattern is characterized by a low amplitude ridge over the west-central United States, and is similar to the Pacific pattern (Figure 22) in that a Gulf of Alaska trough exists (though amplified) and the flow is generally zonal. The occurrence of Dry Tropical air in this season is very uncommon because, in order for the air mass to occur, the upper air ridging pattern must persist long enough for heating to take place in the Dry Tropical source region. This heating is necessary because during usual conditions in the winter, the Dry Tropical source region is substantially cooled from summer, such that it is seldom able to produce a recognizable air mass quickly. Further complications may be posed by snow cover in the source region, which must be melted before substantial heating can occur.

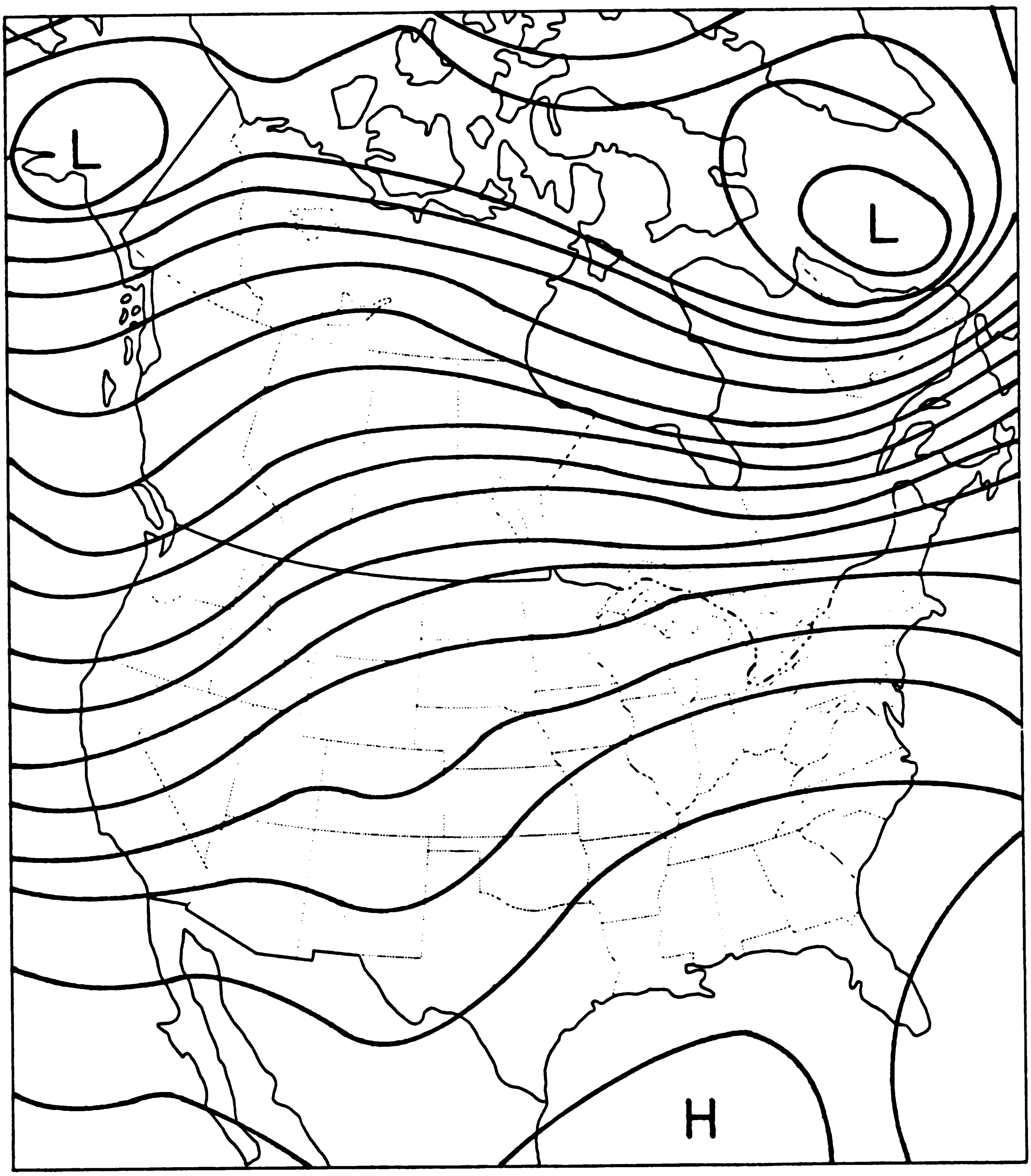


Figure 22. Configuration of the 500mb surface for 00Z on Wednesday 17 January 1973 associated with a Pacific air occurrence in the study area (showing areas of high (H) and low (L) pressure height). Source: Adapted from National Meteorological Center facsimile product.

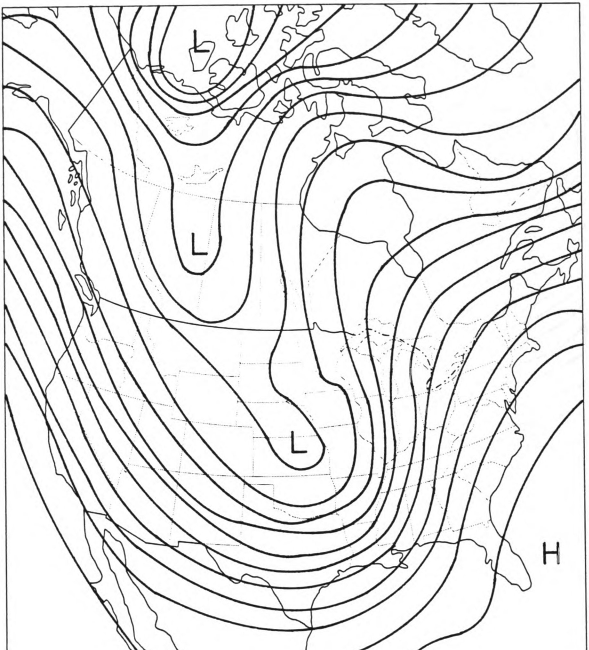


Figure 23. Configuration of the 500mb surface for 00Z on Saturday 11 January 1975 associated with an occurrence of Dilute Tropical/Tropical air in the study area (showing areas of high (H) and low (L) pressure height).
Source: Adapted from National Meteorological Center facsimile product.

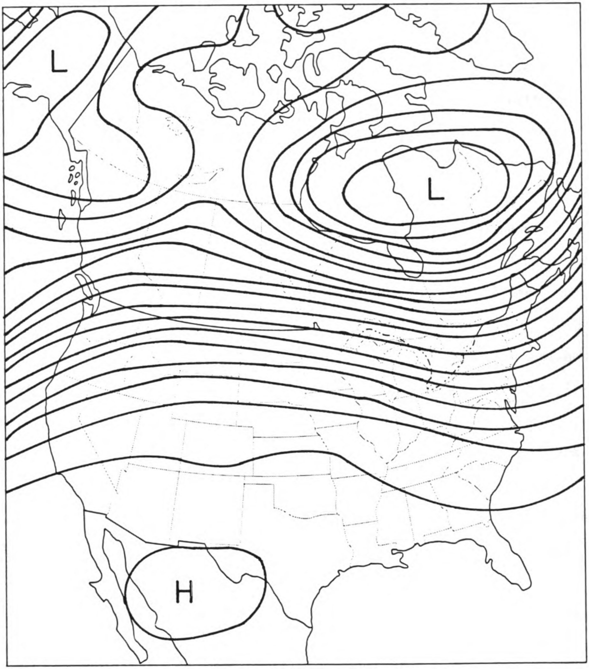


Figure 24. Configuration of the 500mb surface for 00Z on Wednesday 16 January 1974 associated with a Dry Tropical air occurrence in the study area (showing areas of high (H) and low (L) pressure height). Source: Adapted from National Meteorological Center facsimile product.

From this description of some of the components of the monthly mean, it should be evident that the features of the flow associated with Continental air are most similar to the mean condition and could represent the modal circulation. During a typical January, Continental air is the dominant air mass, but Pacific air also occurs for several days. These Pacific occurrences (Figure 25) may be associated with the mid-winter "January" thaw. Occasionally, Continental air flow is so prevalent that it persists essentially unchanged for an entire month or more, producing below normal temperatures across the central and eastern United States because of the constant Continental influence. January 1977 was an example of such a period (Figure 26). The occurrences of Tropical and Dry Tropical air are rare, and likewise the patterns that produce them are markedly dissimilar from the mean pattern.

Spring--The mean 500mb height map for April (Figure 27) is somewhat different from that of January, in that the western ridge has less amplitude and lies slightly east of its January position, and the eastern trough also displays less amplitude but generally maintains its position. In comparison to winter the spring flow is more zonal, and the north-south pressure height gradient is reduced. In review, during this season the Continental air mass decreased in importance from winter throughout the study area but remained common in the northeast. Pacific air was prominent and Dry Tropical air increased its importance in the southwest, while the influence of Dilute Tropical/Tropical air increased in the southeast portion of the study area.

Examination of the major upper air flow patterns common in the spring indicated that, with the exception of Tropical air, the flow

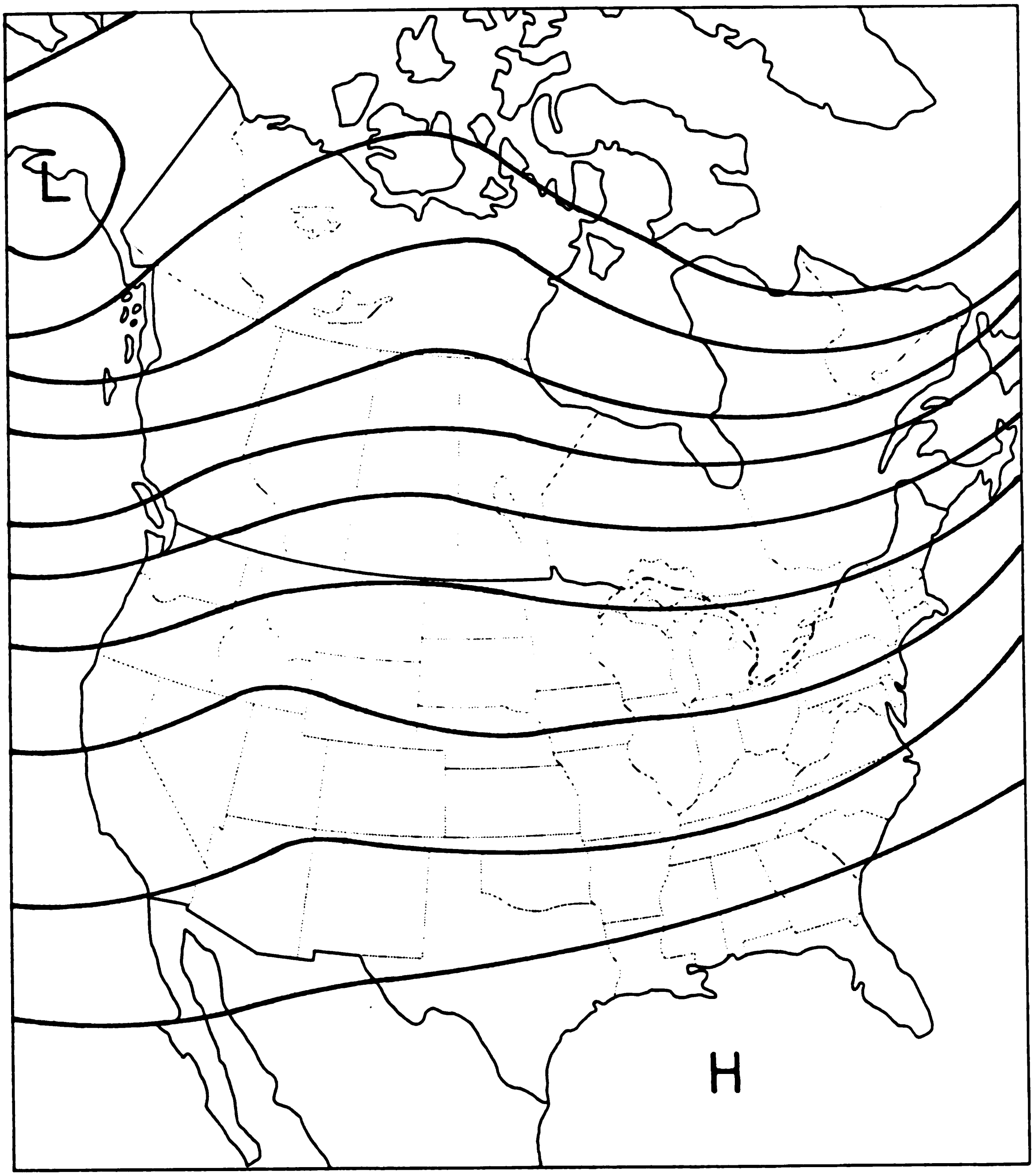


Figure 25. Mean configuration of the 700mb surface for the period 15-19 January 1973 (showing areas of high (H) and low (L) pressure height).
Source: Adapted from Wagner (1973a).

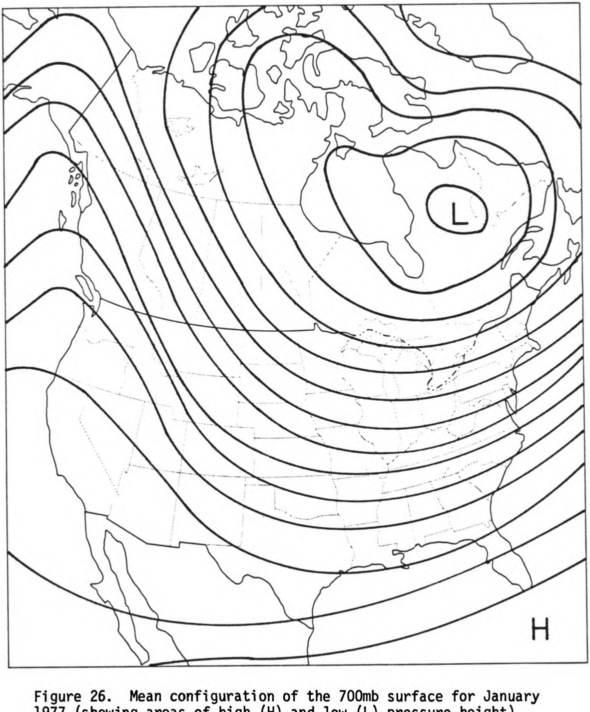


Figure 26. Mean configuration of the 700mb surface for January 1977 (showing areas of high (H) and low (L) pressure height). Source: Adapted from Wagner (1977).

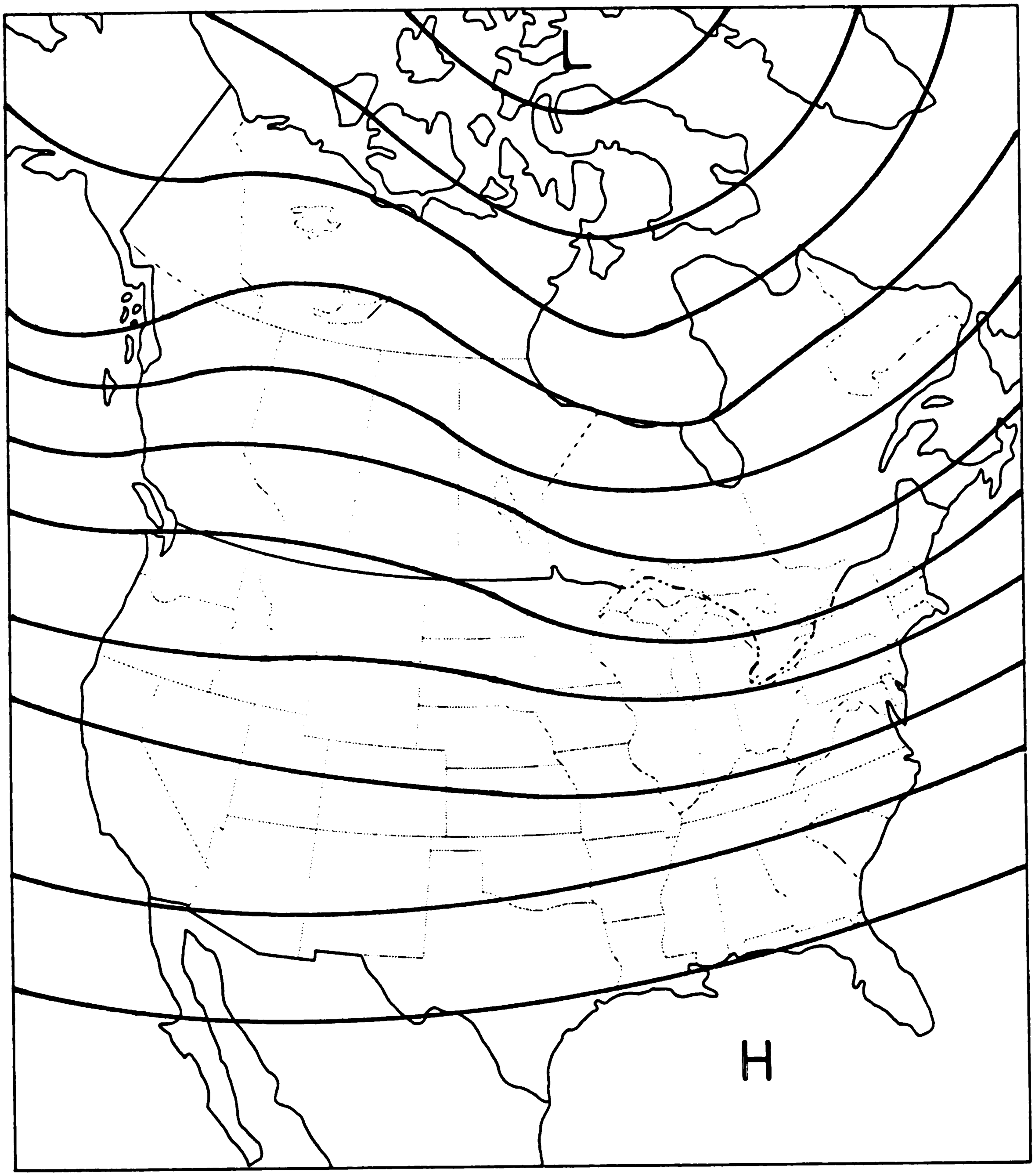


Figure 27. Mean configuration of the 500mb surface in April (showing areas of high (H) and low (L) pressure height). Source: Adapted from Lahey et al. (1958).

associated with each air mass type was essentially the same as in winter. The new Tropical pattern (Figure 28) moves the deep trough from the central United States into the desert Southwest and California. If a surface low were associated with this new trough position, it would most likely form in the Colorado area and track northeastward. Tropical moisture, already directed northward by high pressure over the Gulf of Mexico, would be incorporated into the southerly flow of this cyclone and consequently be transported into the southeastern portion of the study area.

Although it appears that most of the component upper air patterns and associated surface pressure features of spring are essentially the same as winter, the different air mass distributions remain to be accounted for. Because the air mass criteria were seasonally adjusted for spring warming of all the air mass categories, the different percentages of spring in comparison to winter must reflect seasonal contrasts in the flow aloft. For example, the upper air arrangement linked with Continental air is probably less frequent in the spring though the pattern itself is essentially the same as in winter, whereas flows associated with Pacific, Tropical, and Dry Tropical may be expected to increase in frequency (and thus in overall importance). This change in relative frequency of the component patterns probably accounts for the new monthly mean. The April mean cannot be explained in relationship to a modal flow, as in winter, since there no longer appears to be a single predominant pattern. Rather, it is probably best understood as the areal average of several equally frequent flow arrangements.

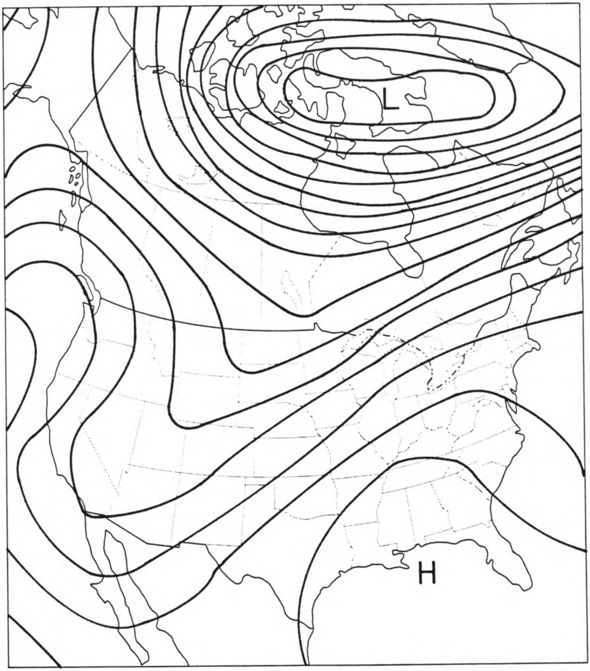


Figure 28. Configuration of the 500 mb surface for 00Z on Monday 29 April 1974 associated with a Tropical air occurrence in the study area (showing areas of high (H) and low (L) pressure height). Source: Adapted from National Meteorological Center facsimile product.

In the central United States during the spring and particularly in April, upper level cyclonic flow (troughs and closed lows) occurs more often than in any other season (O'Conner 1964, p. 306). The mean storm track associated with these circulations brings surface lows through the study area in substantial numbers (Reitan 1974). The increased occurrence of these upper level and surface pressure features is caused by increased troughing in the western United States which, more importantly to this study, is associated with the same circulation that brings Tropical air into the study area (Figure 28).

Why western troughing increases in the spring is not well understood. Pyke (1973, p. 26) thought that modification in the west and mid-Pacific wave position might be responsible. He postulated that, in spring, western Pacific cyclones develop at a somewhat lower latitude than in fall and move toward the northeast. Increased temperature gradients at these lower latitudes cause the cyclones to deepen rapidly and reach maturity in the Aleutian area instead of in the Gulf of Alaska. "As the result of this tendency for intensification and northeastward curvature of Pacific cyclones at longitudes farther to the west during early spring, the downstream ridge and the next downstream trough should be located further west than they are in late fall." Such a situation would favor a mean trough over the western United States. Thus, the frequent occurrence of the western trough pattern in spring produces a change in the relative distribution of air masses in the study area and also modifies the mean long wave pattern from winter.

Although a western trough is associated with northward invasion of Tropical air, this type of circulation does not always result in the occurrence of the air mass in the study area. Many times when this pattern occurs, Tropical moisture moves northward at only upper levels, and in other cases the cyclones associated with western troughing move through too fast to allow time for Tropical air to be drawn northward into the study area (Harman and Harrington 1978, p. 404). Therefore, although the western trough is a common circulation feature of spring, the occurrences of Tropical air in the study area remain comparatively small.

Summer--The mean 500mb circulation in July (Figure 29) is composed of three main features: a trough off the west coast, a ridge in the west-central United States, and another trough in the east. Compared to spring, the summer flow is positioned farther to the north and greatest wind speeds are generally north of the study area. In review, the Continental and Pacific air masses were indistinguishable in this season, and "Polar" was used as the name for this mixture of airstreams. Polar air was an important factor in the north, but of limited influence in the southern portion of the study area. Tropical air substantially increased in frequency throughout the study area, while Dry Tropical was dominant in a large area of the west.

A major change takes place in the circulation from spring to summer. Increased insolation during the summer (particularly at high latitudes) warms the polar atmosphere, which reduces the meridional thermal gradient. The strongest winds in association with a reduced north-south temperature differential would generally be located farther to the north (toward the pole where the greatest temperature contrasts are found) and the stationary wavelength would also be reduced, thereby

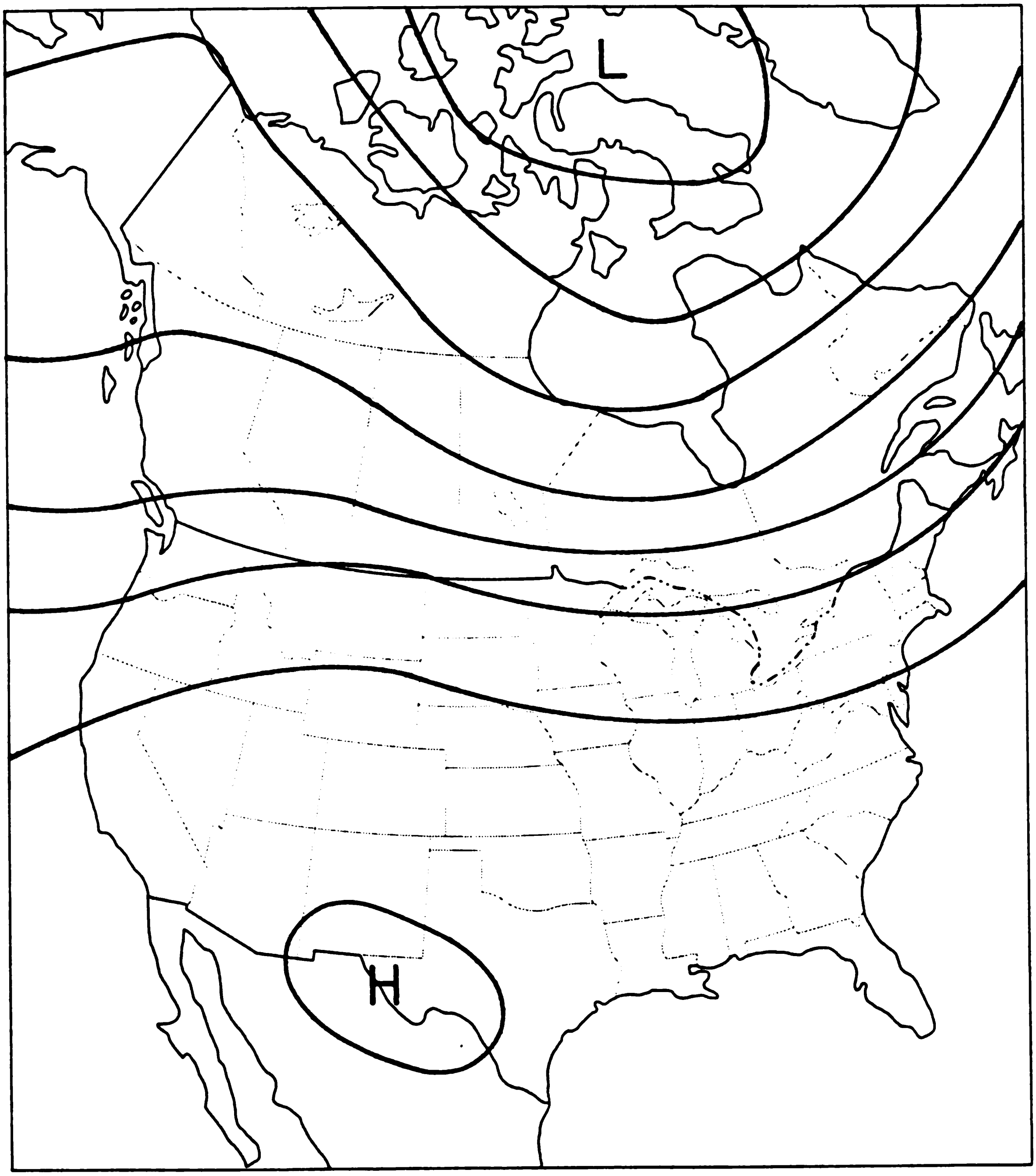


Figure 29. Mean configuration of the 500mb surface in July (showing areas of high (H) and low (L) pressure height). Source: Adapted from Lahey et al. (1958).

increasing the number of planetary waves necessary for hemispheric stability. Thus, an increase in the number of mean planetary waves is consistent with a decrease in mean wavelength across North America from spring to summer. Regarding the positioning of the flow in summer, the arid and semi-arid regions of the western United States and Mexico are heated to extreme temperatures in this season, which would cause pressure heights to rise and favor ridging over these areas (Sutcliff 1951), in strong contrast to the troughing frequent in spring. Therefore, the summertime mean ridge over the central United States is most likely thermally induced (University of Chicago 1947). This seasonally forced feature, coupled with the decrease in the stationary wavelength and consequent increase in the number of mean waves, then helps account for the transformation of the modal upper air circulation from the two-feature spring pattern (ridge-trough) to the characteristic three-feature summer pattern (trough-ridge-trough).

As in spring, the summer air mass criteria were seasonally adjusted to allow for warming of all the air mass categories, so the different percentages of summer in comparison to spring must reflect seasonal contrasts in the flow aloft. Even with these summertime modifications in the overall circulation, the patterns associated with the individual air masses remained similarly distributed to that of spring, though universally shifted to the north. Polar air occurrences throughout the study area were associated with an amplification of the western ridge and eastern trough, as in spring, but the air mass seldom influenced the southern portions of the study area because of the northern position of the westerlies.

During both Tropical and Dry Tropical occurrences, a trough was located near the west coast with a ridge in the central United States and another trough in the east, although the ridge associated with the Tropical pattern was of greater amplitude. Since this trough-ridge-trough pattern is similar to the mean, it could be the modal pattern of summer, which would account for the relative prominence of both the Tropical and Dry Tropical air masses in this season. The Dry Tropical air mass could be pulled into the western portion of the study area in association with the southwesterly flow to the south of a cyclone moving eastward through the northern United States or southern Canada. Klein (1957) has demonstrated that this trajectory is a mean storm track in July, which would then account for the large number of Dry Tropical occurrences in this season. Tropical air also could be transported into the study area in the southerly flow of cyclones crossing the northern Great Plains, but amplification of the central United States ridge would change the direction of storm movement from east to northeast. This change in trajectory would then divert Dry Tropical air northward into Canada and allow Tropical air to move into the northern study area.

In summary, the northward migration of the westerlies is the primary agent responsible for the changes in the distribution of air masses across the study region from spring to summer. With most of the study area positioned south of the strongest winds, the Dry Tropical and Tropical air masses could be easily transported northward by cyclones following the mean storm track. Likewise, Polar air (found generally north of the strongest circulation) was prevalent in the north, but had limited influence on the southern portion of the study area.

Fall--The mean 500mb circulation of October (Figure 30) is composed of a low amplitude ridge in the west and trough in the eastern United States. In comparison to summer, the fastest wind speeds in fall are positioned farther to the south (University of Chicago 1947). Although the October mean is similar to the April mean circulation, the fall pattern displays less amplitude and is nearly zonal across the United States. In review, Continental and Pacific air were again recognized as separate air masses in this season. The frequency of Continental air increased to spring-like levels, and Pacific air became important in the west. The frequencies of Dilute Tropical/Tropical air in the southeast and Dry Tropical air in the western portion of the study area were reduced from their summertime maximum during the fall.

The fall mean circulation returns to the two feature (ridge-trough) circulation that is typical of all seasons except summer. This change is consistent with the fall cooling in high latitudes, which increases the stationary wavelength in response to an increased meridional thermal gradient. The fall air mass criteria were seasonally adjusted to account for cooling of all the air mass categories, and the different percentages of fall in comparison to summer must reflect seasonal contrasts in the flow aloft.

Even though the fall mean circulation resembles that of spring, the two appear to be produced from somewhat different component flows, and the strongest winds in October are located north of their position in the April circulation (University of Chicago 1947). The occcurrences of Continental air in this season were associated with amplification of the western ridge and eastern trough into a flow pattern similar to that

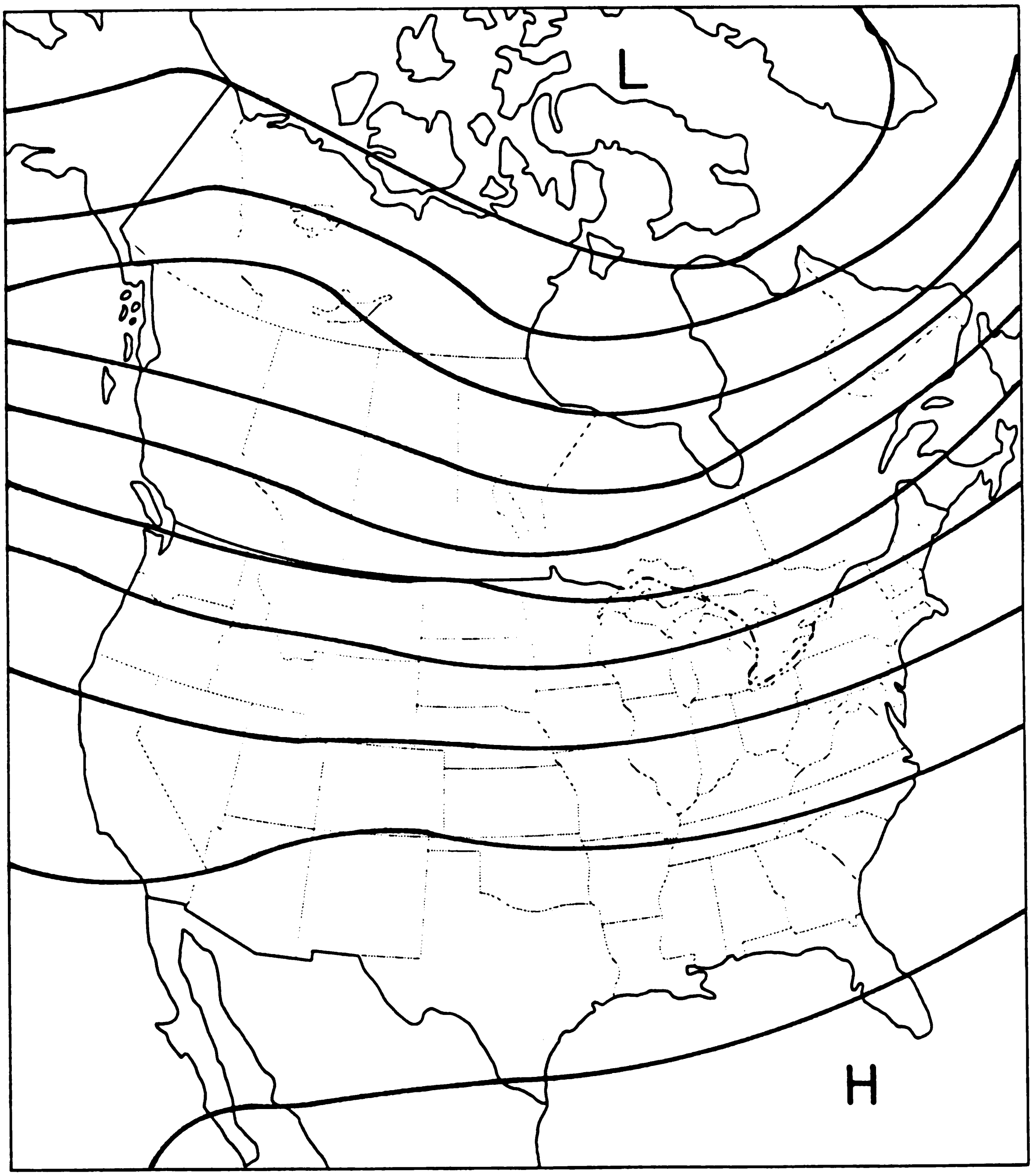


Figure 30. Mean configuration of the 500mb surface in October (showing areas of high (H) and low (L) pressure height). Source: Adapted from Lahey et al. (1958).

associated with Polar air in the summer. The northern location of the fall mean jet stream generally confined Continental air to the northeast, and thus limited its influence elsewhere in the study area. Pacific air occurrences in the study area were associated with a circulation composed of a trough off the west coast of Canada and zonal flow across the northern United States. If a surface low were associated with this circulation it would most likely form near the Gulf of Alaska and track eastward across central Canada in connection with a moving trough. Pacific air would be pulled into the study area behind this system. Klein (1957) found this trajectory to be a mean storm track in October, which would account for the importance of Pacific air in this season throughout much of the study area.

The upper air circulation associated with Dry Tropical and Tropical air occurrence in the fall are similar to those of summer, although shifted slightly southward. As in summer, during this season these air masses moved into the study area in response to the circulation around cyclones following a storm track eastward across the northern Great Plains. In the fall, the modal North American circulation is a two feature (ridge-trough) system, which reduces the number of central United States ridge occurrences (a component of the Dry Tropical/Tropical pattern) in favor of a mean ridge position farther to the west (O'Conner 1964). This autumn decrease in central United States ridging is consistent with the decreased frequency of the Dry Tropical and Tropical air masses in the study area.

In summary, Continental air was important in the northeast but of reduced influence elsewhere because of the northern location of the fall mean jet stream. Pacific air was particularly important in this season in the west, as passing cyclones following the mean storm track brought this air mass into these portions of the study area. Dry Tropical and Tropical air were reduced in importance from summer throughout the study area in this season probably because their component flow patterns became less frequent. This change in air mass distribution from summer to fall is consistent with a mean circulation that has been modified from a three feature (trough-ridge-trough) to a two feature system (ridge-trough), with the highest wind speeds shifted somewhat to the south.

## Special Topics

Throughout my presentation and discussion, I have alluded to several special problems that have resulted either as a direct consequence of my analysis technique or as a possible product of the uncertainty associated with specific air mass limits in certain locations. Since these topics deserve additional discussion, I will present a more detailed examination of each in this section.

Transition Conditions--One of the innovative aspects of my method of air mass classification is the recognition of "transition conditions" between the various air masses. Although the existence of these conditions has been noted in previous research (Bryson 1966, p. 238), the problem of their delimitation has been largely ignored. The usefulness of the "limits system" employed in this study can be judged to a large degree by its ability to correctly quantify these elusive boundaries.

The method should place days in their appropriate air mass categories while at the same time excluding and identifying as "transition conditions" all remaining days.

In general, it is difficult to pre-determine exactly what percentage of the total days at a station should be classed as transition conditions. My initial quess was that perhaps seventy-five percent of the days should be included in air mass categories, which leaves twenty-five percent unclassed. After completing my study I found that in almost all cases the number of transition days accounted for between about twenty and thirty percent of the total days at a station in any season.

One of the largest exceptions to the above results was noted in the southwest portion of the study area during July. In that area the number of transition days exceeded forty percent and approached fifty percent of the total in some cases. Clearly, some of this excess number could be caused by inadequacies of my limits, and I decided to study this situation in greater detail. An inspection of the characteristics of these days revealed that many were warm enough at the 850mb level to be classified as Dry Tropical but had too high a surface dewpoint to be accepted into that category. Most of the others failed both tests, i.e., their surface dewpoints were too high and their 850mb temperature too low for them to be classed as Dry Tropical.

I suspect, since this area (Kansas and Nebraska) is situated between regions that I found to be dominated by Dry Tropical and Tropical air masses during July (Figure 31), and, as previously mentioned, both of these air masses are drawn northward into the study area by similar synoptics, that these transition days might represent actual mixtures of

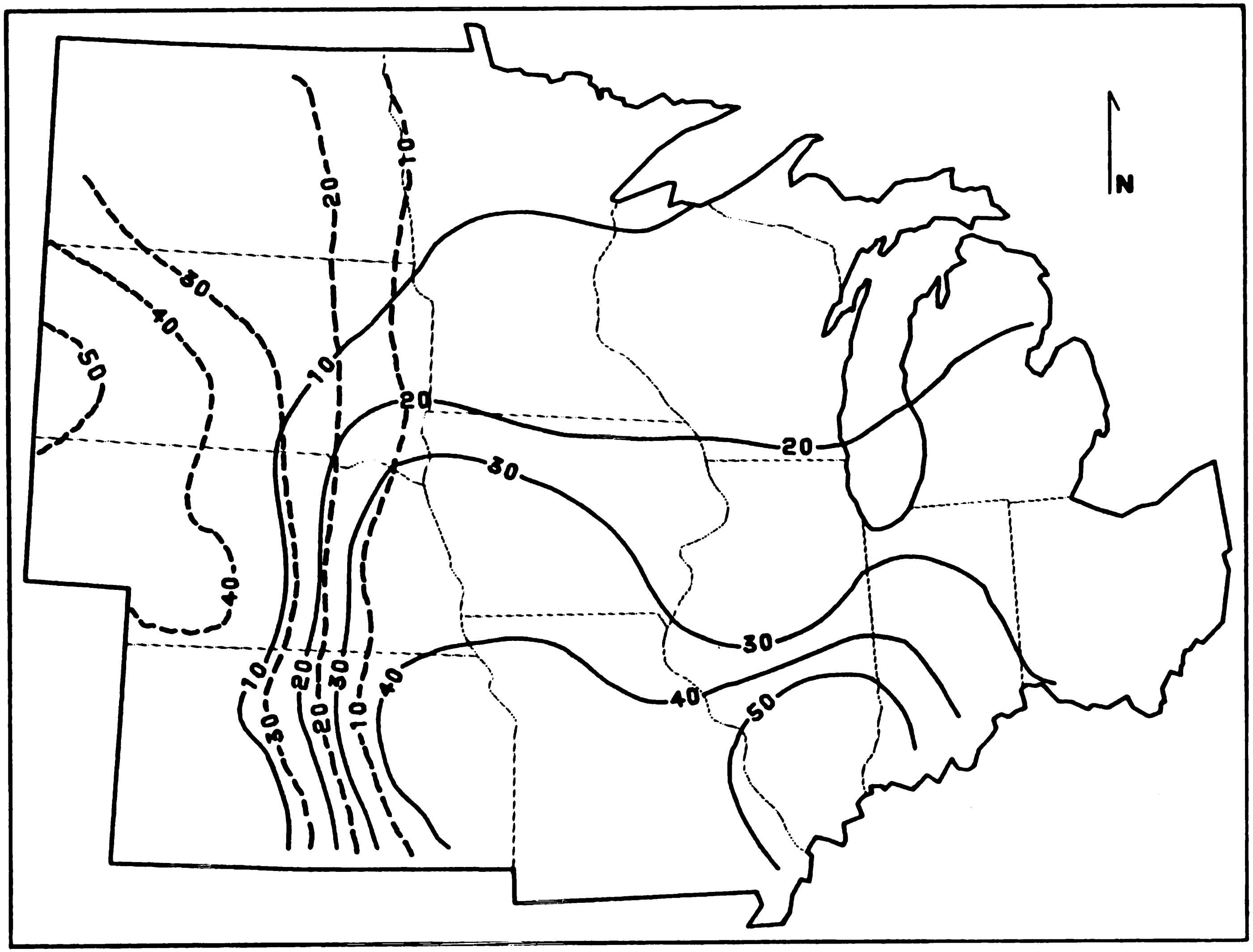


Figure 31. Percentages of Tropical (solid lines) and Dry Tropical (dashed lines) air in July 1970-1979.

the two air masses. Using Dodge City as an example, I found that the number of transition conditions days was inversely related to the number of days classified as Dry Tropical, while unrelated to the other air mass totals (Polar and Tropical). I identified the air mass distributions during July of 1973 and 1974 as examples of this relationship. During July of 1973, the number of unclassified days was 54.8%, while Dry Tropical air accounted for only 22.6% of the total. In contrast, July 1974 had 19.3% of its days unclassed, and 74.2% classified as Dry Tropical. The climatic difference between these two summers has been noted by Wagner (1973b;1974). July 1973 was distinguished by cooler and moister-than-normal conditions across the central United States caused by a westward displacement of the mean long wave ridge. July 1974 found a mean ridge displaced eastward across the central states (Dry Tropical pattern) with warmer and drier-than-normal conditions prevailing there.

Based on this preliminary analysis it seems reasonable to conclude that many of the large average number of "transition conditions" days found in the southwest portion of the study area during July were in fact produced by a mixture of Tropical and Dry Tropical air. During summers when the mean long wave ridge is displaced to the west of its normal position, the distribution of Dry Tropical air is moved west of the study area. The area of Dry Tropical/Tropical mixing is also displaced westward in this situation, which leads to a greater-than-normal frequency of unclassed days in the southwest portions of the study area. Conversely, during summers when the mean ridge is displaced to the east (mean Dry Tropical pattern), the number of transition conditions days decreases, since Tropical air is then synoptically inhibited from moving into the southwest portions of the study area.

<u>Increased Occurrences of "Pacific" Air in Ohio During October</u>--As was evident from Figure 9, my limits identified a larger percentage of Pacific air occurrences in Ohio than in Indiana and Illinois during October. Since this situation is inconsistent with the physical placement of Ohio in relationship to the Pacific source region, the limits used to identify Pacific air at this station may have been inappropriate. A closer examination of days identified as "Pacific" at Dayton, but not at Peoria, revealed two different synoptic arrangements. In the first, a low pressure area stalled over the east coast of Virginia. This pressure cell caused the wind flow at the 850mb and surface levels to be from the northeast across most of the northeastern United States. This arrangement favored mixing of air from the Atlantic with air of Continental origin, thus producing a pseudo-Pacific air mass at Dayton. In the second situation, a high pressure area positioned off the Carolina coast directed air from the southeast toward Dayton. This air was a mixture of Tropical and return flow Continental air, which was not moist enough to be correctly identified as Dilute Tropical, but was instead classed as "Pacific".

Therefore, the limits of Pacific air may be inappropriate at the Dayton station in October, as they have incorrectly classified several mixtures of other air masses as Pacific air. Because these days do not account for more than approximately five percent of the total number of days at the station in October, this problem does not represent a serious limitation.

Synoptic Agreement--One of the problems encountered in numerical air mass classification is that of agreement between the results of numerical and synoptic analysis in air mass designation. The circulation on each day must be consistent with the air mass category determined for that day by the quantitative method. For example, in establishing the limits of Tropical air, I discovered a large number of days that were not being classed as Tropical because of low dewpoint temperatures despite the fact that their associated circulation pattern appeared to be similar to days that were classed as Tropical. An example of one of these days is shown in Figure 32. The warm front has moved through Michigan, and by frontal and wind analysis alone this area would be classed as Tropical. In contrast, an analysis of dewpoints indicates that Tropical air has reached only Illinois (dewpoints greater than 59°F). I felt that days of this type should not be considered as "transition conditions", since they were clearly associated with an identifiable synoptic pattern. Further, since the upper air flow on these days was essentially the same as days I identified as being "Tropical", these days must be tropically influenced. Thus I applied the name "Dilute Tropical" to conditions where Tropical synoptics were associated with air masses that nonetheless had depressed dewpoint values.

## Validity of the Limits Technique

Only two known previous studies (Bryson 1966, Brunnschweiler 1952) produced results similar enough to mine to be effectively compared. Unfortunately, neither of these studies addressed the air mass distributions of spring or fall, and only one (Brunnschweiler 1952) examined

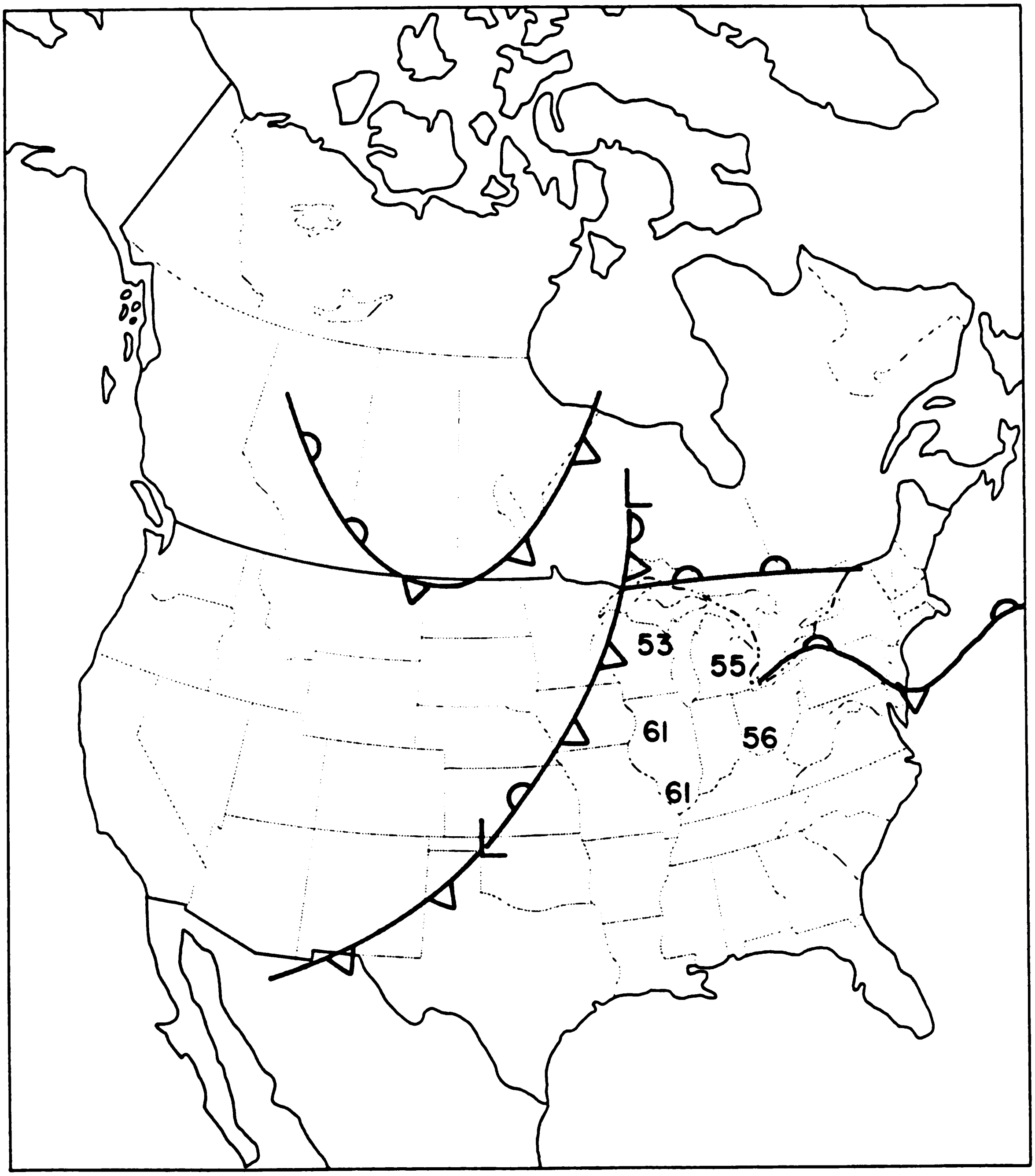


Figure 32. Frontal positions and Midwestern dewpoints for 1200Z on Wednesday 25 April 1979.
Source: Adapted from National Meteorological Center facsimile product.

winter. A comparison of my results with those of Bryson (1966) for July showed general agreement between the two studies, particularly regarding regions dominated (more than fifty percent) by an air mass. Considering that I dealt with only major air mass types, that my "Polar" category was a mixture of the Continental and Pacific airstreams, and the limits I selected placed Dry Tropical air dominance farther north than Bryson's method did, I believe the results of the two studies show similar distributions. The greatest contrast between the results of these two studies occurred with regard to the width of the transitional areas between regions of single air mass dominance. Bryson's work showed these transition zones to be rather narrow bands, while the method I employed allowed for broader transition zones.

My results also compared well to those of Brunnschweiler (1952) in most cases. For example, both methods revealed the dominance of Continental air over most of the study area in January. In July, there was low spatial agreement between Brunnschweiler's results and both mine and those of Bryson. The generally favorable comparison between the patterns yielded by my research and those produced by previous research leads me to conclude that the "limits method" is a valid technique of air mass classification.

CHAPTER VI

# SUMMARY, RECOMMENDATIONS, AND CONCLUSIONS

## Summary

The method of air mass classification employed in this study delimits air masses and the transition conditions between them through the use of both surface and upper air temperature data. The limits were determined through map analysis of surface and 850mb level conditions of air masses of known origin. Temperatures that did not clearly fall into one air mass category were designated "transition conditions" and were not included in any air mass total.

My results showed that:

1. Continental air was the dominant air mass in all seasons in the north, and it was also influential in the southern portions of the study area.

2. Pacific air was prominent in the western portions of the study area, particularly in spring and fall, but of less importance elsewhere.

3. The Dilute Tropical and Tropical air masses were important only in the south and east portions of the study area.

4. Dry Tropical air was primarily a summer season phenomenon affecting mainly the western portions of the study area.

Also, I demonstrated that a unique 500mb flow appears to be associated with the occurrence of each air mass in the study region, and that mean and modal flow patterns of the various seasons may be explainable in terms of the frequency of these component patterns.

## Recommendations

The results of this study were only a first approximation of air mass distributions and there are a number of ways I recommend that the method could be improved. First, the Jenks method of data classification (or a similar system) should be used as another input into the air mass delimitation problem. Although this statistical method does not handle "transition conditions" well, it can be useful in finding natural breaks in the data distributions. Secondly, a mean 500mb map should be compiled for each air mass category in every season. I propose that these maps be a statistical composite of the 500mb surface on all days when the particular air mass occurred in fifty percent or more of the study area. In order to test the assumption that these mean flow maps, when compiled, would reflect a single persistent or characteristic pattern rather than an average of several dissimilar ones, a mean map could be drawn from a randomly selected subset consisting of perhaps ten percent of the days from each air mass category. If the map from this subset is areally similar to the overall mean flow map of each air mass, a single pattern was probably responsible for the mean, supporting the contention that specific upper air flows are associated with the occurrences of different air masses in specific geographical locations.

Another improvement of my method would be to decompose the "transition conditions" days into sub-groups related to specific air masses. For example, this procedure would allow the origin of unclassified days occurring between Continental and Pacific air masses to be explored as a problem separate from unclassified days between other air masses. Examination of the distribution of these component "unclassified" days and their associated flow patterns may help in redefining the numerical limits for better agreement with synoptic conditions.

One of the assumptions of the partial collective method employed by Bryson (1966) is that different source regions produce air of different mean characteristics, with a normal distribution of temperatures about that mean. This assumption could be used to address the problem of the adequacy of sample size in my study. Assuming that the frequency distribution of an infinite number of temperatures associated with a particular air mass is indeed normal, a sample air mass distribution would not significantly differ from normal if the sample size is adequate. Therefore, an analysis of the frequency distribution of temperature and moisture in each air mass could be used to statistically determine the adequacy of a particular sample size.

The results of a partial collective analysis similar to Bryson's, but also using 850mb temperature and surface dewpoint data as input, could be useful in developing an approximation of the appropriate number of "transition conditions" days at a particular station. Since Bryson's method breaks a temperature frequency distribution into component normal distributions associated with each air mass, the points where these component distributions intersect should be within the numerical transition zones. The limits themselves probably would be located between the intersection points and where the component distributions approach zero. Analysis of this type could thereby approximate the number of transition days, as well as provide another independent verification of the limits themselves.

## Conclusions

In future research, the air masses of any region could be recognized and delimited from surface and upper air data using the "limits method" and utilizing the various improvements I have suggested. If the relationship between 500mb flow patterns and various air mass distributions could be statistically verified, a more detailed summary of expected regional temperature and moisture patterns could commonly accompany upper air forecasts. Also, the relative air mass dominance in a region (or at a station) over a given time period could be inferred from a known mean temperature deviation from normal by comparing the deviated mean to the range of temperatures associated with the regional air masses. Furthermore, once the limits for the four seasonal months (January, April, July, October) are firmly verified, it would be possible to interpolate the most appropriate limits for the months between, thereby facilitating the study of monthly changes in the air mass distributions. Thus, this method could be easily applied to the problem of air mass quantification and may facilitate the integration of air mass research into the mainstream of modern climatological/meteorological research.

# BIBLIOGRAPHY

## BIBLIOGRAPHY


Barry, R. G. 1967. Seasonal location of the Arctic front over North America. Geogr. Bull. 9: 79-95.

Belasso, J. E. 1952. Characteristics of air masses over the British Isles. Geophys. Mem. 11(87), 34 pp.

Bolin, B. 1950. On the influence of the Earth's orography on the general circulation. Tellus 2: 184-195.

Brunnschweiler, D. H. 1952. The geographic distribution of air masses in North America. Vierteliahrschr. Naturforsh. Ges. Zurich. 97: 42-49.

________. 1957. Die luftmassen der Nordhemisphare, versuch einer genetischen auf aerosomatisher grundlarge. Geogr. Helv. 12: 164-195.

Bryson, R. A. 1966. Air masses, streamlines, and the Boreal forest. Geogr. Bull. 8: 228-269.

Burbidge, F. E. 1951. The modification of Continental Polar air over Hudson Bay. Quart. J. R. Met. Soc. 77: 365-374.

Burke, C. J. 1945. Modification of Continental Polar air over a water surface. J. Met. 2: 94-112.

Craddock, J. M. 1951. The warming of Arctic air masses over the eastern North Atlantic. Quart. J. R. Met. Soc. 77:351-364.

Crowe, P. R. 1965. The Geographer and the Atmosphere. Trans Inst. Brit. Geogr. 36: 1-19.

Dodd, A. V. 1965. Dewpoint distribution in the contiguous United States. Mon. Wea. Rev. 93: 113-122.

Frisby, E. M., and Green, F. H. 1949. Comparison of the regional and seasonal frequency of air masses. Comptes Rendus, Congres Internat. de Geogr. (Lisbon) 2: 307-314.

Geb, M. 1971. Theory of air masses and fronts: new aspects and interpretations. Meteorologische Abhandlungen, Band 109/Heft 2, Institute fur Meteorologie, Zentraleinrichtung 2, der Freien Universitat Berlin, pp. 112-120.

Godson, W. L. 1950. The structure of the North American weather system. Centen. Proc., Royal Met. Soc. (London), pp. 89-106.

Harley, W. S. 1962. Distribution of wet bulb potential temperatures in North American air masses (1957) and a statistical analysis of results. Met. Branch CIR-31622, TEC-400. Toronto: Dept. of Transportation. 46 pp.

Harman, J. R., and Harrington, J. A. 1978. Contrasting rainfall patterns in the Upper Middle West. Annals of the Amer. Assoc. of Geogr. 68: 402-413.

Henry, W. K. 1979. Arbitrary method of separating Tropical air from return flow Polar air. Nat. Wea. Digest 4: 22-26.

James, R. W. 1969. Elementary air mass analysis. Met. Rund. 22: 75-79.

________. 1970. Air Mass Climatology. Met. Rund. 23: 65-70.

Klein, W. H. 1957. Principal tracks and frequency of cyclones and anticyclones in the Northern Hemisphere. Research Paper No. 40, United States Weather Bureau, Washington, D. C. 60 pp.

Lahey, J. F., Bryson, R. A., Wahl, E. W., Horn, L. H., and Henderson, V. D. 1958. Atlas of the 500mb Wind Characteristics for the Northern Hemisphere. The University of Wisconsin Press, Box 1379, Madison, Wisconsin, 53701.

Mather, J. R., Field, R. T., Kalkstein, L. S., and Willmott, C. J. 1980. Climatology: The challenge for the Eighties. Professional Geographer 32: 285-292.

McDonald, N. S. 1975. Eigenvector analysis as an aide to air mass recognition. Archiv. fur Meteorologie, Geophysik und Bioklimatologie, Ser A. (Vienna) 24: 229-234.

McIntyre, D. P. 1950. On the air mass temperature distribution in the middle and high troposphere in winter. J. Met. 7: 101-107.

Miller, A. A. 1953. Air Mass Climatology. Geography 38: 55-67.

Myachkova, N. A. 1979. Geographical characteristics of advection of air masses and the formation of climate. Moscow Universitet, Vestnik, Ser. 5, Geografuja 5: 23-28.

Namias, J. 1969. Seasonal interactions between the north Pacific Ocean and the atmosphere during the 1960's. Mon. Wea. Rev. 97: 173-192.

O'Conner, J. F. 1964. Hemispheric distribution of 5-day mean 700mb circulation centers. Mon. Wea. Rev. 92: 303-315.

Pyke, C. B. 1972. Some meteorological aspects of the seasonal distribution of precipitation in the Western United States and Baja California. Contribution No. 139, Water Resources Center, University of California.

Reitan, C. H. 1974. Frequencies of cyclones and cyclogenesis for North America 1951-1970. Mon. Wea. Rev. 102: 861-868.

Sands, R. D. 1966. A feature-of-circulation approach to synoptic climatology applied to the Western United States. Publications in Geography Technical Paper Number 66-2, Department of Geography, University of Denver. 332 pp.

Showalter, A. K. 1939. Further Studies of American air mass properties. Mon. Wea. Rev. 67: 204-218.

Soronking, V. N. 1976. Features of air mass transfer and types of summer weather resulting from it in the far east of the U.S.S.R., Moscow Universitet, Vestnik, Ser. 5 Geografuja 2: 70-76.

Stark, L. P. 1965. Position of monthly mean troughs and ridges in the Northern Hemisphere, 1949-63. Mon. Wea. Rev. 93: 705-720.

Stessel, J. P., and Van Isacker, J. 1975. Application of numerical techniques to the analysis of air masses, Instit. Royal Meteorologique, Brussels, Belguin, Publications, Ser A 91: 223-232.

Stopa, M. 1970. Probabilities of the appearance of definite extreme temperature values and the diurnal amplitudes in various air masses. Katedra Klimatologii, Prace i Studia (Warsaw) 4: 177-205.

Sutcliff, R. C. 1951. Mean upper contour patterns of the Northern Hemisphere. Quart. J. R. Met. Soc. 77: 435-440.

University of Chicago, Department of Meteorology staff. 1947. On the general circulation of the atmosphere in middle latitudes. Bull. of the Amer. Met. Soc. 28: 255-280.

Wagner, A. J. 1973a. Weather and circulation of January 1973. Mon. Wea. Rev. 101: 381-386.

_______. 1973b. Weather and circulation of July 1973. Mon. Wea. Rev. 101: 777-782.

Wagner, A. J. 1974. Weather and circulation of July 1973. Mon. Wea. Rev. 102: 736-742.

________. 1977. Weather and circulation of January 1977. Mon. Wea. Rev. 105:553-560.

Weedfall, R. O. 1970. Application of air mass classification to West Virginia climatology. U. S. Environmental data service, Technical memorandum, EDSTM, 13 Jan. 1970. 23 pp.

Wendland, W. M., and Bryson, R. A. 1981. Northern Hemisphere Airstream Regions. Mon. Wea. Rev. 109: 255-270.

Willett, H. C. 1940. Characteristics of North American Air Masses. Air Mass and Isentropic Analysis. Namias, J., Ed. Amer. Met. Soc., Milton, Mass. pp. 73-108.

# APPENDIX

## AIR MASS PERCENT OCCURRENCE BY STATION FOR JANUARY, APRIL, JULY, AND OCTOBER 1970-1979

## APPENDIX

### JANUARY

| Station | Cont. | Pacif. | Dil. Trop. | Trop. | Dry Trop. | Unclassed |
|---|---|---|---|---|---|---|
| Bismarck | 72.6 | 14.5 | 0 | 0 | 0 | 12.9 |
| Dayton | 61.0 | 16.1 | 4.5 | 0.3 | 0 | 18.1 |
| Dodge City | 38.1 | 47.4 | 0.3 | 0 | 0.3 | 13.9 |
| Flint | 77.4 | 9.4 | 0.3 | 0 | 0 | 12.9 |
| Green Bay | 82.9 | 6.5 | 0 | 0 | 0 | 10.6 |
| Int. Falls | 89.6 | 3.6 | 0 | 0 | 0 | 6.8 |
| Monette | 36.2 | 35.8 | 3.2 | 0.4 | 0 | 24.4 |
| North Platte | 50.3 | 36.1 | 0 | 0 | 0 | 13.6 |
| Omaha | 57.1 | 25.5 | 0.3 | 0 | 0 | 17.1 |
| Peoria | 60.0 | 19.4 | 1.3 | 0 | 0 | 19.3 |
| Rapid City | 55.2 | 28.7 | 0 | 0 | 0 | 16.1 |
| St. Cloud | 84.5 | 10.0 | 0 | 0 | 0 | 5.5 |
| Salem | 50.3 | 21.9 | 3.6 | 1.0 | 0 | 23.2 |
| S. Ste. Marie | 90.6 | 2.9 | 0 | 0 | 0 | 6.5 |
| Topeka | 46.8 | 32.5 | 1.6 | 0 | 0.3 | 18.8 |

### APRIL

| Station | Cont. | Pacif. | Dil. Trop. | Trop. | Dry Trop. | Unclassed |
|---|---|---|---|---|---|---|
| Bismarck | 40.0 | 32.3 | 1.0 | 0 | 0.7 | 26.0 |
| Dayton | 28.7 | 30.7 | 14.7 | 3.3 | 0 | 22.6 |
| Dodge City | 10.0 | 49.0 | 12.0 | 1.7 | 4.7 | 22.6 |
| Flint | 44.7 | 30.0 | 7.0 | 1.7 | 0 | 16.6 |
| Green Bay | 45.0 | 29.0 | 5.3 | 0 | 0 | 20.7 |
| Int. Falls | 61.0 | 22.7 | 0.7 | 0 | 0 | 15.6 |
| Monette | 10.4 | 43.3 | 24.1 | 5.2 | 0 | 17.0 |
| North Platte | 21.7 | 43.7 | 4.7 | 0.3 | 2.7 | 26.9 |
| Omaha | 23.7 | 41.3 | 11.0 | 2.0 | 0 | 22.0 |
| Peoria | 28.7 | 36.7 | 11.3 | 2.7 | 0 | 20.6 |
| Rapid City | 25.3 | 45.3 | 0.7 | 0 | 0.7 | 28.0 |
| St. Cloud | 44.3 | 26.7 | 5.0 | 0 | 0.7 | 23.3 |
| Salem | 17.7 | 32.0 | 23.7 | 9.3 | 0 | 17.3 |
| S. Ste. Marie | 61.3 | 19.3 | 3.0 | 0 | 0 | 16.4 |
| Topeka | 15.0 | 41.3 | 19.7 | 4.0 | 0 | 20.0 |

APPENDIX--continued

JULY

| Station | Polar | Tropical | Dry Tropical | Unclassed |
|---|---|---|---|---|
| Bismarck | 42.9 | 1.0 | 23.7 | 32.4 |
| Dayton | 34.8 | 29.4 | 1.0 | 34.8 |
| Dodge City | 13.6 | 5.5 | 37.1 | 43.9 |
| Flint | 52.9 | 24.5 | 0.7 | 21.9 |
| Green Bay | 56.1 | 16.5 | 0.7 | 26.7 |
| Int. Falls | 72.6 | 2.6 | 1.3 | 23.5 |
| Monette | 15.4 | 42.3 | 1.8 | 40.5 |
| North Platte | 26.5 | 0.7 | 41.0 | 31.8 |
| Omaha | 21.7 | 35.8 | 6.1 | 36.7 |
| Peoria | 35.8 | 24.2 | 2.3 | 37.7 |
| Rapid City | 26.5 | 0.7 | 50.3 | 22.5 |
| St. Cloud | 48.1 | 11.6 | 4.2 | 36.1 |
| Salem | 19.0 | 57.7 | 0.7 | 22.6 |
| S. Ste. Marie | 69.7 | 6.8 | 1.9 | 21.6 |
| Topeka | 15.8 | 45.8 | 2.9 | 35.5 |

OCTOBER

| Station | Cont. | Pacif. | Dil. Trop. | Trop. | Dry Trop. | Unclassed |
|---|---|---|---|---|---|---|
| Bismarck | 38.4 | 37.1 | 0.7 | 0 | 2.3 | 21.5 |
| Dayton | 25.8 | 33.5 | 18.4 | 1.6 | 0 | 20.7 |
| Dodge City | 9.0 | 42.6 | 10.3 | 0 | 13.6 | 24.5 |
| Flint | 37.4 | 25.2 | 15.8 | 0.7 | 0 | 20.9 |
| Green Bay | 42.3 | 27.4 | 11.6 | 1.0 | 0.7 | 17.0 |
| Int. Falls | 53.3 | 23.2 | 3.6 | 0 | 0 | 19.9 |
| Monette | 7.5 | 40.8 | 25.5 | 4.3 | 1.1 | 19.8 |
| North Platte | 21.3 | 44.5 | 1.9 | 0 | 10.3 | 22.0 |
| Omaha | 19.4 | 36.5 | 15.8 | 1.3 | 1.3 | 25.7 |
| Peoria | 23.6 | 30.0 | 18.4 | 2.6 | 0 | 25.4 |
| Rapid City | 27.7 | 42.9 | 0 | 0 | 9.7 | 19.7 |
| St. Cloud | 39.4 | 28.7 | 8.4 | 0.7 | 1.0 | 21.8 |
| Salem | 14.5 | 26.8 | 26.8 | 7.7 | 0 | 24.2 |
| S. Ste. Marie | 51.0 | 17.7 | 7.4 | 0 | 0 | 23.9 |
| Topeka | 13.2 | 37.7 | 17.7 | 3.9 | 1.6 | 25.9 |