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EFFECT OF CONTRAIL CIRRUS ON SURFACE WEATHER CONDITIONS IN THE MIDWEST - PHASE I

by

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ABSTRACT

The effect of aircraft contrails on surface climate was assessed by first determining the density of jet traffic across a ten state area of the Upper Midwest, and comparing that distribution with observed changes of various meteorological parameters over the past 50 years, both within and outside of the principal contrail areas. Commercial jet traffic density was found to be greatest in 1979 along a band running from central Ohio westward to central and northern Illinois, with one branch leading westward across northern Missouri, and another branch leading toward the southwest through central Missouri. Another high density region, within the area studied, was eastern Kentucky and Tennessee.

The surface meteorological characteristics were compared for stations within the area of high jet traffic density and those areas less affected by jet traffic, from the middle 1950's until the present. Percent possible sun and number of clear days decreased within the areas of high traffic density from about 1935 to 1950, decreasing more slowly thereafter to the present. The same parameters showed no change or slight increases elsewhere in the study area. The frequency of moderated temperatures, i.e., daily temperature maximum minus daily temperature minimum, increased from the late 1940's with the most pronounced increased found over northern Illinois and Indiana.

In-flight observations from in excess of 16,000 pilot reports suggest that observations with contrails are more frequently also associated with turbulence. In addition and perhaps of more importance to surface climate, aircraft producing contrails typically observe more frequent cloud cover both

below and at the aircraft level. Indeed, only about 1/3 of all contrails can be seen from the surface of the earth due to a natural clouds occurring below the contrails.

There appears to be no difference between the percentage of daytime flights which produce contrails as opposed to those flown during the night. There is a strong relationship however, between contrail areas and pressure features of the middle and upper troposphere, i.e., contrails are much more frequently observed within the area of an upper level trough as opposed to a ridge, and there is a slight preference for contrail areas to be located closest to surface low pressure areas.

Cirriform clouds increased in frequency from 1951 to 1976 according to standard surface meteorological observations. Frequency of clear days decreased over the 26 years at 10 of the 12 first order stations studied. The greatest decline occurred from Chicago to southern Iowa and from Chicago to southern Illinois.

INTRODUCTION

The objectives of the one-year contract were to essentially address two questions: (1) Do contrails measurably alter surface weather conditions in the Midwest? and 2) How well do climatic records from the Upper Midwest indicate the presence of contrails?

To fulfill the objectives, the scope of research included three major thrusts:

(1) Document and analyze jet traffic density over the Upper Midwest from the mid-1950s to the present. If the effect of contrails on climate was to be studied, the location of jet aircraft and contrails must first be identified. This required the collection of a large mass of formatted pilot report information, which included a pilot option to comment on the presence of contrails (either persistent or non-persistent). In addition, since these formatted pilot reports also contained entries regarding several other meteorological parameters, relationships between contrail occurrence and other parameters could also be investigated.

(2) Identify and quantify trends in cloud cover over the Upper Midwest from about 1950 to the present. Researchers have suggested that aircraft contrails have modified natural cloud cover, both forming and spreading into veils of cirrus, and by seeding supercooled high level clouds. This effect, if true, may be preserved in the meteorological observations of cloud cover made routinely at National Weather Service (NWS) offices. Records since about 1950 from NWS first order stations of low, middle and high clouds were analyzed for trends in amount over the last 30 years. The areal distribution of cloud amount (all types) changes relative to jet traffic, and changes of amount of high cloud relative to jet traffic were studied.

(3) Identify changes in the total amount of sky cover, numbers of clear, partly cloudy and overcast days, and changes in "moderated temperature" (decreased diurnal temperature variation) over the Midwest. These parameters were analyzed from the cooperative meteorological network, a much more dense network than the first order stations. The spatial distribution of changes in these parameters was of particular interest, to determine whether observed changes in these potential "response" functions were spatially and temporally related to changes in jet traffic and attendant contrail production.

CHAPTER ONE

SKY COVER, SUNSHINE, AND TEMPERATURE TRENDS FOR 1901-1977

Introduction

This chapter presents results of one phase of the one-year project conducted to investigate the possible extent of influence of contrails on the weather and climate of the Midwest. This particular phase of the study investigated long-term, 77-year records of available data on sky cover, sunshine, and surface temperatures, to examine their temporal variability on an areal basis. The principal goal was to discern any evidence of possible man-made influences on cloud frequencies in the post-1960 period when high flying jet aircraft became more frequent and left many contrails in the upper atmosphere. Examination of the sunshine and temperature data alone could not be considered at all conclusive of a contrail effect, but are useful as material to substantiate whether atmospheric influences from contrails were sizeable and important.

Other chapters of this report delve into possibly more meaningful cloud data, but they are limted to only recent, post-1950 years. Hence, data sets on sky cover conditions and sunshine percentages, as measured at several stations around the Midwest, become the only means for looking backwards beyond the 1950's at the fluctuations in the amount of light being received at the surface and the overlying cloudiness.

This chapter first examines the possible causes for changes in clouds, then briefly describes the cloud climatology of the 10-state study region. This is followed by a section that treats the sky cover and sunshine data (and its quality) and the analyses of these data. The next major section addresses the results for the study of clear days, and this is followed by section on days with cloudy and partly cloud skies. Sunshine results appear in the next section, then results on surface temperatures, and finally a summary and conclusions section.

Causes of Changes in Clouds

Anyone familiar with the continental climate of the' central United States is aware of the great year-to-year variability in most atmospheric conditions. Indeed, variation on a variety of time scales is the norm of the climate; hence, variations are to be expected, but become major problems when looking for longer term, potentially subtle, trends in weather condition. Any change in the frequency or magnitude of a weather event extending over five or more years in this climate can generally be ascribed to three causes, which may act independently, or in some collective manner, to produce a shift in the climate.

Climatic Variation Due to Natural Causes. The first of these factors are the natural climatic variations due to large scale, hemispheric or global, variations in weather patterns. Unfortunately their causes are not yet well understood. History has shown us that nature has provided a wide range of climates in the Midwest over the past several thousand years. An amazing number of different scales of variations due to natural causes are not only evident but likely. It is also important to recognize that there are at least two types of natural variations that can be expected in cloud frequencies and other weather phenomena. The first might be labeled "the anomalous" type of variation which represent shifts ranging anywhere from five to fifteen years. Such anomalous periods do occur, but the frequency of the weather event returns to its preanomaly level after the anomalous excursion. Another type of shift is labeled a "climate fluctuation." This often represents a longer term trend ranging from perhaps 50 to 1000 years. Imprinted on both of these are year-to-year variations, but an inspection of their frequencies with some smooth statistical curve fitting, will often reveal a downward or upward type of trend extending over many years. Hence, any systematic change in cloudiness and sunshine noted during the 1901-1977 period must consider that the natural atmospheric shifts could be the cause.

Errors in the Observations. Another reason for apparent systematic changes in cloud cover or sunshine cloud relate to errors or shifts in data collection procedures. The cloud cover data (labeling of each day as clear, partly cloudy, or cloudy) could contain false changes for at least two reasons. First is some form of systematic observer error at a given location, such that the observers are labeling cloudy days as partly cloudy, since the sky observation is somewhat subjective. The other possiblity is that the instructions for record keeping have changed leading to differences in how sky cover is defined. The sunshine records since 1900 have been kept by sunshine recorders, an instrument that inscribes the minutes of sunshine on a chart based on sun falling on the instrument. Errors could come about because of poor instrument calibration, or changes in instrument sensitivity. Similar changes in observation procedures, instruments, or sites could influence temperatures.

Inadvertent Climate Modification. A third reason for climatic shift in the cloud cover frequencies and resulting changes in sunshine and temperature is man's accidental influence on the atmosphere. There appear to be at least three, potentially interactive, ways that man could have systematically been influencing cloud cover since the start of the 20th Century. In the central

United States, the period from 1900 to 1977 has been one of a major shift from an agriculturally oriented economy to a manufacturing oriented economy. In 1900, 12% of the population in the Midwest lived in urban areas, and by 1977 about 70% lived in urban areas. This is also a period of major growth in industrial activity and development of the automobile, particularly since 1940. Hence, there have been major influences on the atmosphere from midwestern cities and industries (Changnon, 1973).

There appear to be at least three ways in which man's emissions into the atmosphere could have systematically influenced the clouds, sunshine and temperatures. First, are the effects of increased pollutants (aerosols) in the atmosphere. Changnon (1976) has shown how the frequency of smoke and haze days changed dramatically at a series of locations in Illinois with major increases in the number of days beginning in the late 1930's and 1940's. Such increases in man-derived pollutants, generally noted to develop before and during World War II (1935-1945) and remaining high since, have produced additional haze not only in and around cities but now at times over the entire Midwest (Braham, 1977). This haze reduces visibility and restricts one's ability to view clouds. It, of course, also intercepts sunshine and reduces incoming radiation.

A second potential effect of the added pollutants, as has been noted at St. Louis (Grosh 1978), has been to help produce localized urban increases in cloud cover. A 5 to 10% increase in clouds related to the ability of man-made pollutants to serve as cloud nuclei is well recognized (Landsberg, 1970). Most of these pollutants are urban-related (although automobiles and scattered power plants also add pollutants over a region) and have been realized mostly in low level clouds.

A third inadvertent influence of man on cloudiness, the one that is the subject of this study, is the influence of jet-produced contrails. The potential seems obvious in parts of the Midwest having a notably high frequency of persistent contrails. What is uncertain however is how significant this influence is; that is, whether the contrail-induced cirrus represents an increase in cloud cover of 0.1% , 1%, or 10% or more. In addition to directly producing added cirrus and in inducing more cirrus to form, another influence has been suspected. That is, the ice crystals formed by the contrails could descend into middle level clouds resulting in a) more middle level cloud cover, and/or b) increase in the precipitation.

In essence then, there are several potential causes for anomalous short or long term climate variations in clouds and their influence on the sunshine received at the earth and surface temperatures. Discerning which of these causes is existent and most critical is difficult but the effort is an essential part of this project if the contrail influence is to be isolated.

Climate of Sky Cover and Sunshine in the Midwest

The following sections relating to results of the sky cover and sunshine analysis present the actual numbers on clear days, partly cloudy days, cloudy days, and percent of sunshine for various seasons, years, and stations throughout the 10-state study area (see Tables 2-5). These numbers will not be repeated here, but a short general discussion is offered. The pattern of sky cover in the study area (Fig. 1) shows that, in general, in all seasons, there are more clear skys (and hence more sunshine received) in the southern and western parts of the study area, as opposed to the northern and eastern. The northeastern part of the study area includes the Great Lakes which produce

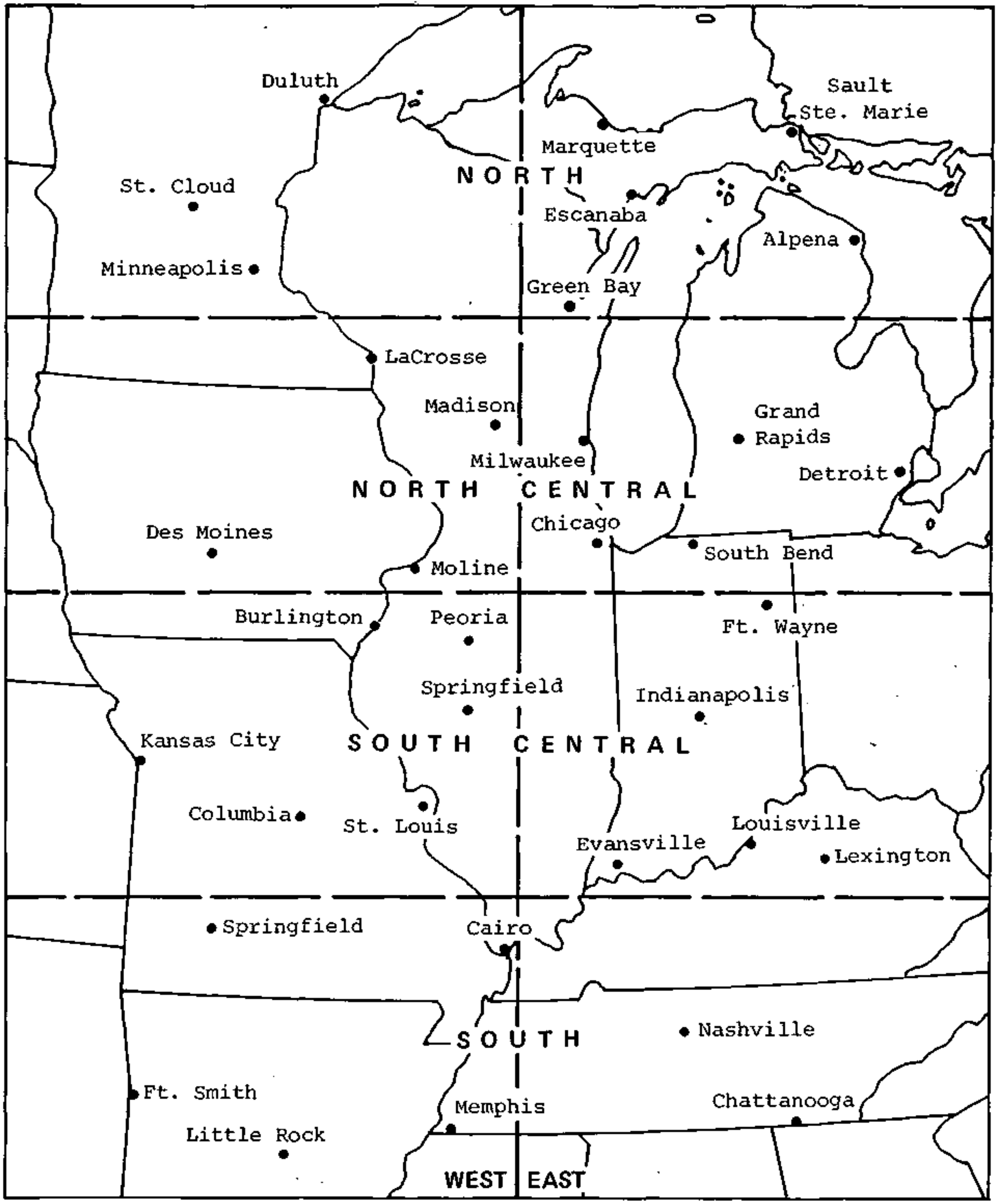

Figure 1. Stations and areas used by sky cover and sunshine studies.

sizeable influences on cloud cover, to decrease it in summer and increase it in the colder half year (Changnon, 1968). Current average annual values of sunshine percentages in the north are 48% at Sault Ste. Marie and 51% at Minneapolis, as opposed to 63% at Memphis and 62% at Kansas City. If one considers the annual frequency of cloudy days, the current average at Sault Ste. Marie is 213 days with 174 days at Minneapolis. Comparable average values to the south are 151 cloudy days at Kansas City and 153 days at Memphis..

There are also systematic differences across the region in the seasonal frequencies of sky cover. For example, in the South Area (see Fig. 1), the leading season of clear days, on the average, is fall followed by summer, spring and winter. In the South Central Area, clear day frequencies in fall are equalled by those in summer, followed in order by the frequencies in spring and winter. As one moves farther north into the North Central Area, clear day frequencies become greatest in summer with fall values ranked second, then spring and winter. In the northernmost part of the study area, summer clear days, on the average, rank first, followed by the number in spring, with fall frequencies ranking third and winter last.

If one examines the average seasonal frequencies of clear days on a west to east basis, one finds that the fall frequency leads in the west followed by summer, spring, and winter values. However, in the eastern half of the study area (Fig. 1), summer is the leading season with clear days followed by fall, spring, and winter.

In general, in most parts of the study area, the fall and summer are the seasons with the greatest frequencies of clear skies and hence more sunshine. Winter ranks last among the four seasons in the amount of sunshine and number of clear days, and obviously ranks first amongst the four seasons in the number of cloudy days.

Cloud and Sunshine Data and Related Analyses

The stations for which data on sky cover and sunshine were available for all or most of the 1901-1977 period are shown in Figure 1. Except for a few stations such as South Bend, Indiana, most all stations had complete records of sky cover for this 77-year period. However, records of sunshine at most stations began in the 1910-1915 period, and very few stations had available sunshine records prior to 1910. The periods of record are indicated on Table 1.

Great care was also made in the study of the historical records to consider any possible observational or instrumental errors. During the 1901-1977 period, there were no changes in instructions to Weather Bureau (now National Weather Service) observers about how to list the sky cover as being cloudy, partly cloudy, or clear. Since observations were made by a large number of persons over the 77-year period, it is doubtful that any systematic observer biases existed to produce long term trends. Hence observer error is discounted as a major factor causing any trends discerned.

The potential of faulty equipment or poor calibrations of the sunshine recorders, and hence systematic time biases cannot be discounted. Instruments were maintained, as near as one can learn, reasonably well and instrument problems or changes should not be a reason for any long-term (greater than 5 to 10 years) trends in sunshine data. Wahl's (1968) study of data from several midwestern stations of both the mid 19th Century and mid 20th Century suggets near equal precision of temperature from both periods.

One of the "checking procedures" used in this entire study to verify the potential of "errors" in the sunshine or sky cover data was to inter-compare them. Their results (trends) should agree, and yet one set of data (sky cover) is by human observations and other is based on instruments. As will be noted in the results, there is general agreement in the trends of sky cover and sunshine, suggesting that the observer error or equipment problems, as causes for trends, was negligible. However, one important change at 34 of 36 stations (Cairo, Illinois, and Marquette, Michigan excluded) was a relocation of the station site from the city (or town) central business district to the rural airport. As shown in Table 1, these largely occurred in the 1940's but began in the mid 1930's and continued into the early 1950's. These shifts involved relocation, at least at the largest cities, to locales where less urban pollution existed (or would exist). Hence, the site change represented a possible improvement in visibility, and the potential for less cloud cover and a potential for more sunshine.

The various analyses were based on daily values of sky cover and percent of possible sunshine. The daily sky cover values of clear (0 to 0.3 sky cover), partly cloudy (0.4 to 0.7 sky cover), and cloudy (0.8 to 1.0 sky cover) are values derived from hourly observations made at the U.S. Weather Bureau first-order stations scattered throughout the area. These hourly observations were combined into daily values. Monthly frequncies of clear, partly cloudy, and cloudy days were obtained in this study either from published records or original records of the first-order stations. Once compiled and totaled, the values were entered into punch cards for subsequent analysis.

The daily sunshine recorder data were used in a similar fashion. Daily sunshine values are recorded both as to actual time and as percent of possible sunshine for the day. We chose to analyze the percent of possbile sunshine which accounted for changes in length of day during the season. Daily values of possible percent of sunshine were combined into monthly means. These

Table 1. Periods of records and dates of shift in the location of First Order Stations from inner city sites to airport sites, during 1901-1977.

	City to Rural airport site	Period of sky cover data (1)	Period of sun-shine data
Memphis, TN	Sept. 1950	C	1902-77
Nashville, TN	June 1941	C	1919-77
Chattanooga, TN	June 1940	C	1919-77
Sault St. Marie, MI	July 1951	C	1922-77
Marquette, MI	Always in city	C	1905-77
Grand Rapids, MI	Aug. 1950	C	1922-77
Detroit, MI	July 1942	C	1922-77
Alpena, MI	Aug. 1959	C	1922-77
Ft. Wayne, IN	Aug. 1939	1902-77	1912-77
South Bend, IN	Feb. 1933	1914-77	none
Indianapolis, IN	May 1941	C	1916-77
Evansville, IN	Aug. 1940	C	C
Milwaukee, WI	Aug. 1940	C	1916-77
Madison, WI	Sept. 1939	C	1916-77
La Crosse, WI	Dec. 1950	C	none
Green Bay, WI	Aug. 1949	C	1903-77
Little Rock, AR	Dec. 1938	C	1916-77
Ft. Smith, AR	Sept. 1945	C	1916-77
St. Louis, MO	July 1958	C	1916-77
Springfield, MO	Aug. 1940	C	C
Kansas City, MO	Jan. 1934	C	1916-77
Columbia, MO	Jan. 1936	C	1916-77
Louisville, KY	June 1945	C	1916-77
Lexington, KY	July 1944	C	none
St. Cloud, MN	Feb. 1936	1916-77	none
Rochester, MN	Nov. 1943	C	none
Minneapolis, MN	Oct. 1937	C	1916-77
Duluth, MN	March 1950	C	1911-77
Dubuque, IA	June 1951	C	none
Burlington, IA	Oct. 1940	1914-77	none
Des Moines, IA	Oct. 1950	C	C
Moline, IL	Dec. 1939	C	C
Springfield, IL	Jan. 1948	C	C
Chicago, IL	June 1942	C	C
Cairo, IL	Not moved	C	1920-77
Peoria, IL	May 1943	C	C

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[1] C = complete for 1901-77

monthly mean values of percent of possible sunshine were calculated from historical records of the first-order stations, punched onto IBM cards, and subsequently used to develop seasonal and annual values.

Much of the analysis was based on seasonal and annual values of sky cover and percent of sunshine. The seasons chosen for analysis of the sky cover and sunshine data were spring (March-May), summer (June-August), fall (September-November) , and winter (December-February). For the sky cover data and the sunshine data, the seasonal and annual values were used to develop moving averages of 2-, 5-, 10-, and 20-year periods. Graphs of these moving averages were plotted to search for the most informative means for portraying the results and removal of small scale fluctuations. In most cases, the 10-year totals were chosen to study the trends in sky cover and sunshine.

One phase of the analysis included inspecting the data and trends of the 36 individual stations in the study region (Fig. 1). Basically, various descriptions of the temporal behavior of the 10-year values of the individual stations, when plotted on base maps, suggested the existence of various regions having similar temporal characteristics, as defined by the stations within them. To further investigate areal differences on a more systematic bases, the study region was divided into six areas, as shown in Figure 1. Four equal sized (north-to-south) areas were chosen to allow for a target-control approach in the comparative analysis. Available evidence on persistent contrail frequencies across the Midwest (see Chapter 3), and on commerical jet aircraft traffic across the study region (see Fig. 2), both show that the "central" portion of this study region is the one with the greatest likely contrail influence. This central area is an east-west area bounded on the north by southern Wisconsin and on the south by southern Illinois (and also includes northern Missouri, Iowa, the northern 2/3's of Indiana, and southern Michigan). This general hypothesis of effect in the

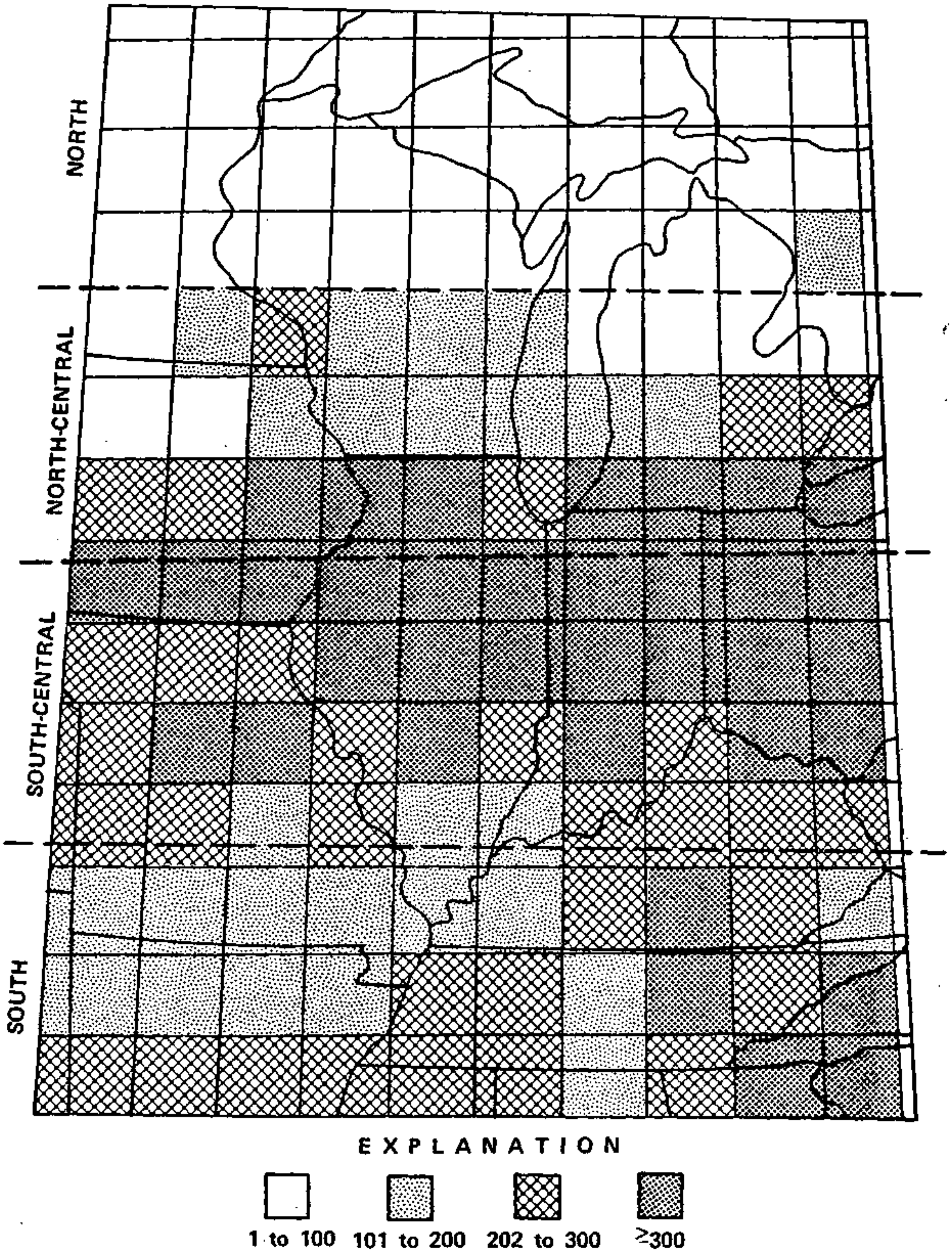

Figure 2. The daily frequency of commercial jet traffic in 1979, based on number of flights per 12, 380 km^2 area.

central areas was tested by discerning whether the frequency of sky cover conditions and sunshine in the two central area sections (labeled North Central and South Central in Fig. 1) differed from those in the northern and southern areas where less jet aircraft existed along with lesser urban industrial development. In the north and south areas there is less likely man-made effect from other causes (fewer big cities, lesser population), and any sky cover and sunshine changes there are thought to be due mostly to natural variations in climate. Hence, the areal comparisons became a major means of evaluating man-made influences in the study region.

The daily frequency of commerical jet aircraft flights across the study area in 1979 is shown in Figure 2. This was determined by measuring each of the flight tracks on a Lambert Conformal Projection, and counting these based on a grid 60 x 60 nautical miles squares. The flight data came from the August 1979 issue of the Official Airline Guide. Flights were counted only if they exceeded 200 nautical miles in length (shorter flights typically do not reach contrail producing levels). The ending or starting 50 nautical miles of each flight also were not counted since this is typically a distance of being below contrail levels (takeoff and descent for landing). The pattern of Fig. 2 clearly shows the predominance of flights in the two central areas, and particularly in the South Central Area. The averages and extremes of the grid squares in the four study areas are:

	Average	Maximum	Minimum
North Area	41	105	10
North Central	224	700	22
South Central	345	504	116
South Area*	211	508	130

Although the South Area is used as a "central area" in these analysis, the high frequency of flights in its eastern portions indicates possible contrail influences there. Also, the upper tier of squares in the North Central Area have low values suggesting a potentially lesser influence than one might expect for the South Central Area. Inspection of Figure 2 and grid areas ≥ 300 flights per day shows the east-west oriented flyway that is bounded on the north by northern Illinois and extreme lower Michigan and bounded on the south by a line through St. Louis.

Clear Day Results

Annual results. At all but two of these 36 stations, general downward trends in clear day frequencies were found during the 1901-77 period. Only Cairo, Illinois and Green Bay, Wisconsin (Fig. 1) had essentially flat unchanging trends in clear days. Curves of the average annual frequencies of clear days of the four areas are shown in Figure 3. Essentially, frequencies were highest in the 1901-1940 period; followed by sharp declines during the 1940's; followed by a flatter trends since 1950. Notable on these time curves are the regional climatological differences with higher frequencies in the south and the least number of clear days in the north. The concern over the effects of the city-to-rural site changes of the stations seems of little consequence in the 1940's. The visibility improved at a time when clear skies decreased greatly indicating little effect on the sky cover observations.

Also notable on the graph (Fig. 3) are other temporal features. For example, the high value of 1931-40 in the South Central Area (with decreases existed in other areas) is a reflection of the severity of the drought of the

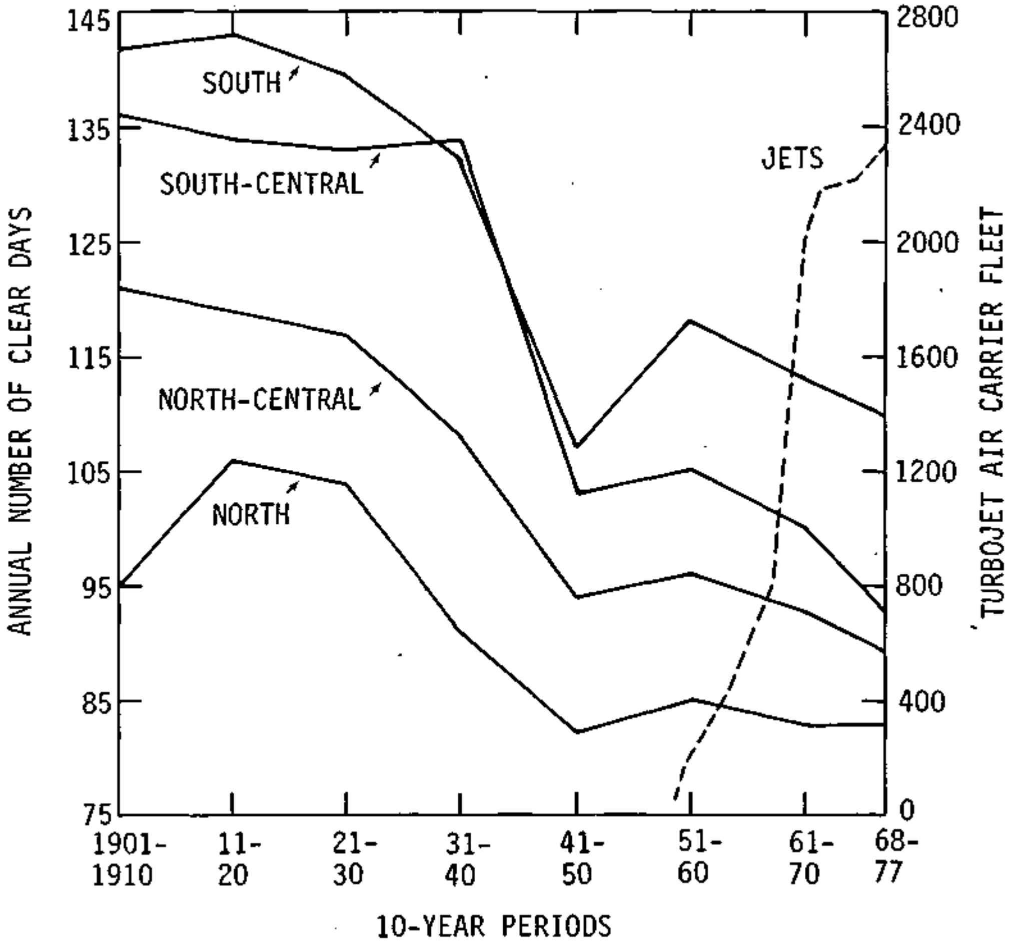

Figure 3. Area near 10-year values in clear days.

1930's in that area, as opposed to other parts of the region where it was less severe. Quite likely, there was less industrial development in that southern area in the 1930's than elsewhere.

Following the major decrease to the low number of clear days in the 1941-50 period (which was also a notably wet decade in the Midwest), slight increases in the annual number of clear days occurred for the following decade, 1951-60. This was followed by decreases having different rates (by area) since 1960. The greatest rates of recent decrease are found in the two "target" areas, the North Central and South Central Areas. The declines are much sharper during the last 10 years, 1968-77.

In one sense, the shapes of the 1901-77 frequencies of clear days (Fig. 3) fall into three types. The first of these is a general smooth downward trend from 1901 to 1977 shown by the North Central Area. Another type is a downward trend showing the lowest values of the study period to be in 1941-50. It is found both in the North and South Areas. The third type has several trends and two minima, with a major low in 1941-50, and then a subsequent greater low in the 1970's. It is reflected in the South Central Area curve. Differences between the curves shown on Figure 3 are very important, indicating different climatic regimes or influences for clear days in the two central areas. Their clear day values and those to the north and south show differences after 1940 (greater decreases in the two central areas) suggesting man-made influences in these two central areas. Both central areas are more industrialized, have greater population centers, and have more contrail producing aircraft traffic (Fig. 2).

The regionality of the annual clear day results is further reflected in Figure 4. Here, the characteristics of the trends in annual clear days for the 1901-77 period are shown, as based on the characteristics found in the 36

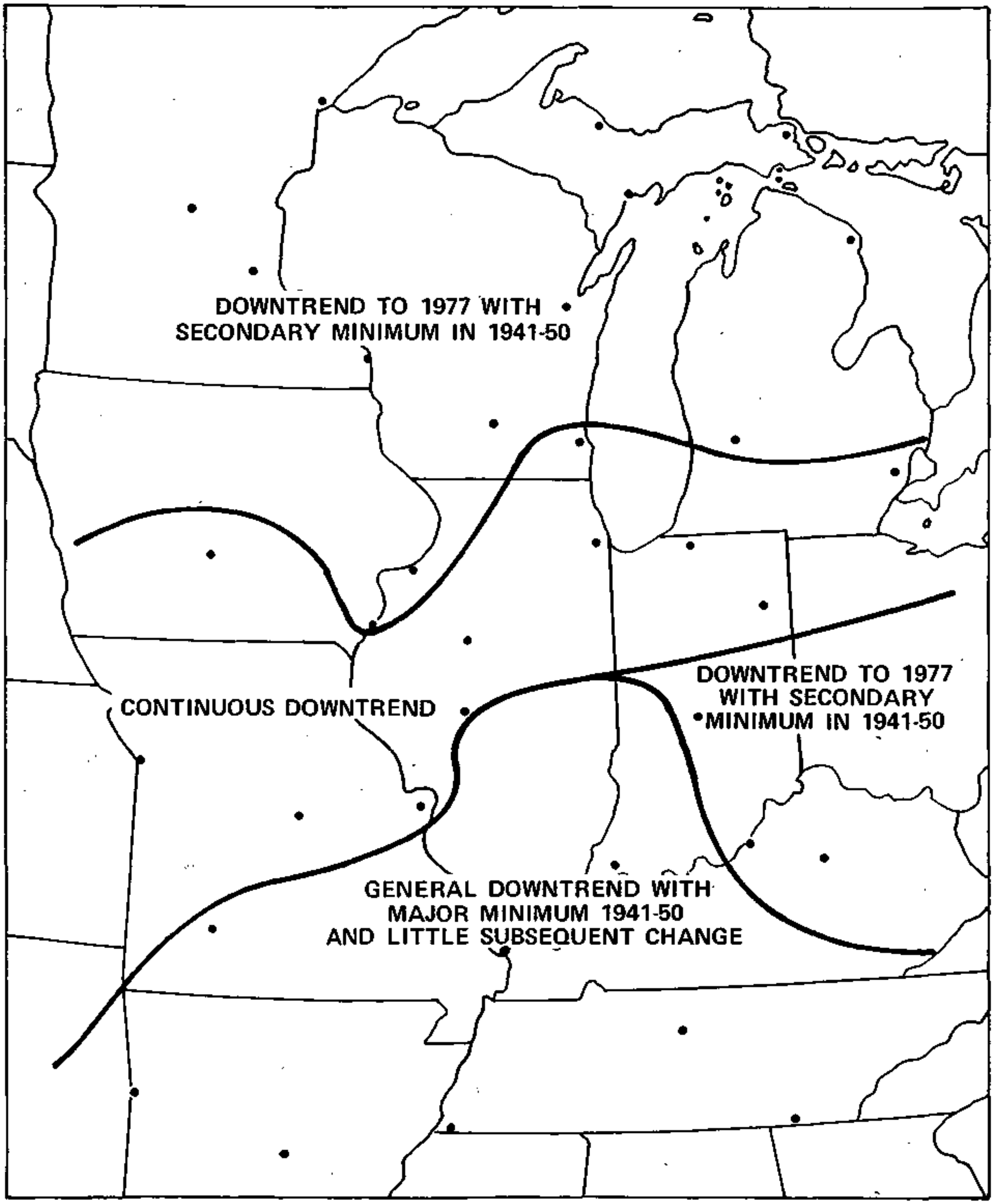

Figure 4. Characteristics of trends in annual clear day frequencies for 1901-1977 period.

individual first-order station (10-year) curves. Through the central section, a continuous downtrend is evident and it occurs where the greatest air traffic exists. To the north and to the southeast of that area, the station curves showed a downtrend to a minumum in the 1970's but with a major secondary minimum in the 1941-50 period. To the south, there is a general downtrend but with the major minimum occurring in 1941-50. Hence, Figures 3 and 4 reveal that there have been two major minima found at most stations in the study region, one coming in the 1941-50 period and one in the 1968-77 period.

Another means for displaying the regionality of the clear day frequencies is portrayed in Figure 5. Here, the year ending the lowest 10-year clear day values at the 36 stations were plotted. Regions were developed from these ending year values. One notes that a large portion of the central and eastern section of the region had its lowest 10-year frequency of clear days ending during the 1974-1977 period. However, there are other areas in the north and south where the lowest year came in the 1940's and up through 1951. One area in the west had its lowest 10-year value of clear days in 1963-65.

Table 2 presents the annual percentage changes between two decades, the earliest (1901-10) and latest decades (1968-77) for the 6 areas. These reveal that the greatest percentage decrease (32%) occurred in the South Central Area, but there was no difference on a west-east basis. The average 10-state decrease was 26%.

Comparison in the lower part of Table 2 of the annual "predicted" values reveals that the decreases between the early and late decades were 9 to 11% greater than would be expected, or predicted, on a "climatological trend basis." The predicted values shown in Table 2 were derived from a linear interpolation of the "control area" values in the north and south and are considered to be best estimates of changes due to natural variations.

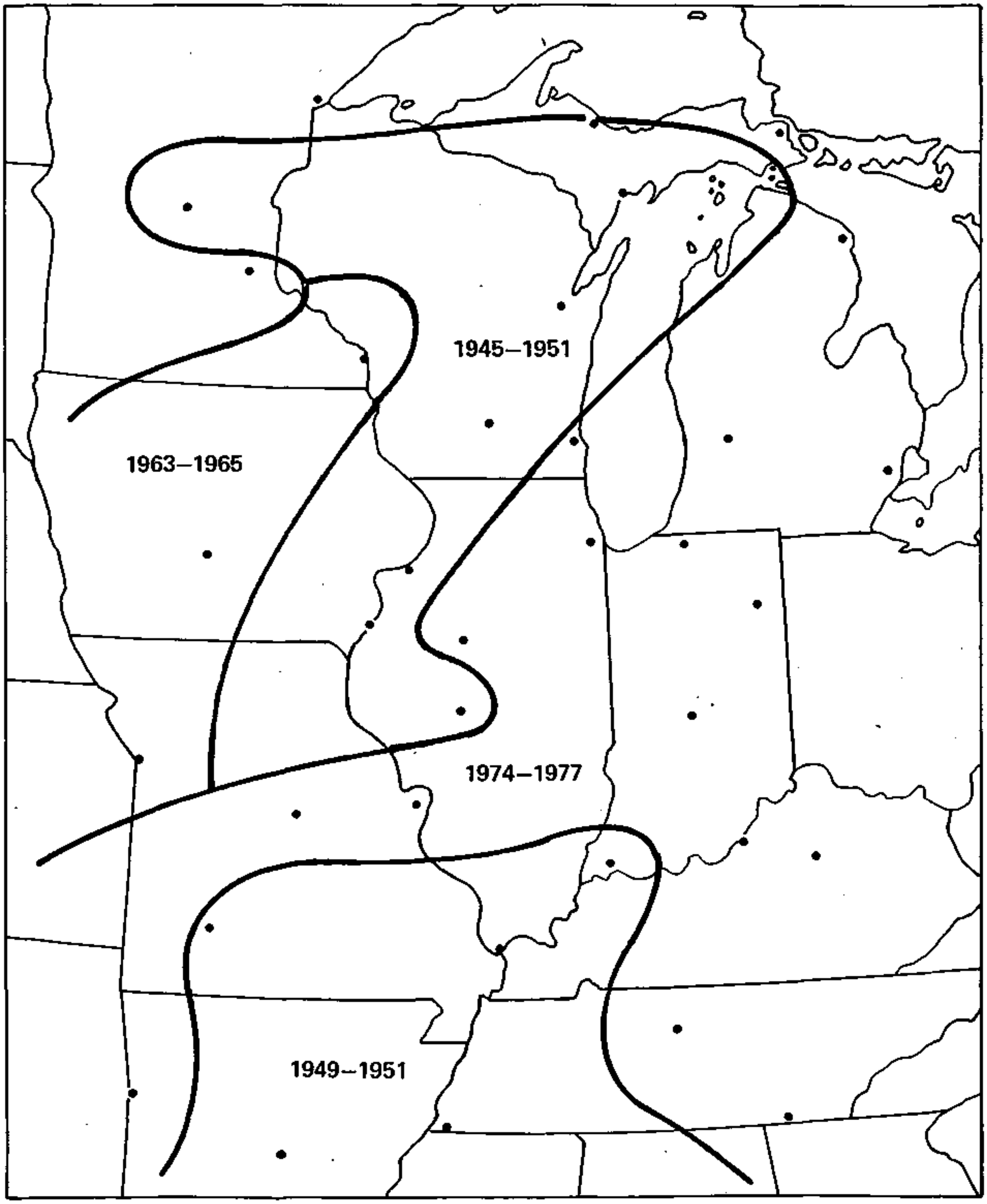

Figure 5. Areas based on ending years of lowest 10-year values of clear days (annual) for 1901-1977 period.

Table 2. Change in 10-year values of clear days from 1901-10 (early) to 1968-77 (late).

	Early-late differences X 100 Early Value				
Areas	Spring	Summer	Fall	Winter	Annual
North	-27	-23	-30	-29	-18
North Central	-23	-23	-35	-33	-29
South Central	-28	-32	-42	-29	-32
South	-13	-19	-33	-14	-22
West	-27	-28	-35	-24	-26
East	-20	-27	-35	-25	-26
Total Area	-23	-27	-35	-24	-26

	Summer			Fall			Annual		
Area	P$^{(1)}$	A$^{(2)}$	C$^{(3)}$	P	A	C	P	A	C
NC	-21	-23	+ 2	-31	-35	+ 4	-20	-29	+ 9
SC	-20	-32	+12	-32	-42	+10	-21	-32	+11

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(1)$_P$ = predicted value based on a linear interpolation between the north and south area.

(2)$_A$ = Actual area value.

(3)$_C$ = Change or difference between actual and predicted values.

Seasonal results. Area average values for 1901-77 (such as displayed in Fig. 3) were developed for each season. Basically,these showed general downtrends in all seasons.

Inspection of the areal seasonal values presented in Table 2 reveals that the least percentage change (betwen the early and late decades) occurred in spring and the greatest in fall. East-west seasonal differences are small (except in spring), but the differences among the north-to-south areas are considerable. The least changes occurred in the South Area in most seasons. The greatest percentage decreases occurred in the South Central Area in all but the winter when the greatest decrease occurred in the North Central, or other "target" area. The total area average values show that the fall (-35%) and summer (-27%) were the seasons of greatest decreases in clear days.

Shown at the bottom of Table 2 are the differences for these two seasons and for the North Central Area and South Central Area, the two target areas. The difference between actual values and the predicted values (based on climatological interpolation) revealed the "change value" believed indicative of man-made influences. These show that in the South Central Area there was an anomalous 12% decrease in summer and a 10% decrease in fall, both due presumably to man-made influences.

Since the greatest seasonal decreases, both in total percentages and those expressing potential man-made influences, were found in the South Central Area, the 10-year values of each season in that area are presented in Figure 6. These are the averages based on the 11 stations located in this area (Fig. 1). One notes a generally flat trend for 1901-1940, although winter and spring values begin to decrease after 1930. All four seasons show a marked decrease in clear days in 1941-50, followed by generally flat trends thereafter. However, the fall and summer seasons show definite decreases

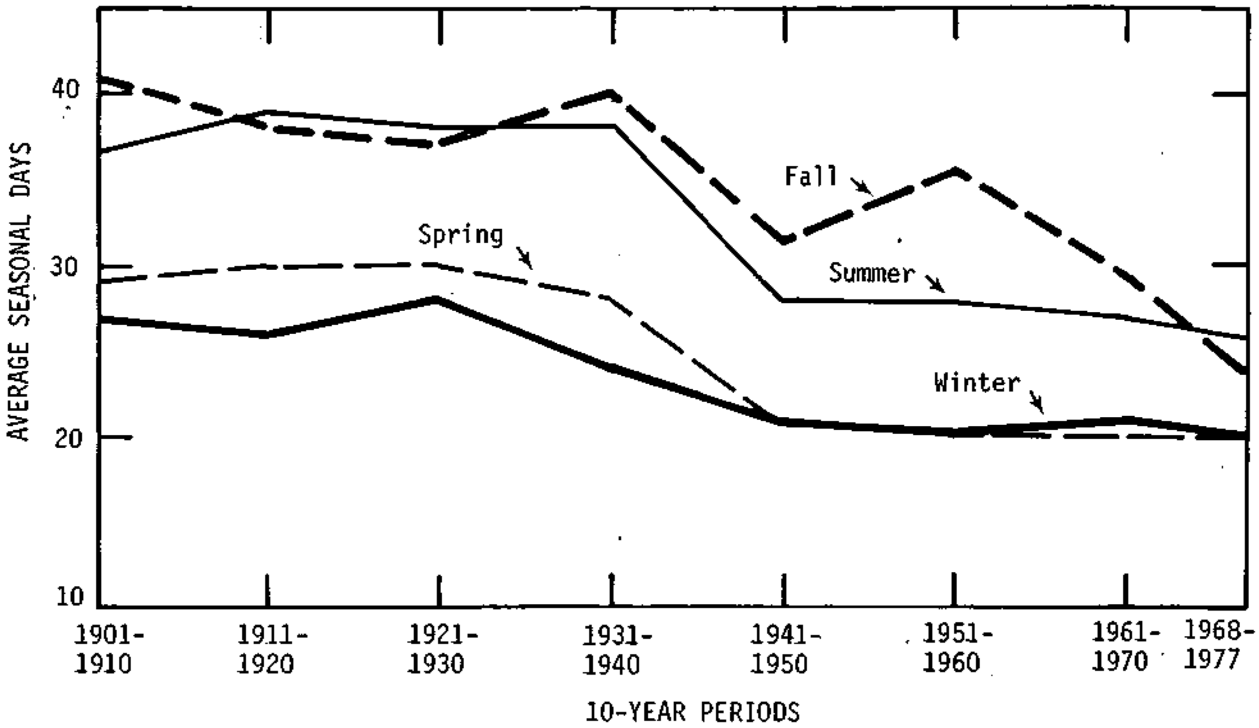

Figure 6. 10-year area mean values of clear days in South Central Area.

after 1960 in the number of clear days, but the winter and spring frequencies remained constant after 1960. Since jet aircraft traffic in the area increased sharply in the early 1960's, the values shown for 1961-70 and for 1968-77 are potentially related to contrail effects and might be reflected in the number of seasonal clear days. The summer decrease in clear days over this South Central Area went from 28 days in 1951-60 to 25 days in 1968-77 (a 3-day decrease). The fall season change went from 35 days in 1951-60 to 24 days in 1968-77. Both seasons exhibit their 77-year minima in the last 10 years.

In general, the seasonal curves of Figure 6 strongly suggest a man-made influence leading to a decrease in clear skies beginning in 1941 and likely related to the great expansion of industrial activity related to WWII and which continued thereafter. The more recent decreases shown since 1960 may be a mixture of effects of the greater urban growth and the jet contrail influences.

Summer season. Analysis of the individual stations and their summer frequencies of clear days was revealing. In Figure 7, the 10-year values of three stations selected from the north, southeast, and southwest parts of the study region are presented. Inspection of these trends reveal interesting differences; for example, the Minneapolis frequency of summer clear days fluctuates but has no discernible up or down trend during the 77-year period. However, both the Columbia and Evansville curves exhibit down trends with a much greater down trend at Columbia, ranging from 39 clear days per summer in 1901-10 to 25 clear days per summer in 1968-77. Evansville, which has a minimum in recent years, had its greatest minimum in 1941-50.

The characteristics of the curves of summer clear days of the 36 stations were plotted to develop a regional map. The general characteristics of the trends in summer clear days frequencies is shown in Figure 8. Major down

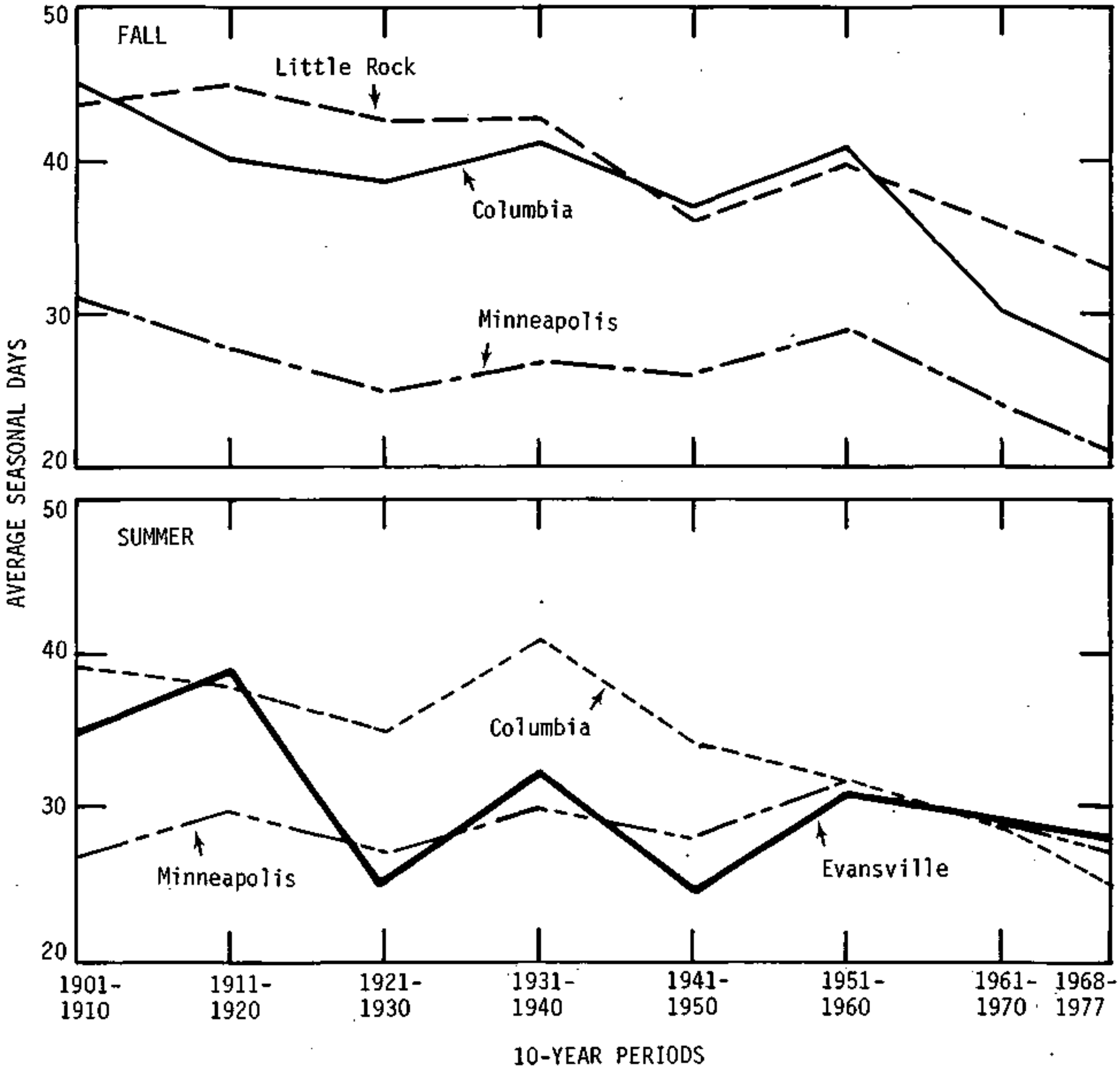

Figure 7. 10-year values of clear days in summer and fall at selected stations.

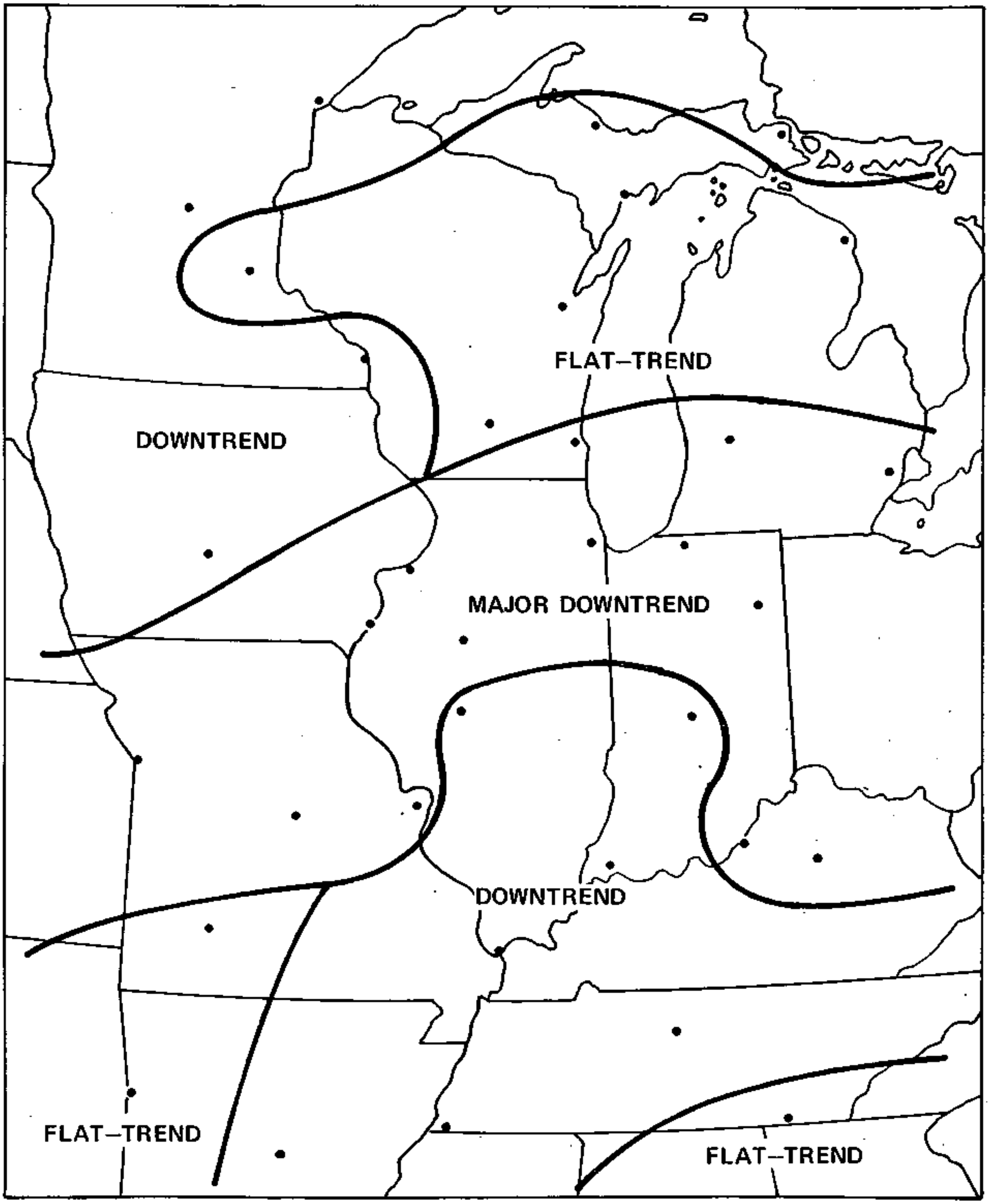

Figure 8. General characteristics of trends in summer clear day frequencies for 1901-1977 period.

trends (as revealed by the Columbia curve in Fig. 7) were found along an east-west corridor through the central section. Lesser downtrends were noted in the northwest and south central districts, with essentially flat trends in the northern, southwestern, and southeastern sections. The pattern of Figure 8 is suggestive of man-made influences, with the greatest downtrends occurring where the major jet air traffic exists (Fig. 2), as well as in the major industrial section of the 10-state region.

Fall season. Individual curves of the 36 stations for their frequencies of clear days in the fall season revealed downward trends everywhere. Examples of the curves of three stations are shown in Figure 8. The values at Minneapolis (North Area) indicate a generally flat trend through 1960 followed by a decrease in recent years. The Little Rock (South) and Columbia (South Central) curves also show recent decreases, but with a much greater downtrend in the recent 20 years at Columbia. In general, the trends in the central areas of the study region showed considerably decreases, particularly since 1960, in frequencies of clear days.

Winter season. The South Area stations showed decreases in clear days to around 1950, followed by up trends to the present. In the central area most stations revealed a maximum of clear days in 1921-30, followed by decreases during the decades thereafter. Five stations had their lowest frequency of winter clear days in 1968-77 including Peoria, Columbia, Des Moines, Ft. Wayne and South Bend. The northern stations indicated flat trends in winter clear days. There appears to be little evidence, other than at a few central stations, of any man-made influence on clear days in the winter season.

Spring season. Stations in the South Area had generally downward trends in clear days in spring until 1950, followed by uptrends to present. They were very similar to winter clear day trends in this same area. In the central section, spring frequencies of clear days generally decreased after 1920 with either a minimum occurring in 1941-50 or in 1951-60. Only a few stations (Peoria, Burlington, Louisville, and Columbia) had their lowest values in the 1970's. In the north, spring values showed decreases and long-term downward trends. Several stations reached their lowest values in the 1970's. In general, the spring results of clear day frequencies were not strongly suggestive of localized influences throughout the North Central or South Central target areas.

Cloudy Day Results

Annual values. The 10-year values of cloudy days for the four areas are shown in Figure 9. All four areas have notable upward trends from 1901 to 1977. The total area average increase (Table 3), or difference between the earliest and latest decades is 41%. In general, the cloudy day curves of Figure 9 exhibit more smooth and notable trends than do the comparable annual clear days curves of Figure 3. The cloudy day values are more indicative of a general, long-term climatic change than are the clear-day frequencies because part of the shifts are in partly cloudy conditions as well as clear conditions. Further comparison of the curves in Figures 3 and 9, such as those for the North Area, reveal a good inverse relationship, particularly up through 1960. It is important to also note that both the "target areas," the North Central and South Central Areas, exhibit sizeable increases in cloudy days in the last decade, 1968-77, particularly evident in comparison with the lesser up trends for this North and South Areas for this period.

Inspection of the annual values in Table 3 also reveals that it has become relatively cloudier in the south, central, and west areas with a lesser increase in cloudy days in the eastern and northern areas of the study

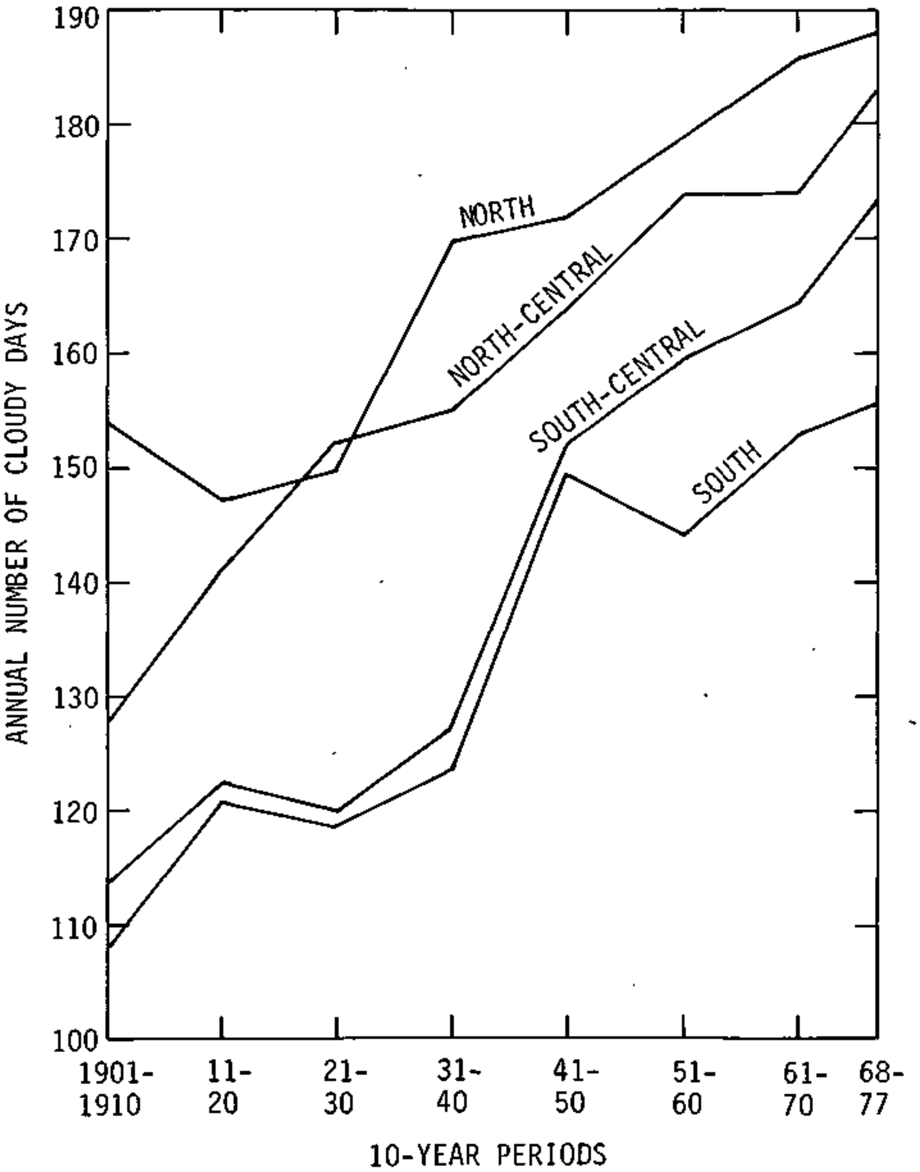

Figure 9. Area mean 10-year average annual values of cloudy days.

Table 3. Changes in 10-year cloudy day frequencies from 1901-10 (early) to 1968-77 (late).

	$\frac{\text{Early-Late Differences}}{\text{Early Value}} \times 100$				
Area	**Spring**	**Summer**	**Fall**	**Winter**	**Annual**
North	+21	27	21	22	22
North Central	+38	52	52	33	43
South Central	+41	82	91	30	53
South	+25	69	86	21	44
West	+41	58	65	32	46
East	+28	52	42	24	33
Total Study Area	+34	56	60	27	41

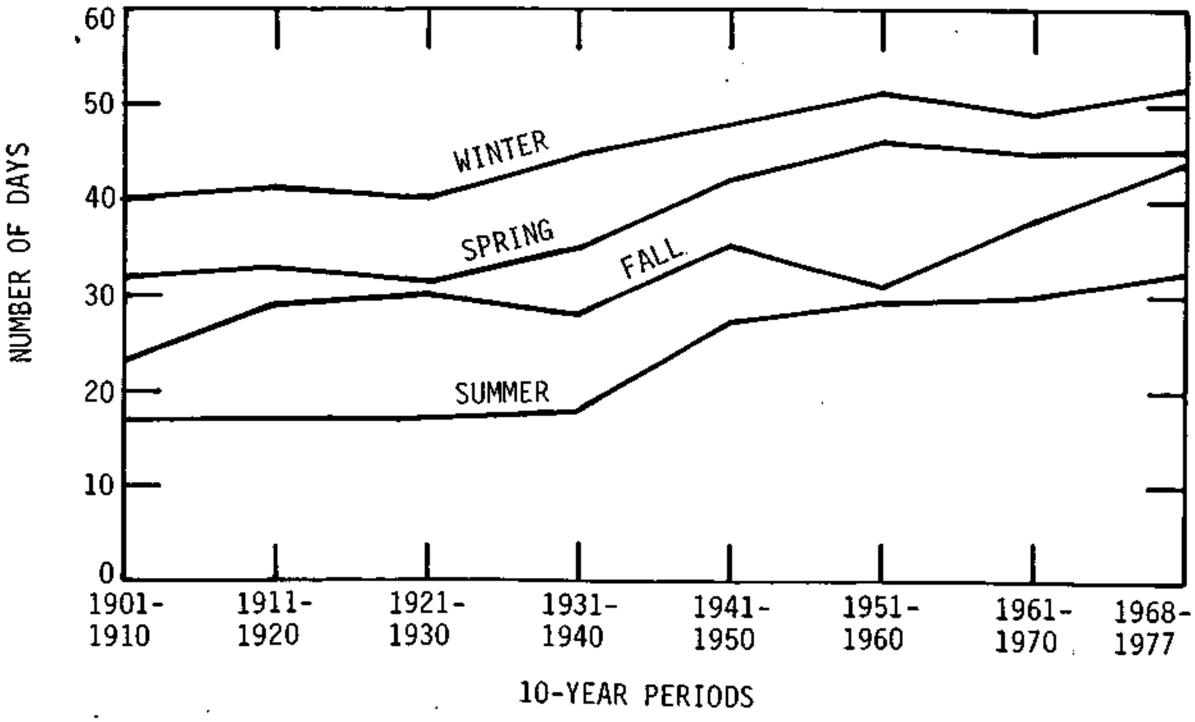

Figure 10. Seasonal area mean frequencies of cloud days in South Central Area.

region. This is, the areas that in the early part of the 20th Century were the clear, less cloudy areas have become cloudier faster than the areas which were, on the average, cloudiest (north and east).

This suggests, as do the later results of greater increased cloudiness in summer and fall seasons, that the additional cloudiness has been occurring in these areas and seasons which normally are most clear. This indicates that whatever the causes, the influences are more obvious during periods and places which in the past have been more clear. This is supportive, in general, of the type of influence that added high clouds could be expected to produce. Additions of high clouds in areas and times that are already relatively cloudy would be less noticeable than in relatively clear areas.

Seasonal results. The trends in cloudy day seasonal values at most stations in the 10-state region were generally flat during the 1901-40 period. They then began to increase, particularly in the South and South Central Areas. Please note these features in the seasonal curves (Fig. 10) . As shown in Table 3, the greatest changes percentagewise in cloudy days from the early decade (1901-10) to the latest decade (1968-77) occurred in the fall season. The total area average increase is 60%, closely followed by summer with 56%, with much lesser increases in spring and winter. The percentage changes shown in Table 3 for cloudy days are much greater than those shown for clear days (Table 2), except in the North Area where the clear day percentage changes exceeded those for cloudy days in spring, fall, and winter.

As with clear days, the percentage changes in cloudy days were greatest in the South Central Area in all seasons except winter when in the North Central Area was greatest. There are also west-east differences shown in all four seasons with the greatest increases found in the western region in all four seasons. It is important to note that the South Central percentages approach 100% for summer and fall. Thus, there have been notable increases in cloudy days in this area of greatest jet aircraft traffic.

The North and South Areas were considered to be control regions and either non-affected by contrails, or less affected by contrails than the atmosphere over the North Central and South Central Areas. Thus, their values were used as controls to estimate the likely "natural variability values" for the North Central and South Central Areas. The differences calculated between these climatologically predicted (interpolated) values and the actual values for the North Central and South Central Areas are an indication of possible man-made influences.

Table 4 shows the changes in the two central areas for all four seasons, based on the comparison of the predicted and actual values. The changes indicate anomalous increases in the recent decade in all four seasons with about 10% being representative of the regional value of increases in the spring and winter. However, in the fall and summer seasons, the South Central Area had about 26 to 27% anomalous increases in cloudy days with about 10% in the North Central Area. The annual values in Table 4 suggest a 14 to 17% anomalous increase in cloudy days over that expected. Hence, results indicate the greatest potential influence has occurred in the South Central Area.

As a result the South Central Area seasonal curves are presented in Figure 10. These indicate a generally flat trend until 1930, or 1940, followed by increases in cloudy days, generally sizeable for the 1941-50 period. The fall and summer season curves also show substantial increases after 1960. These are not found in the spring and winter seasons. The shift from 1960 to 1977 in the cloudy day values in fall is from 31 days to 44 days (up by 13 days), and in the summer the shift is from 29 days to 32 days.

Table 4. Comparison of predicted and actual percentage changes from 1901-10 to 1968-77 in cloudy days.

	Spring			Summer			Fall			Winter			Annual		
Area	P(1)	A(2)	C(3)	P	A	C	P	A	C	P	A	C	P	A	C
NC	26	38	+12	41	52	+11	43	52	+ 9	22	33	+11	29	43	+14
SC	30	41	+11	55	82	+27	65	91	+26	21	30	+ 9	36	53	+17

(1)P = Predicted value based on lindear interpolation between control values, the North and South areas.

(2)A = Actual area value.

(3)C = Change, or differences, between actual and predicted value.

Partly Cloudy Days Results

Comparison of the cloudy and clear day results has shown great similarity. Much of the increase in cloudy day frequencies was reflected in the decrease in clear days. Inherently this means that frequencies of days with partly cloudy skies were not changed greatly, and hence their results are not presented in great detail.

The summer season trends in partly cloudy days of the 36 stations define three areas. The area south of a line from Springfield, Mo. to Lexington, Ky., had essentially flat trends for 1901-77 in the number of partly cloudy days. The stations in the area north of a line from Burlington to Alpena also had flat trends. The remaining central area had down trends in their summer frequencies of partly cloudy days, generally decreasing by 10 to 15% from 1910 to 1977, with the lowest values in 1968-77.

The fall season trends in partly cloudy days were similar to those in summer. Moderate down trends of 10 to 20% were evident at most stations in the South Central Area. Elsewhere the 1901-77 values varied but did not reflect any down or up trend. The winter and spring frequencies of partly cloudy days showed no trends.

The down trends in partly cloudy days, reaching a low in the 1968-77 period during summer and fall, and largely within the South Central Area do suggest a contrail related influence. The most important finding is that shifts to cloudier conditions in the Midwest were largely associated with a decrease in clear days, with lesser change in partly cloudy days. This helps indicate the shift was sizeable.

Sunshine Results

Annual Results. The percentage of possible sunshine values were analyzed on an annual and seasonal basis. Additional cloudiness and loss of clear days, as shown in the previous sections, should be reflected in a decrease in sunshine, on an annual basis and all seasons, but particularly in fall and summer. The general characteristics of the trends of the annual percent of sunshine values for 1901 (or whenever records started in the 1901-22 period) to 1977 are shown by the pattern in Figure 11. The station trends were found as having a general down, up, or flat trend. Importantly, one notes the general downward trend throughout the central section where clear day trends were downward (see Fig. 4). To the north and south of this central area (the major jet flyway as shown in Figure 2, and urban-industrial section of the study region) one finds either flat or upward trends in the sunshine data.

The years representing the year ending the lowest 10-year percent of sunshine value in the 20th Century are shown in Figure 12. This pattern strengthens the trend results showing the lowest values have come in the late 1970's in the central section and largely where jet traffic is greatest. In other areas to the north and south of the central section, the major minima occurred in a variety of other years, but mainly in the late 1940's as with clear days. In general, the sunshine results and clear days results are remarkably similar indicating equal quality of both sets of data.

The changes in the annual 10-year percent of sunshine values, between 1921-30 (early) and 1968-77 (late) were quantified, as shown in Table 5. The annual values, although much less percentagewise than those found for clear days or cloudy days, do show greater decreases in the central target areas than those in the north and south control areas. Comparison of the

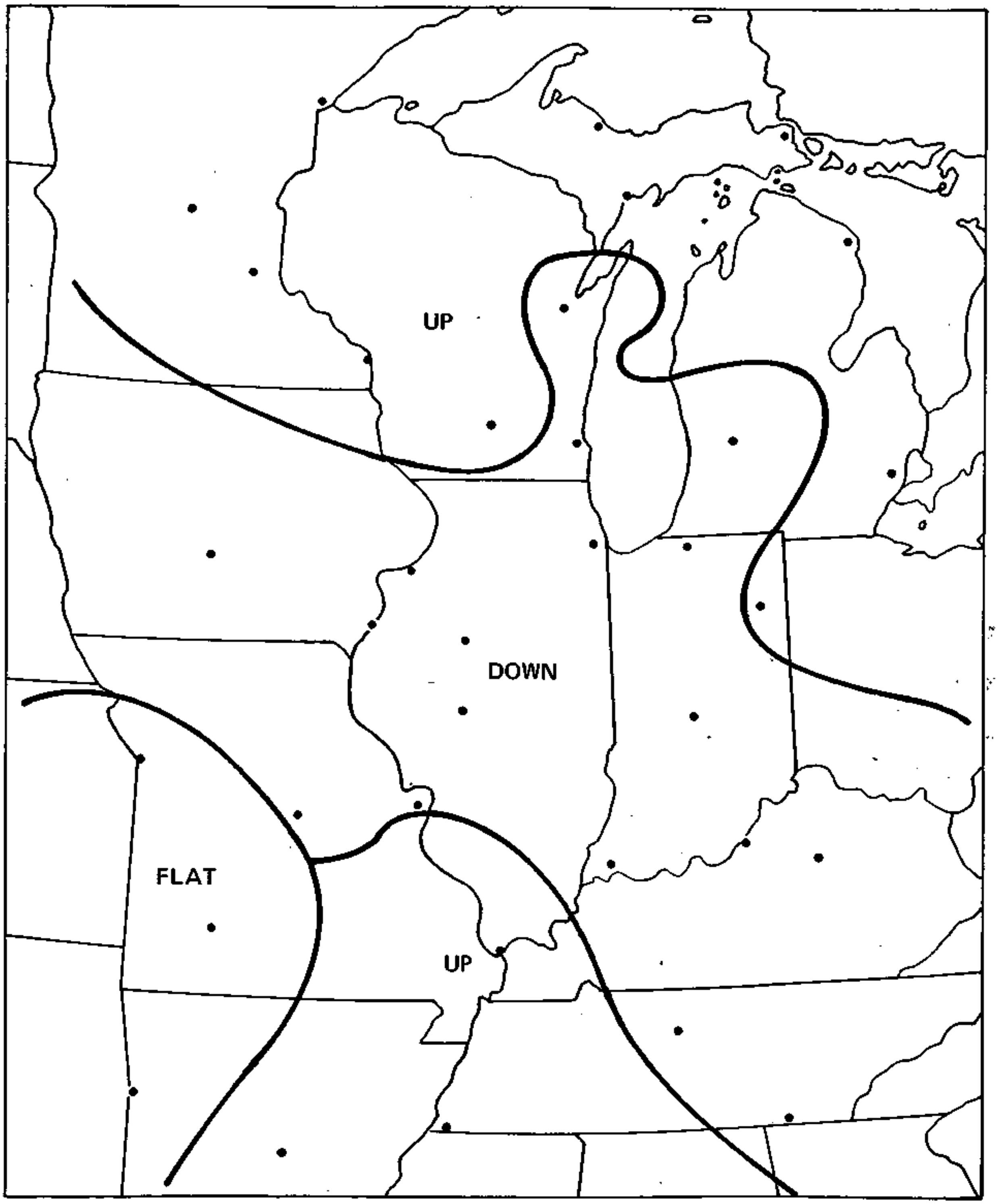

Figure 11. General characteristics of trends of annual percent of possible sunshine values for 1911-1977.

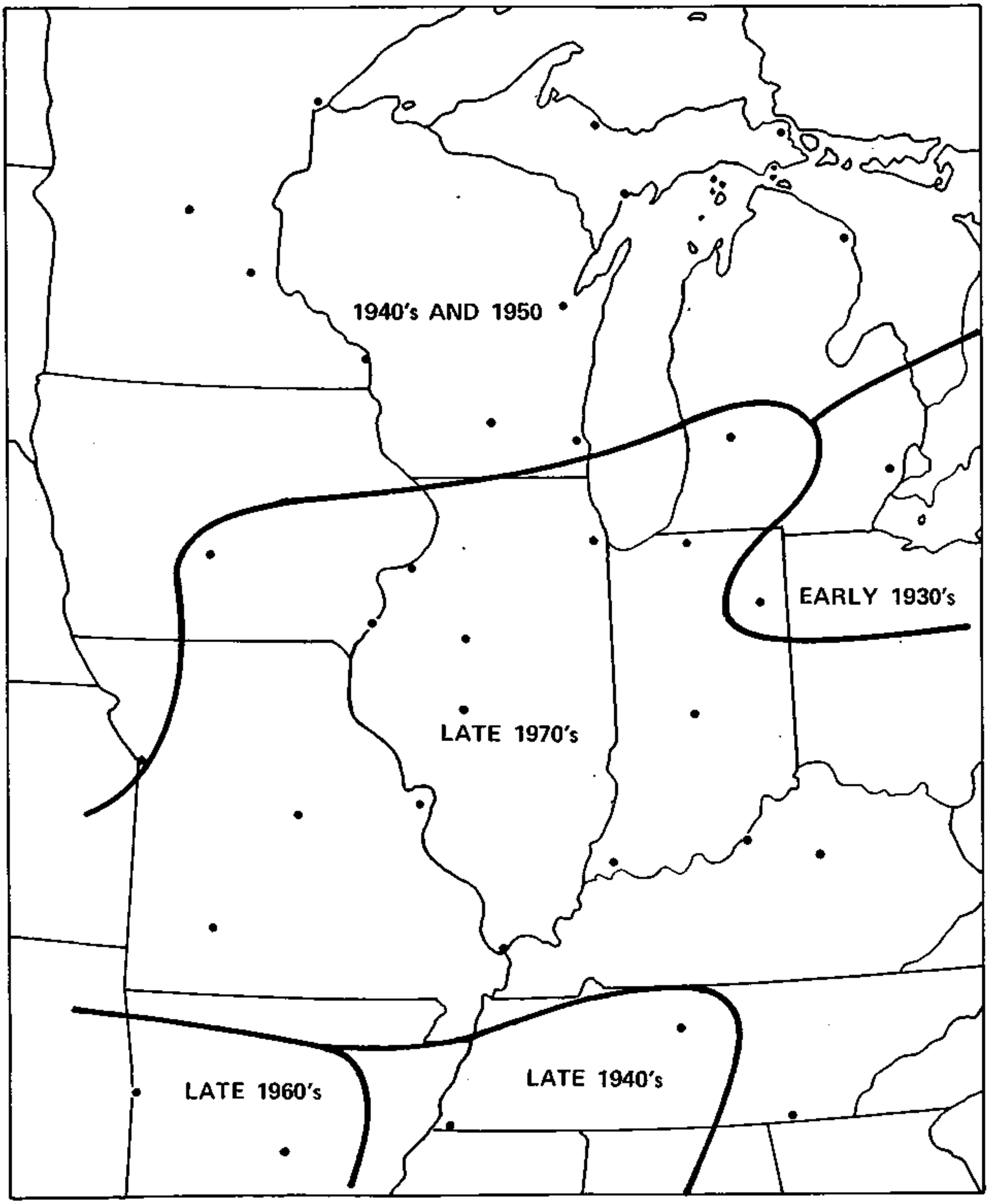

Figure 12. Ending year of lowest 10-year values of annual percent of possible sunshine in 1901-1977 period.

Table 5. Changes in 10-year average percent of sunshine values from 1921-30 (early) to 1968-77 (late).

$$\frac{\text{Early-Late}}{\text{Early Value}} \times 100$$

Area	Summer	Fall	Annual
North	+2	0	-2
North Central	-3	- 9	-4
South Central	-4	-10	-6
South	-1	- 6	-2

	Summer			Fall			Annual		
	P(1)	A(2)	C(3)	P	A	C	P	A	C
North Central	+1	-3	-4	-2	- 9	-7	-2	-7	-2
South Central	0	-4	-4	-4	-10	-6	-2	-5	-4

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(1) P = Predicted value based on linear interpolation between central values, the north and south area.'

(2) A = Actual area value.

(3) C = Change.

"predicted" and actual annual values in these two "target areas," shown in the lower part of the Table 5, indicates a change in sunshine of 2% in the North Central Area and a 4% decline in the South Central Area. The shift in the annual sunshine values is further illustrated by the area curves shown in Figure 13. They all show a decrease from 1921 through 1950, with a notably sharp decrease in 1941-50, as found in the sky cover conditions. Furthermore, the North Central and South Central Areas show reductions in 1968-77 that are greater, however, than in 1941-50. The other, control areas have their lowest sunshine values in 1941-50.

Summer. Inspection of the area summer curves for 1921-77 in Figure 13 reveals most stations had down trends in the summer percent of possible sunshine. The curves of the individual stations were analyzed for their trends and a map based on their trends is shown in Figure 14. Again, the central area had down trends, with essentially flat or up trends found to the north and south. As shown in Table 5, the downward trends of 3 to 4% in the North Central and South Central Areas were estimated as being 4% more than climatological prediction suggested, reflecting potential man-made influences.

Fall. Downward trends in the percent of sunshine in the fall season are noted in most areas for the 1961-77 period (Fig. 13). Only the North Area has no downward trend. Station trend values were used to develop Figure 15 showing the patterns of general trends in fall sunshine for 1921-77. Here, again we note the downward trend through the central area with flat trends to the north and to the southwest. As shown in Table 5, the net effect of the fall sunshine trends is to produce an estimated 6 to 7% decrease in sunshine in the North and South Central Areas considered due to man-made influences. The sunshine decrease in the last 17 years and in the period of jet air traffic -suggests a contrail-related influence on sunshine in the fall.

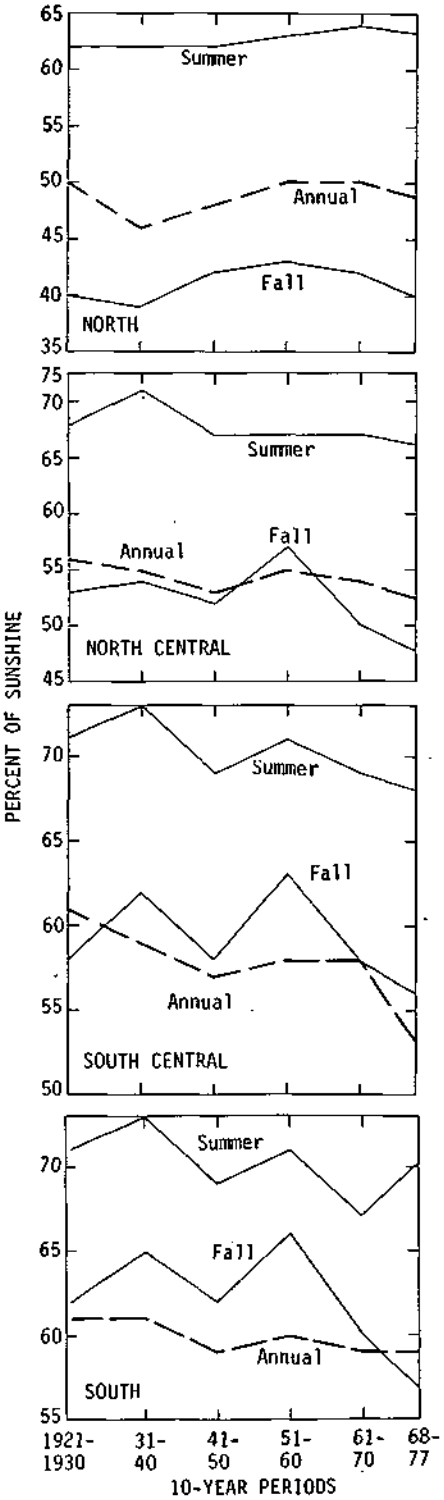


Figure 13. 10-year values of percent of possible sunshine in 4 areas.

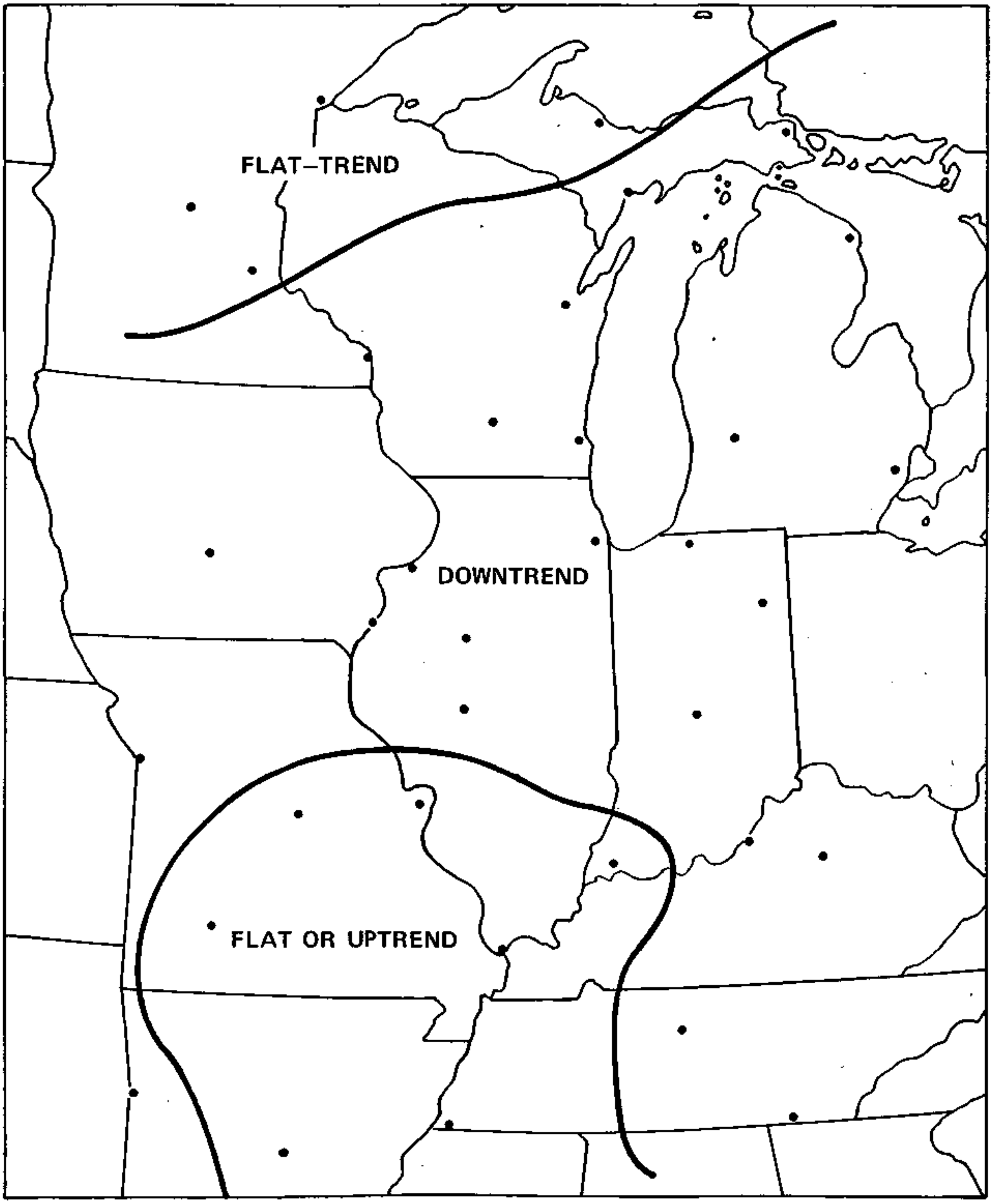


Figure 14. General trends in summer sunshine percentages from 1911 to 1977.

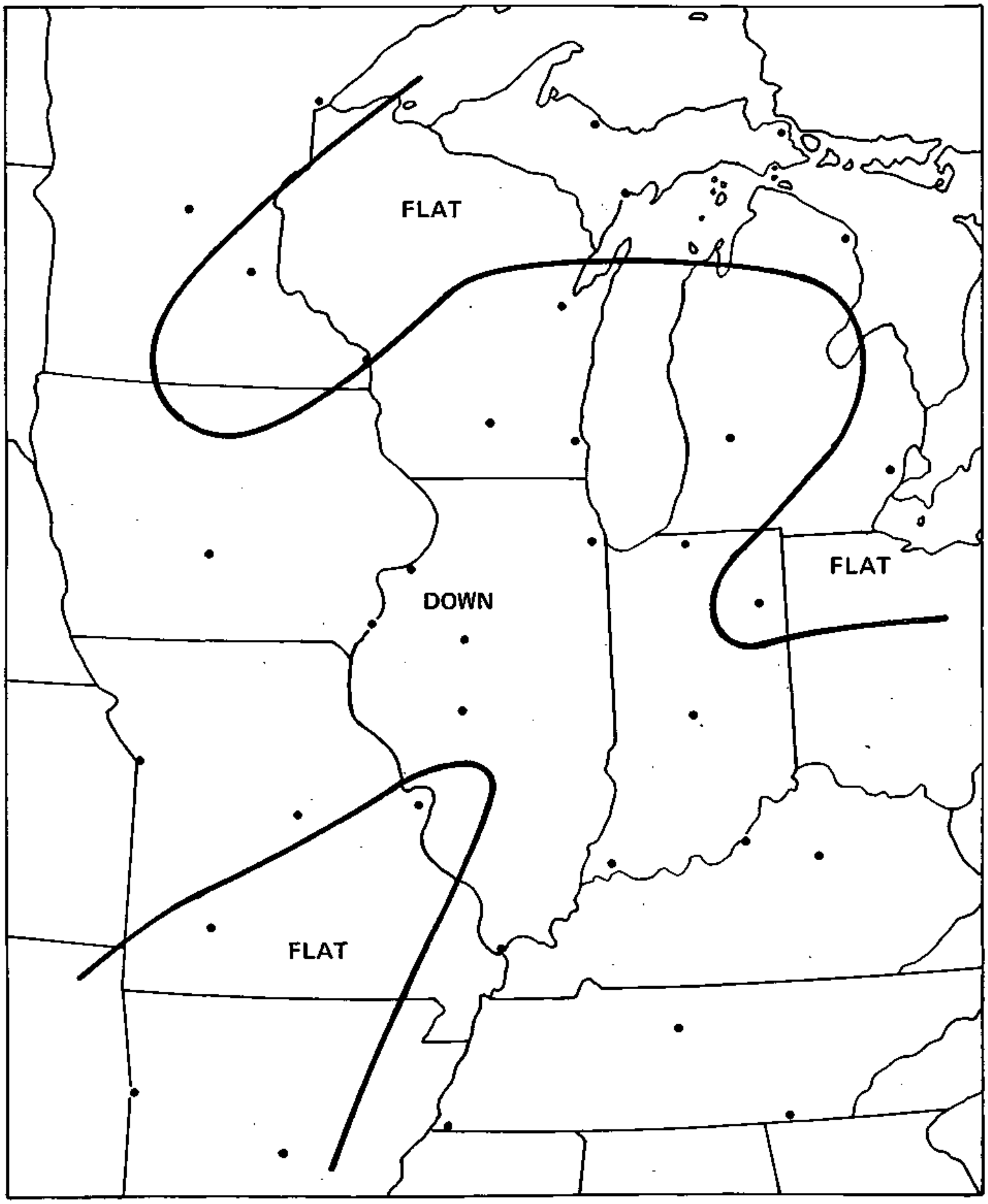


Figure 15. General trends in fall sunshine from 1911 to 1977.

Temperature Results

Much has been presented in the last 25 years about man's impact on weather and climate. It has been clearly demonstrated that man has altered his urban climate so as to significantly change the surface temperature and most other local weather features (Changnon, 197'3) . The fluctuations in global temperatures over the last 90 years have been partially ascribed to man's activities and principally to the release of pollutants to the atmosphere (Mitchell, 1971). The recent increase in moderated (less extreme) temperatures in parts of the Midwest may also reflect a climatic change that appears to be partially attributable to various man-made conditions.

There are two commonly cited hypotheses for how man's pollutants may affect surface temperatures to produce either warming or cooling. First is a belief that the particulates in the atmosphere absorb and reflect incoming visible solar radiation leading to a reduction in solar energy received at the earth's surface, thus resulting in cooling. However, Mitchell (1971) has shown that man-made aerosols in the troposphere may serve to increase surface temperatures in certain areas, whereas aerosols in the stratosphere lead to cooling. Secondly, direct thermal pollution and gases in the atmosphere, such as CO_2 which is opaque to long-wave radiation (re-radiated from the earth), can produce a "greenhouse" effect leading to an increase in surface temperatures. Bryson (1972) claimed that both inadvertent cooling and inadvertent warming conditions have existed in the 20th Century helping to produce initially about 1.0 C warming (1900-1945) and a subsequent 0.4 C cooling since the 1940's.

An interesting possibility relating to increased atmospheric pollutants, both particulate and gaseous, concerns their potential for moderating extremes of temperature. If the incoming solar energy is reduced by particulates during the daytime, the period of maximum heating, then the maximum temperature values would be reduced. If gases are sufficient to decrease the amount of outgoing radiation, particularly at night when minimum temperatures normally occur, then an increase in temperatures might be expected. Certainly, other man-made factors such as increased cloudiness would have a similar "thermostatic" effect since clouds reflect solar radiation and also decrease outgoing terrestrial radiation. In fact, some of the increased cloudiness, at least in recent years, has apparently resulted a) from contrails produced by high altitude jet aircraft, which have been estimated to have increased high-level cirrus clouds by 5 to 10% (Bryson *et al*., 1970), and b) from the added man-made particulates which have furnished more cloud condensation nuclei and ice nuclei to aid low and middle level cloud development.

These possibilities for man-induced moderation of temperatures were investigated by use of 70-year sets of records from several relatively undisturbed weather stations from small midwestern towns. Since contrail influences are believed to produce only subtle temperature changes, stations were selected that had long undisturbed records and were without any major urban influences on them. Several of the stations selected were identified by the National Weather Service as national bench-mark stations, i.e., high quality stations. Other stations were carefully selected for analysis by knowledge of their quality and lack of station relocations. These form N-S and E-W lines across the study region, and their locations are shown in Figure 16.

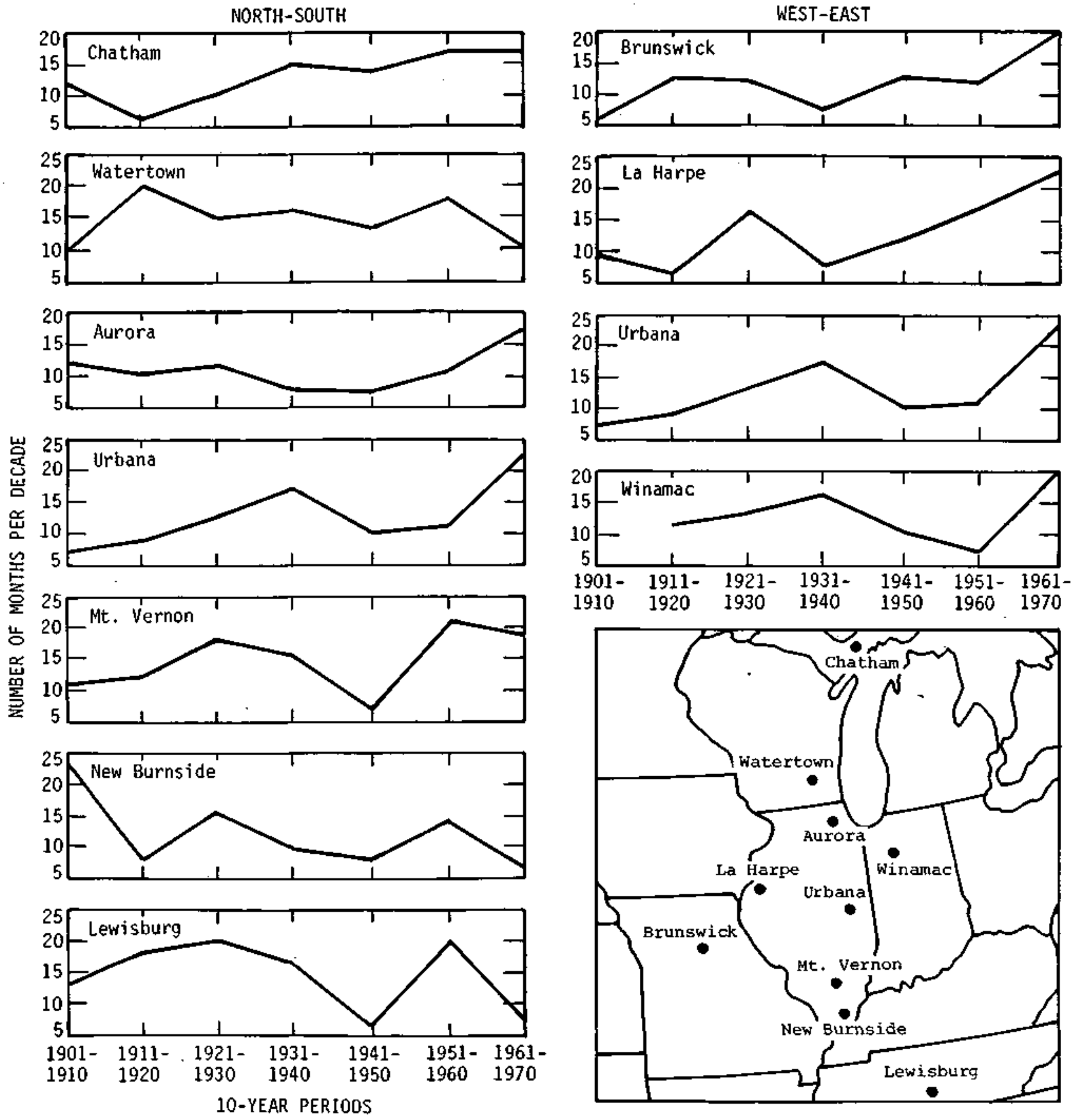


Figure 16. Decadal frequencies of months with moderated temperatures.

Months having both 1) below-normal average maximum monthly temperatures, and 2) above-normal average minimum monthly temperatures were selected to indicate a period of reasonably prolonged moderation of temperature. The monthly temperature data for the 1901-1977 period were examined to identify those months with moderated temperatures.

The seasonal frequencies of these moderated months in 10-year periods are displayed in Table 6. They occurred most frequently in summer (June-August) and fall (September-November). The annual average, based on the 70-year values in Table 6, ranges from 11 to 14 months of moderated temperature per decade about 10 percent of the time). If the departures of the maximum and minimum temperatures were independent events, the probability of a moderated month would be 0.25, or they would occur 25 percent of the time instead of 10 percent. Thus, the incidence of moderated temperatures is not a common event.

Comparison of the decade totals in Figure 16, based on stations aligned along north-south and west-east lines, reveals that stations in the central area exhibited sharp increases in months with moderated temperatures during 1961-70. Stations to the south and north did not. Stations along the east-west line where contrail production is greatest (Fig. 2) all showed a notable increase in moderated months in 1961-70, the period when jet aircraft traffic significantly increased. Comparison of the temperature frequency curves in Figure 16 with those for cloudy days (Fig. 9) reveals general agreement. Since the increased cloudiness in the 1961-77 period may likely be a result of the contrail induced cirrus in the central area, it appears the effect has at least partially caused a moderation of temperatures.

Further study involved comparison of the Urbana temperatures with the sky cover conditions (frequencies of cloudy days) at Peoria. Peoria is located 110 km (75 miles) northwest of Urbana and its cloud cover values should be

Table 6. Seasonal frequency of months with moderated temperatures (max < normal with min > normal) in 1901-1970.

	Average number of months per 10-years				
	Sp	Su	F	W	Annual
Chatham, Mich.*	4.0	3.1	3.1	2.9	13.1
Urbana, Ill.*	2.4	4.4	4.1	1.8	12.7
Brunswick, Mo.*	1.6	3.4	4.6	2.1	11.7
Lewisburg, Tenn. *	2.6	5.3	4.1	2.4	14.4
Dixon, Ill.	3.0	3.6	4.4	3.0	14.0
Aurora, Ill.	3.1	3.0	3.6	1.7	11.4
La Harpe, Ill.	2.3	4.6	4.0	2.1	13.0
Mt. Vernon, Ill.	2.5	4.9	4.8	2.3	14.2
New Burnside, Ill.	2.5	4.4	3.0	2.3	12.2
Winamac, Ind. (1910-70)	2.4	4.5	5.1	2.2	14.2
Watertown, Wis.	1.6	3.8	3.7	1.5	10.6

*Bench-mark Stations.

representative of those at Urbana. Comparison of the cloud conditions and the moderated temperature frequencies for 1901-73 (Fig. 17) reveals that the increase in moderated temperatures at Urbana is partially related to a changing frequency in cloudy sky conditions. The correlation coefficient of the two sets of annual values is +0.1 indicating that the cloudiness explains about 25 percent of the variance in the 75-year record of frequency of moderated temperatures. However, of importance is the fact that the highest values of both conditions occurred together and in the last few years (Fig. 17). The spectacular increase in cloudiness since the 1940's is a matter of considerable interest.

Examination of whether the moderated temperature increases at Urbana relate to particulate and gaseous pollutants (and not clouds) was limited to use of the only long-term records potentially indicative of such pollutants, the frequency of days with haze and smoke at Peoria. These are only a gross measure of the visible pollutants but were examined realizing they may be an index representative of regional pollution influencing Urbana. The smoke-haze curve in Figure 17 shows an increase in the visible atmospheric pollutants during the 1930's, and then again in more recent years. The correlation between the annual values of smoke-haze days and the frequency of moderated temperature months was 0.32. Although the Peoria smoke-haze frequencies are only an index of pollution, and may not represent conditions at Urbana, a weak relationship does exist between their frequencies, suggesting that man-made pollutants may have caused some of the recent doubling of months with moderated tempertures at Urbana.

The peak of smoke-haze conditions in the 1931-40 period (Fig. 17) is not entirely relatable to atmospheric pollutants from combustion, particularly since industrial activity in that period was considerably less than in

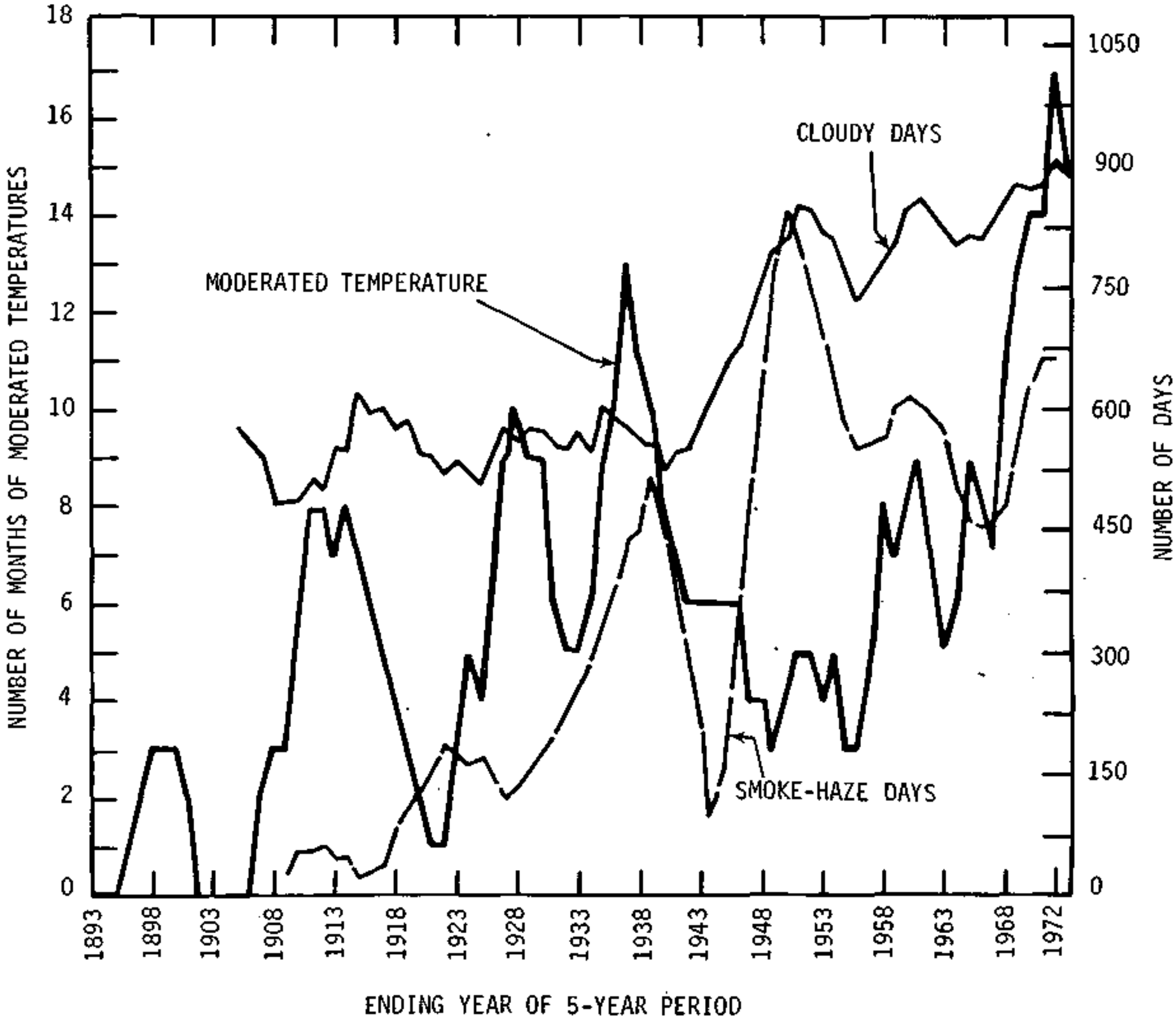


Figure 17. 5-year values of moderated temperatures at Urbana, and cloudy days and smoke-haze days at Peoria.

subsequent decades. However, the 1931-1940 period had record droughts in Illinois and the central United States. These droughts resulted in enormous dust storms creating large volumes of dust particles in the atmosphere which also cloud serve to reflect incoming solar energy and possibly to inhibit long-wave radiation. A means of further investigating this dust explanation for more moderated temperatures in both the 1930's and 1960's is to look at dust "indicator" data for Peoria (dust storms are defined on a daily basis when dust limited visibility during the day to 1/2 mile or less). The number of dust storm per decade since 1905 were 0 in 1911-20, 0 in 1921-1930, 25 in 1931-40, 7 in 1941-1950, 0 in 1951-1960, and 1 in 1961-1970. The singular peak in dust storms activity in the 1930's may help explain the peaks during that period in the frequency of moderated tempertures (Fig. 17), and in the smoke and haze days, since haze is closely related to dustiness.

The added cloudiness and the increase in visible pollutants, both partially man-made, together explain some 45 percent of the fluctuations in the moderated temperature frequencies since 1900. However, these two factors both relate well to the recent (post 1960) large increase in moderated temperatures. This suggests that recent mad-made activities have been reducing temperature extremes, but it is not clear exactly how much of the noted recent change is due to man-made conditions as opposed to natural climatic variation.

A plot of seasonal decadal values of moderated temperature months for three central area stations (Fig. 18) reveals that the total (annual) increase with time, apparent in Figure 16, is largely due to recent increased frequencies in the summer and fall seasons. Little change with time is noted during spring with a decrease at some stations in the 1961-1970 decade. The winter frequencies are uniformly low with an increase in the last 10-year

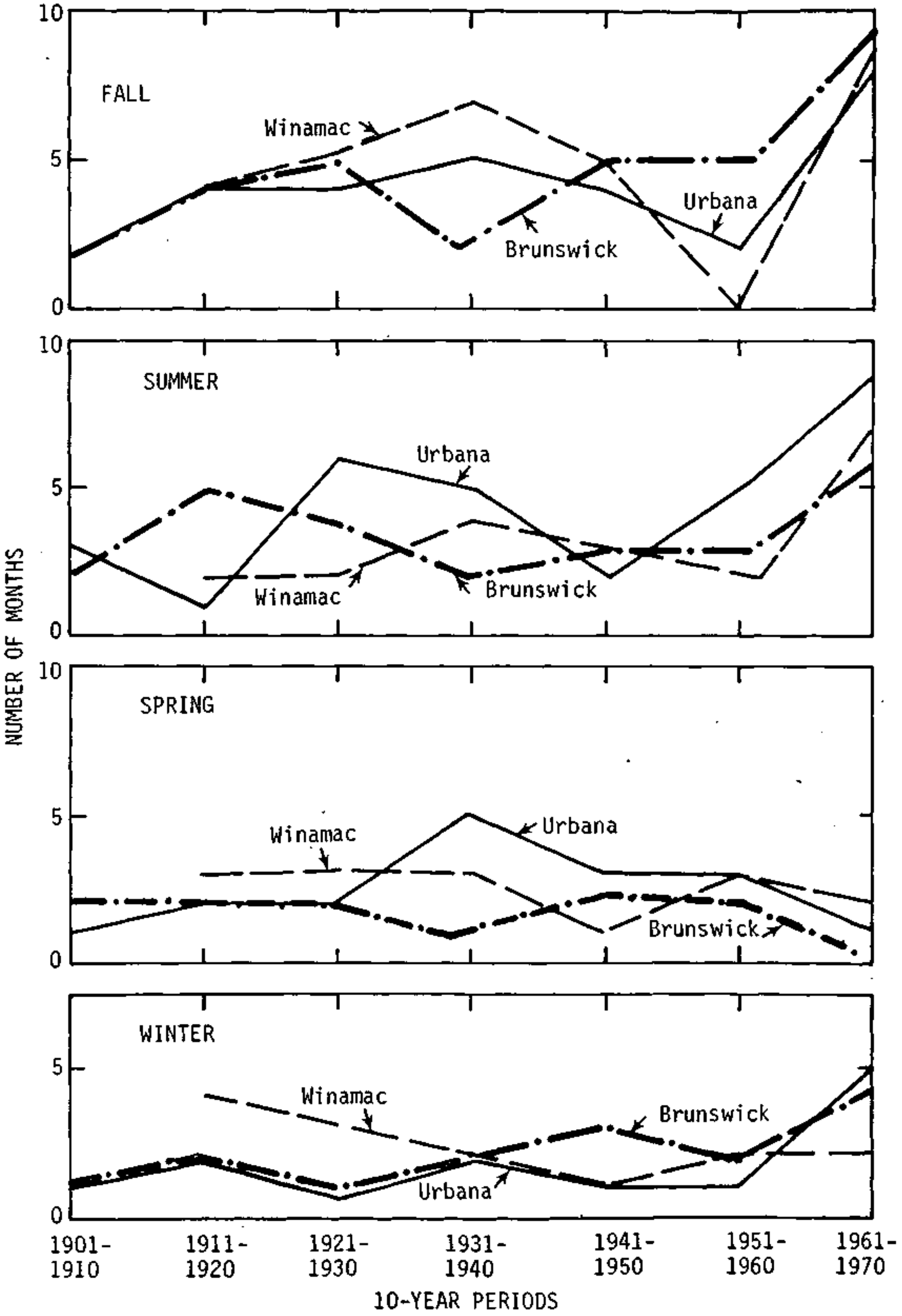


Figure 18. Seasonal frequencies of moderated temperatures at Urbana, Ill., Winamac, Ind., and Brunswick, Mo.

period at 2 stations. Seasonal frequencies for. cloudy skies in the Peoria area showed increases since the 1940's, but the greatest seasonal increases occurred in summer and fall when the moderated temperature increases were found to be greatest. The similarities in the seasonal frequencies between the four stations located along a 1000 km east-west line (Fig. 18) help reveal the regional nature of the temperature influence in the central area (Fig. 1). The seasonal results further support the conclusion that recent increases in cloudiness are largely responsible for the increase in moderated temperatures. Pollutant-related haze seems a less likely cause.

Precipitation Effects

This study did not have as an objective a search for contrail influences on precipitation. However, the decided downward trends in frequency of clear skies and increased cloudy skies, led to a comparison of precipitation with clear sky frequencies at two Illinois stations. The 10-year values of precipitation and the frequencies of clear days were derived for Peoria and Springfield, for 1901-1970, as well as the 7-year value (for 1971-77). This series of eight independent values at each station are plotted on Figure 19. This scattergram indicates a weak relationship between the frequency of clear days and annual precipitation and the correlation coefficient is -0.45. As expected, less precipitation occurs when more clear days occur. This finding suggests that the decrease in clear days found at these stations and elsewhere in the central areas of the Midwest since 1960, is related to a period of greater precipitation, and may reflect part of the cause of more precipitation.

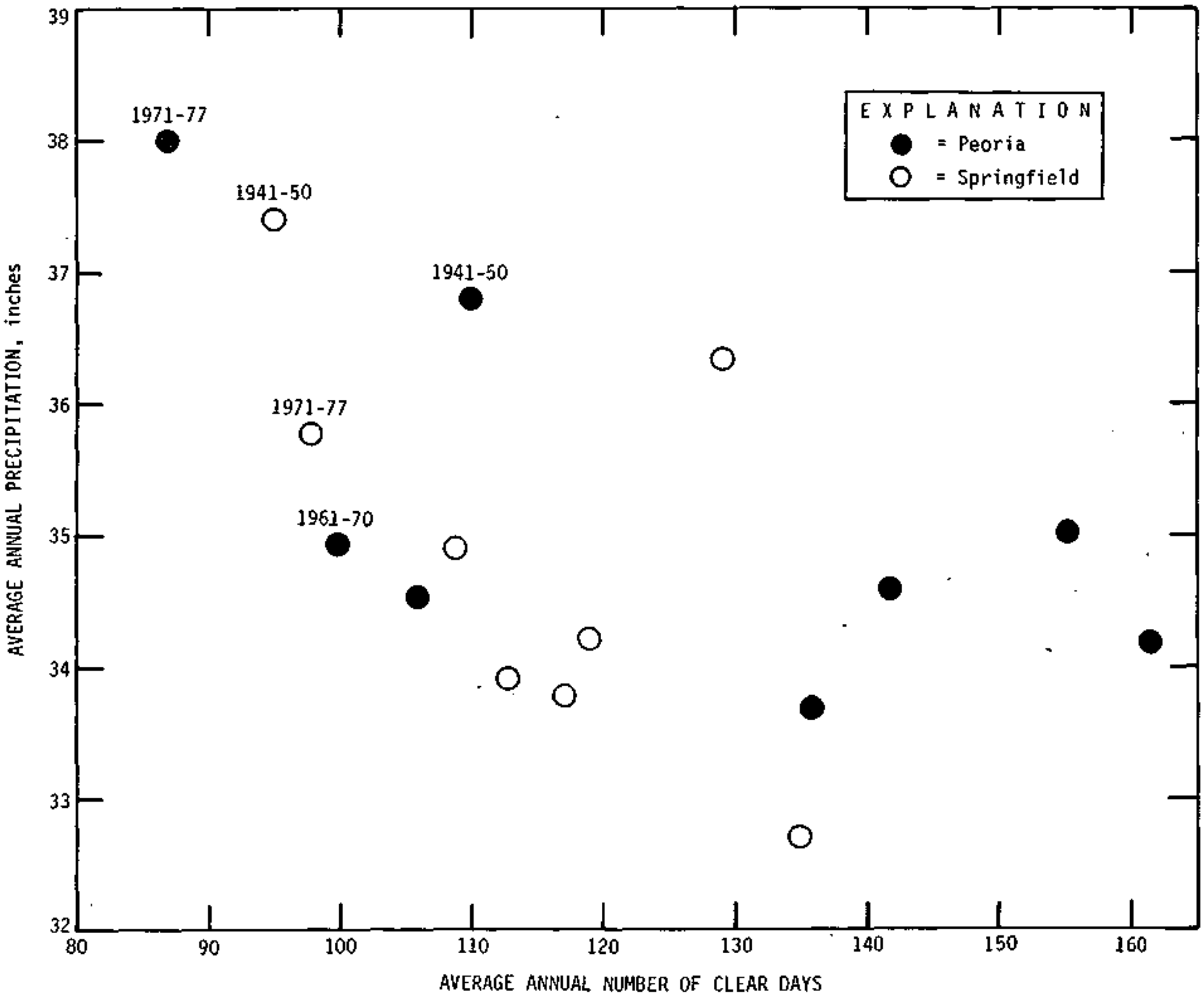


Figure 19. Relationships between clear day frequencies and precipitation at Peoria and Springfield, Ill.

Conclusions

The sky cover frequencies and sunshine values indicate sizeable changes during the 1901-77 period. These occur in most midwestern areas and in most seasons. Basically, the frequency of clear days and the percent of possible sunshine have decreased substantially since 1930, although the sunshine has decreased less than the clear day conditions. Conversely, the cloudy day frequencies have increased but at a greater rate than the clear day frequencies. The partly cloudy frequencies have decreased slightly in the central areas in summer and fall.

The biggest shifts in sky cover and sunshine occurred across the North Central and South Central Areas. These also happened to occur in the periods of jet air traffic and the greatest urban-industrial development. The biggest shifts in sky cover and sunshine also occurred in the fall and summer seasons, when conditions normally are least cloudy. The sunshine changes are totally restricted to the central area and strongly point to regional man-made (not natural) influences. The sunshine decrease from 1920 to 1977 was 4 and 7% in summer and fall, respectively. Cloudy days revealed an anomalous shift from 1910 to 1977 with areal increases varying from 11 to 27% in the summer, and from 9 to 26% in the fall. Clear days and partly cloudy days exhibited lesser shifts, decreases of 10 to 20%, in summer and fall.

Recent upward trends in cloudiness (and decreases in sunshine) have been particularly notable in fall and summer and within the Midwest's central section (across the northern half of Missouri, Illinois, and Indiana, and the southern halves of Iowa, Wisconsin, and lower Michigan) were jet air traffic is greatest and also where urban-industrial development has been greatest in the Midwest.

It was hypothesized initially that the causes of marked shifts in midwestern cloudiness and sunshine could be attributed to any one of three factors. The first of these was natural causes, i.e., short or long term climatic changes on areal scales much larger than that in the study region. The second cause could be attributed to errors in observation or in the sunshine instrumentation. The third possible cause of trends includes inadvertent, man-made influences which could be subdivided into a pollutant-related decreases in visiblity, and radiation, pollutant-related influences on clouds, and a jet contrail influence on clouds.

The results collectively suggest that all of these causative factors were operative in the study region. For example, long-term trends were found in the frequency of cloudy days in all four areas. This suggests a natural large-scale shift in the climate, probably extending over large portions of North America during the 1901-77 period. However, such long-term trends were not found in the sunshine frequencies. Secondly, within the long-term trends in the sky cover conditions are two major anomalies, one of which is found in the sunshine data of certain areas and seasons.

A major anomaly noted was a sharp shift to more cloudiness during 1941-50. This occurred at a time when there was great urban-industrial expansion in the Midwest, and also when most observation stations were relocated from city sites to airport sites. Such a move to more rural sites should have improved sky visibility but occurred at a time when production of pollutants (as reflected in haze-smoke days) was rapidly increasing across the region.. For this and other reasons, the error-related explanation for the trends was discarded. Since the 1941-50 anomaly was most pronounced in the more heavily populated urban industrial parts of the Midwest, it appears that this shift may be due largely to the effects of man-made pollutants acting to decrease visibility of clouds, to decrease incoming sunshine, and to assist in the formation of clouds. The marked increase in frequency of days with haze and smoke in the 1935-1950 period agreed very well with the shifts in sky cover, but not in sunshine. Thus, some of the change at this time was due to pollutants effect on visibility and possibly on low clouds (and not on high clouds).

The other notable anomaly found in the general long-term trends in sky cover and sunshine occurred principally in the central section. It was a decrease in clear skies and sunshine beginning about 1960, and reaching the lowest values since 1900 in the late 1970's. Importantly and conversely, in other areas to the north and south of the central Midwest, the clear day frequencies have increased since they achieved quite low values in the 1940's. This anomaly of the last 15 to 20 years also has occurred largely only in the fall and summer seasons, normally the seasons of clearer skies. There is much indirect evidence pointing towards contrail-related influences in this anomalous period and area. If true, the contrail influence has represented a 5-10% change in the sunshine, clear day, and cloudy day frequencies. Influence on sunshine is less than on cloudy conditions presumably because on many days with contrail cirrus the sunshine still penetrates and is recorded.

The three primary findings of this study are as follows. There has been 1) a long-term trend toward more cloudiness over the 1901-77 period (not as evident in sunshine), 2) a sharp increase in cloudiness during 1941-50, and 3) a second anomalous increase in cloudiness (and decrease in sunshine) in the central sections of the Midwest from 1961 to the end of the study period (1977). The first of these three findings is believed to be a part of a general climatic trend with the last two apparently related to inadvertent man-made influences (pollutants beginning in 1940 and now contrails in more recent years).

The influence of these trends is reflected in surface temperature extremes (less extreme minimum and maximum monthly averages) which have generally increased with time. At weather stations in the central area of the Midwest, increases in moderated temperatures occurred in the 1940's with the anomalous increase in cloudy conditions believed to be related to the massive release of pollutants that began at that time. Finally, moderated temperatures occurrences have shown a sudden upswing in the same area since 1960, which relates well with the decreased sunshine and increased cloudiness noted in this period. In addition, the increased frequency of moderated temperatures since 1960 has occurred largely in the fall and summer, the same seasons when the cloud cover increases were noted. The results are internally very consistent.

These results alone, particularly those relating to the increased cloudiness since 1960, cannot be considered proof of a jet contrail influence. However, this anomalous change is regionally restricted to that area of the Midwest where jet traffic is the greatest, but this may still represent only a natural regional scale fluctuation of sky conditions. Other results of this project presented in later chapters help define the potential of contrail influences on a) cloudiness, b) sunshine received, and c) surface temperatures during this apparent anomalous period that began around 1960.

CHAPTER TWO

CLOUD TYPE CLIMATOLOGY OVER THE RESEARCH AREA

Introduction

The observational data available for the first order stations shown in Figure 20 were used to study the trend of cloud types during the 26-year period 1951-1976. The frequency of types were categorized by standard definition into the simple categories of low, middle, and high clouds according to standard observational definitions. The 3-hour observation times throughout the 24-hour day were used to obtain frequencies for the classes of clouds involved. A fourth class, the frequency of clear sky observations is also included since it may be a sensitive parameter for the determination of long-term trends in cloudiness.

The stations used for this limited study included Duluth, Minnesota; Sault Ste. Marie, Michigan; Madison, Wisconsin; Des Moines, Iowa; Chicago, Illinois; Peoria, Illinois; Springfield, Illinois; St. Louis, Missouri; Ft. Wayne Indiana; and Evansville, Indiana. These provided sufficient density to examine a north-south variation in cloudiness extending from Lake Superior to the Ohio River and a similar east-west transect from Des Moines to Ft. Wayne. In referring to Figure 2, the stations extend across a high density traffic area, i.e., an area of high potential contrail formation. The observed traffic density suggests the use of Duluth and Sault Ste. Marie as controls against which the trends of cloudiness at the central Midwestern stations can be compared.

In this chapter the temporal trend of individual cloud types will be examined culminating in two stratifications of high cloudiness in an attempt to identify an indicator of contrail activity. The parameter used is the

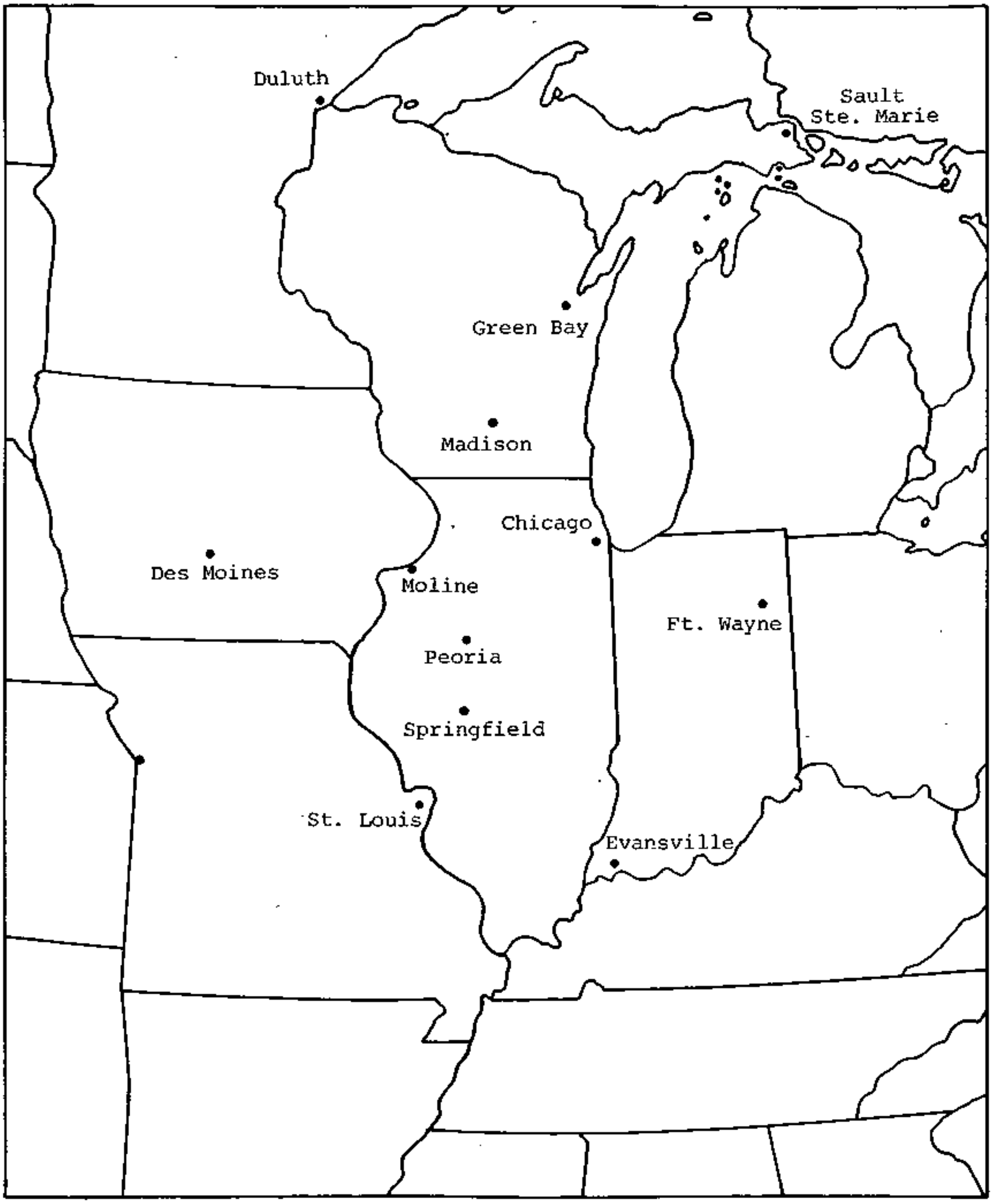


Figure 20. The Midwest area of study with the first-order weather stations used in the cloud-type frequency analysis.

slope of the trend line generated by the data over the 26-year period although further detailed analyses might suggest that shorter interval trend lines may illuminate certain features not readily apparent from the entire period.

Low Cumulus Cloud Frequency Trend

An example of the trend of low cumulus cloud frequency at Peoria, Illinois is shown in Figure 21. The correlation coefficient for the trend line was 0.63. The trend line intercepts the year 1951 at a frequency of 350 and extends upward to 400 at the end of 1976. These end point numbers are an indication of the general climatic variation of cloudiness over the broad area encompassed by this study and are shown for each of the stations in Table 7. The slope of low and middle clouds should represent the climatic trend, i.e., a control, not influenced by jet contrails. The lowest frequency in 1951 was observed at Sault Ste. Marie with a value of about 189 with the highest value of 432 at Springfield, Illinois. Three stations showed negative slopes, that is, decreasing cloudiness, and all others showed increases of low cumulus clouds over the 26-year interval.

The geographic variability of the trend line slope is shown in Figure 22. The pattern reveals the negative slopes for the trend of cloudiness at Springfield, Des Moines, and Duluth with high positive slopes eastward over most of Illinois, Indiana, and northern Michigan. The greater positive slopes are evident from Des Moines southeastward and from St. Louis northeastward merging over central Indiana.

The significance of the study of the low cloudiness trend is to qualitatively assess the potential effect on the observational quality of the high level clouds, including contrails. The high positive slopes of the low

Table 7. The trend line point values of annual cloudiness over the Midwest for 1951 and 1976.

		FTW	DSM	PIA	SSM	MLI	SPI	MDW	MSN	STL	E W	GRB	DLH
Low Strat	1951	1101	1013	838	1514	873	902	1100	1130	1008	1039	1140	[1436]
	1976	1557	1016	1265	2054	1067	1189	1276	1232	1023	1268	1141	[1411]
Low Cu	1951	336	[381]	343	189	408	[432]	305	310	320	371	337	[420]
	1976	344	[354]	443	293	517	[397]	314	352	426	402	354	[357]
Middle	1951	[756]	[925]	[840]	680	839	[978]	[774]	[923]	[846]	[807]	[860]	[1039]
	1976	[752]	[822]	[819]	760	903	[821]	[741]	[739]	[799]	[543]	[728]	[745]
High	1951	615	981	807	522	712	858	676	786	904	761	724	816
	1976	1027	1098	1060	874	1042	1044	935	1038	984	912	847	1038
£0.4 L&M	1951	474	770	652	432	566	675	512	626	697	628	567	620
	1976	768	816	819	649	788	797	690	785	702	678	641	728
£0.4 L&M	1951	254	439	382	209	291	400	231	347	337	[340]	[333]	362
<HC	1976	338	441	390	327	443	407	348	378	351	[335]	[299]	416
Clear	1951	[533]	[553]	[472]	[406]	[707]	[661]	[634]	[537]	[717]	[711]	[544]	336
	1976	[469]	[595]	[555]	[295]	[542]	[550]	[430]	[514]	[655]	[667]	[522]	415

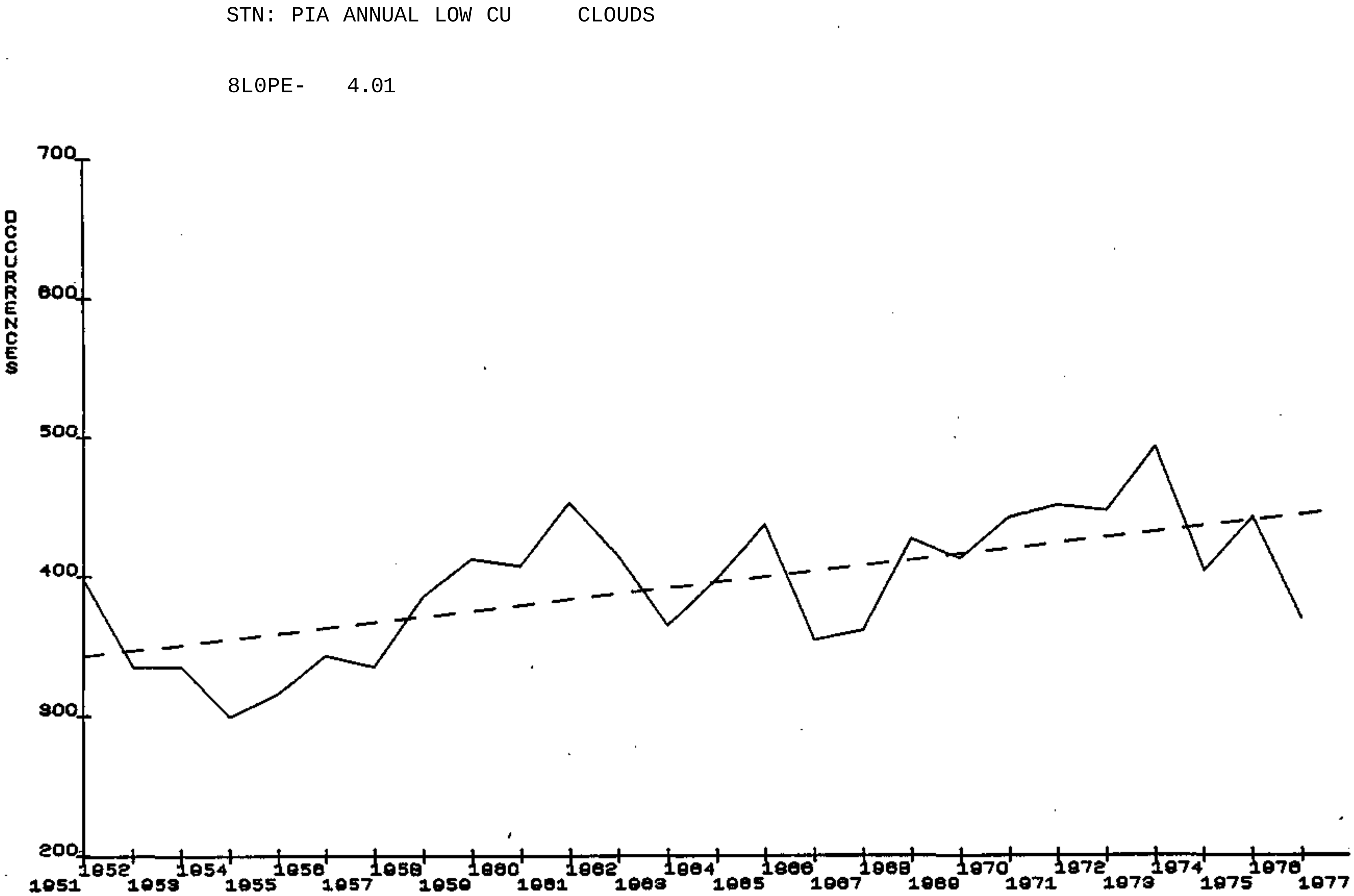


Figure 21. The annual frequency of cumulus in the low cloud category at Peoria, Illinois for the 1951-1976 period.

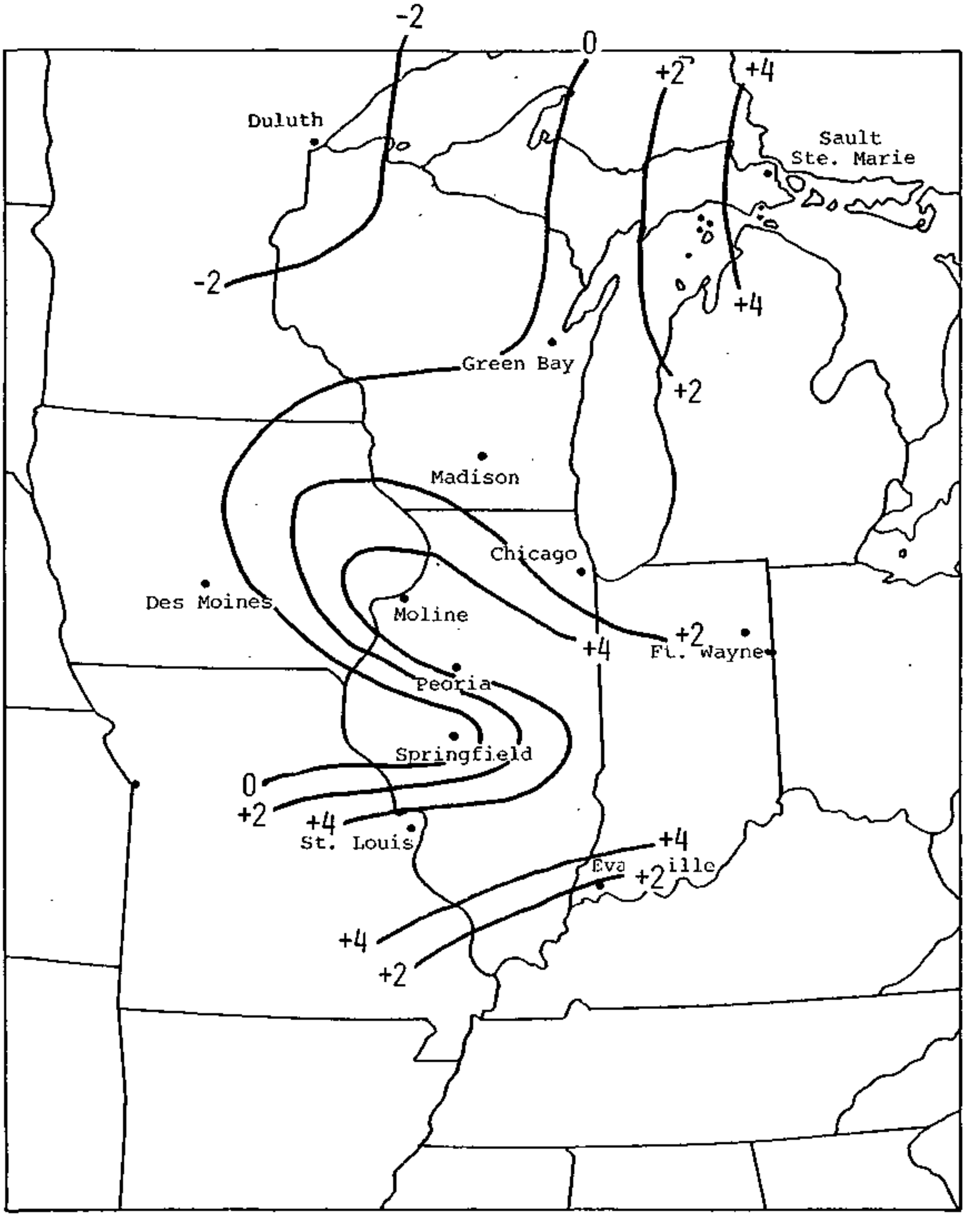


Figure 22. The spatial pattern of the 26-year trend line slope for the "low cumulus" category of clouds.

cumulus category suggests that upper level clouds may be difficult to record due to intervening clouds over north-central and south-central Illinois, and central Indiana.

Low Stratus Cloud Frequency Trend

The low stratus category of clouds showed even a greater tendency than low cumulus toward increased frequency over the past 26 years. The largest change was evidenced at Sault Ste. Marie where the slope of the linear trend line through the 26-year data set was 21.6. However, all stations reported positive slopes with the exception of Duluth showing a small negative change in cloudiness with a slope of -0.69. The spatial variability of the low stratus category trend lines slope is shown in Figure 23.

A comparison of the trend plots for all the stations reveals that between the period 1958 and 1962 there was a relatively high increase in frequency of low stratus clouds at the more southern stations, i.e., in Illinois, Missouri, and Indiana. This period of relatively high frequency of low stratus clouds was followed by a period of values below the trend line for the years 1962 through 1968 at the same stations. However, the northern stations in Minnesota, Wisconsin, and Michigan showed opposite characteristics with frequency values below the trend line in the 1958-1962 period followed by a recovery to values exceeding the trend line during the later period. These variations are certainly a reflection of macroscale synoptic weather patterns which could dominate these two classifications of low clouds.

Middle Cloud Frequency Trend

The trend line for middle clouds at 10 out of 12 stations showed a decreasing frequency of occurrence. As shown in Table 7, this cloud

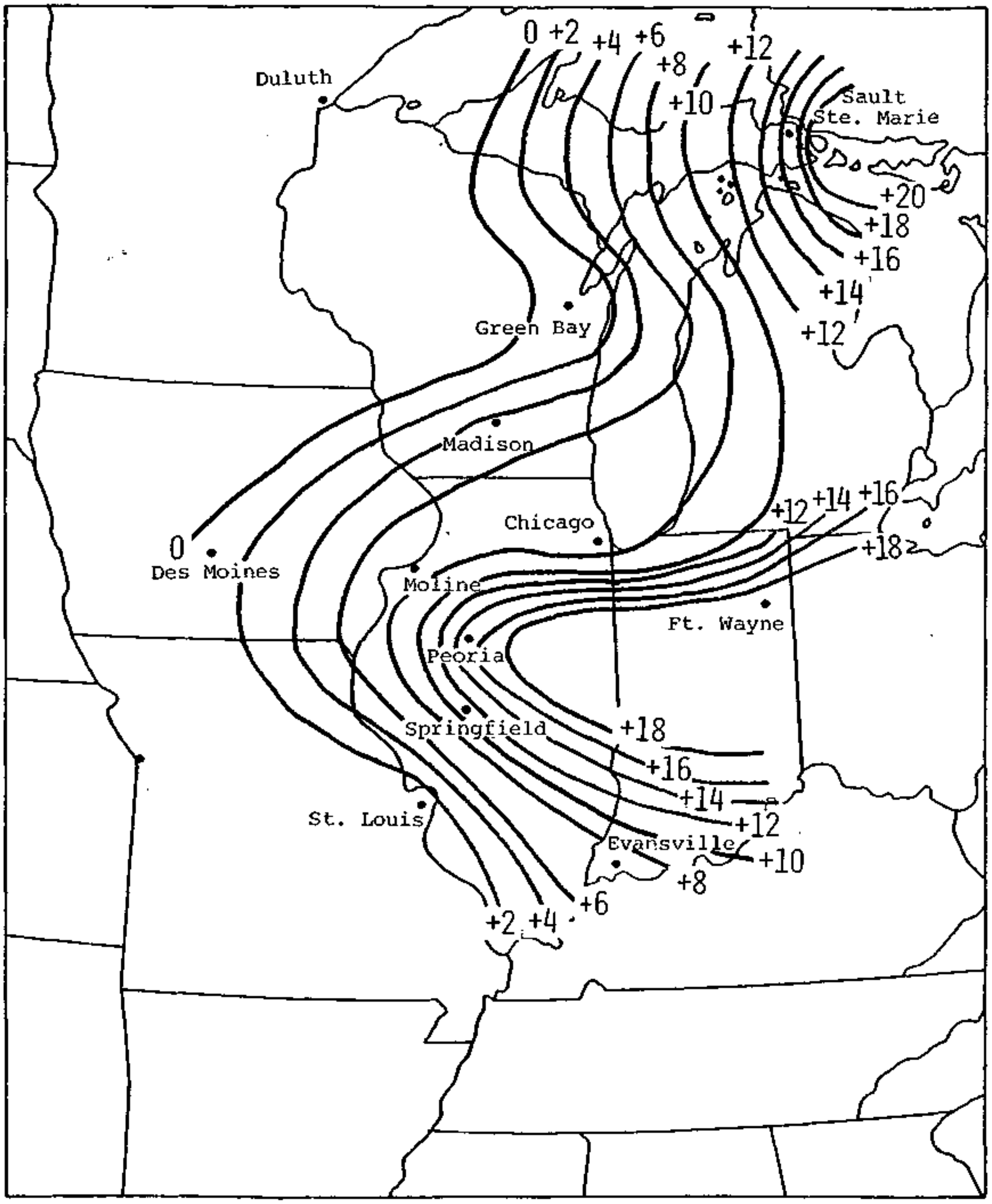
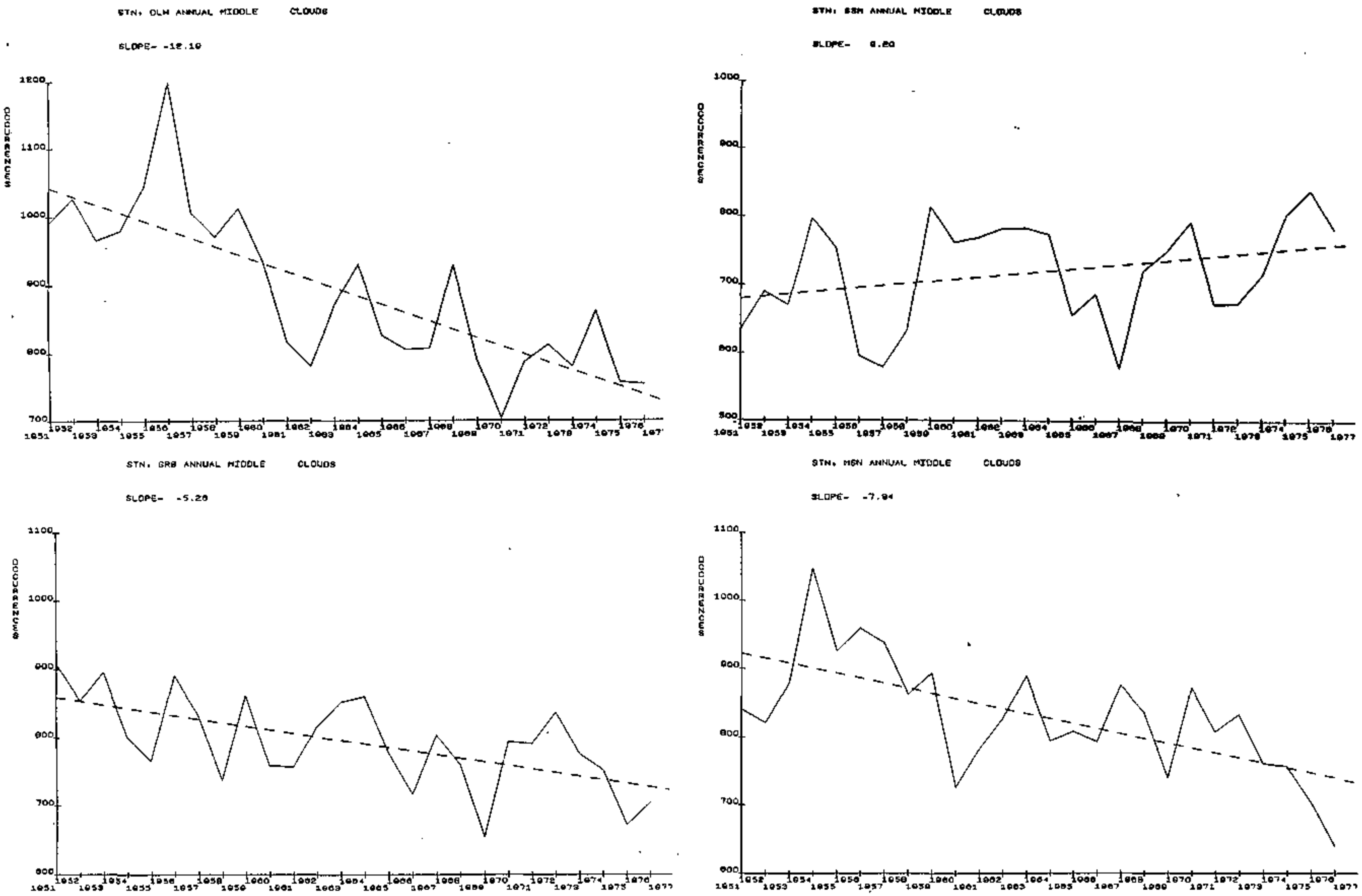


Figure 23. The spatial pattern of the 26-year trend line slopes for the "low stratus" category of clouds.

stratification is anomalous among those used in this study. The obscuration of middle-level clouds by low clouds might explain an apparent decrease, and, thus, predict a similar decrease in high cloud frequencies. If the downward trend, however, was due to macroscale conditions of the middle atmosphere, then the high cloud observations may still be representative of a true frequency change. As will be shown later, the high cloud stratification indicates an upward trend at nearly all stations suggesting the latter explanation is feasible.

The greatest decrease was observed at Duluth (Fig. 24) with a nearly equal trend at Evansville (Fig. 26) during this 26-year record. However, it should be noted that while the decrease is nearly the same at these two stations, the 1976 end point of the trend at Duluth nearly coincides with the 1951 initial point of the Evansville trend. This illustrates that there may be considerably more middle cloudiness in the northern latitudes (represented by Duluth), i.e., a climatological feature of Midwest cloudiness during 1951-1976.

For the most part through the Illinois-Indiana area, the trend of, or the difference between the 1951 and 1976 middle cloud frequencies is somewhat mixed and ill-defined. The data shown in Figure 27 represent the simple difference between the 1951 and 1976 frequency values. As shown in Figure 27, the greatest decrease of middle clouds largely occurred at the western edge of the study area. Smaller changes of cloud frequency occur in approximately the same area as maximum trend line slope of low cumulus shown in Figure 22. Values over the two-state area ranged from -157 (Springfield) to +64 (Moline) which along with Sault Ste. Marie, showed an increase of middle cloudiness (Fig. 24). One might suspect that Sault Ste. Marie may suffer from the effects of Lake Superior to the west, but on the other hand the absolute value



Fiqure 24. The annual frequency of middle clouds during 1951-1976 at Duluth, Sault Ste. Marie, Green Bay, and Madison.

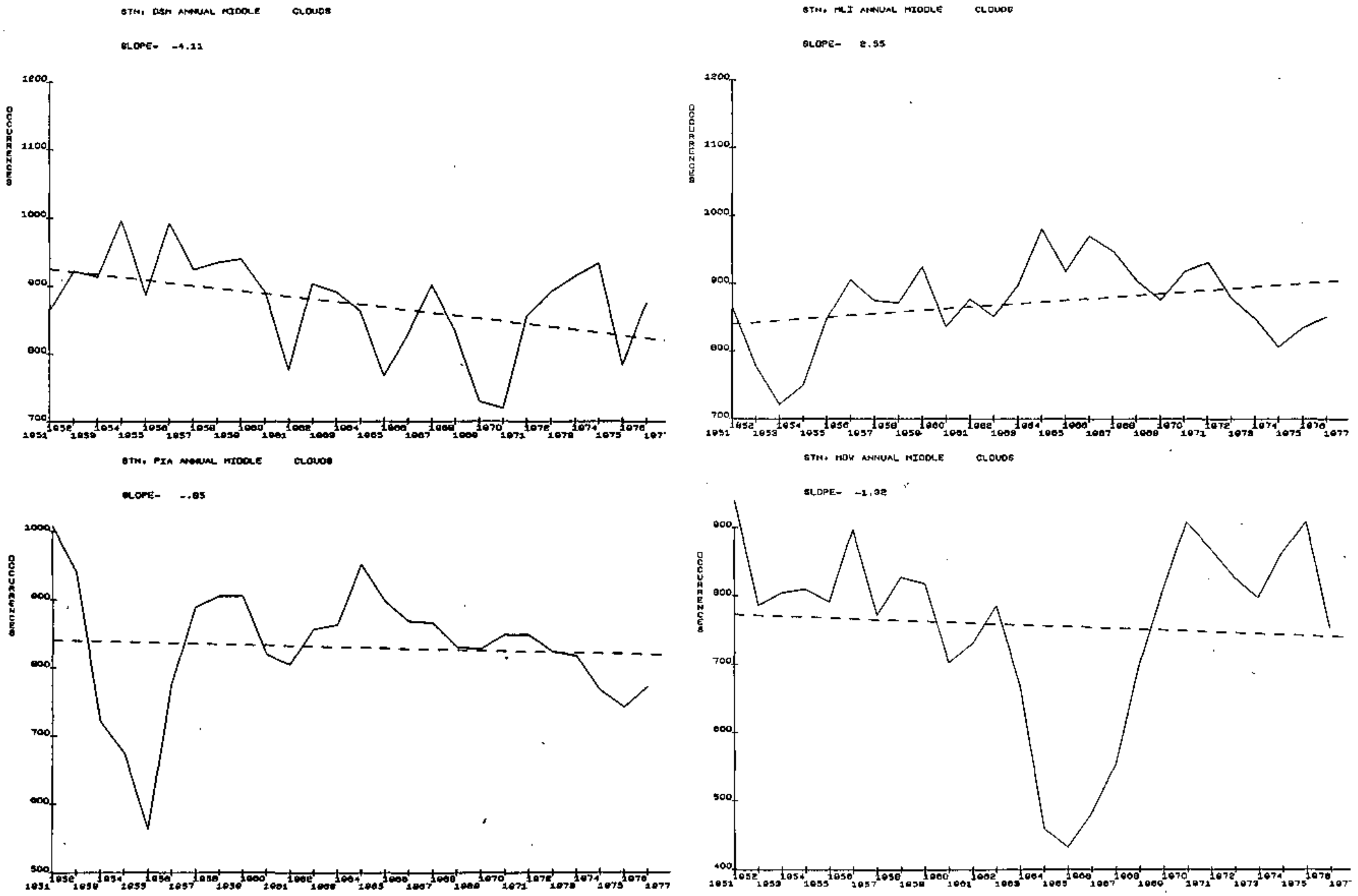


Figure 25. The annual frequency of middle clouds during 1951-1976 at Des Moines, Moline, Peoria, and Chicago.

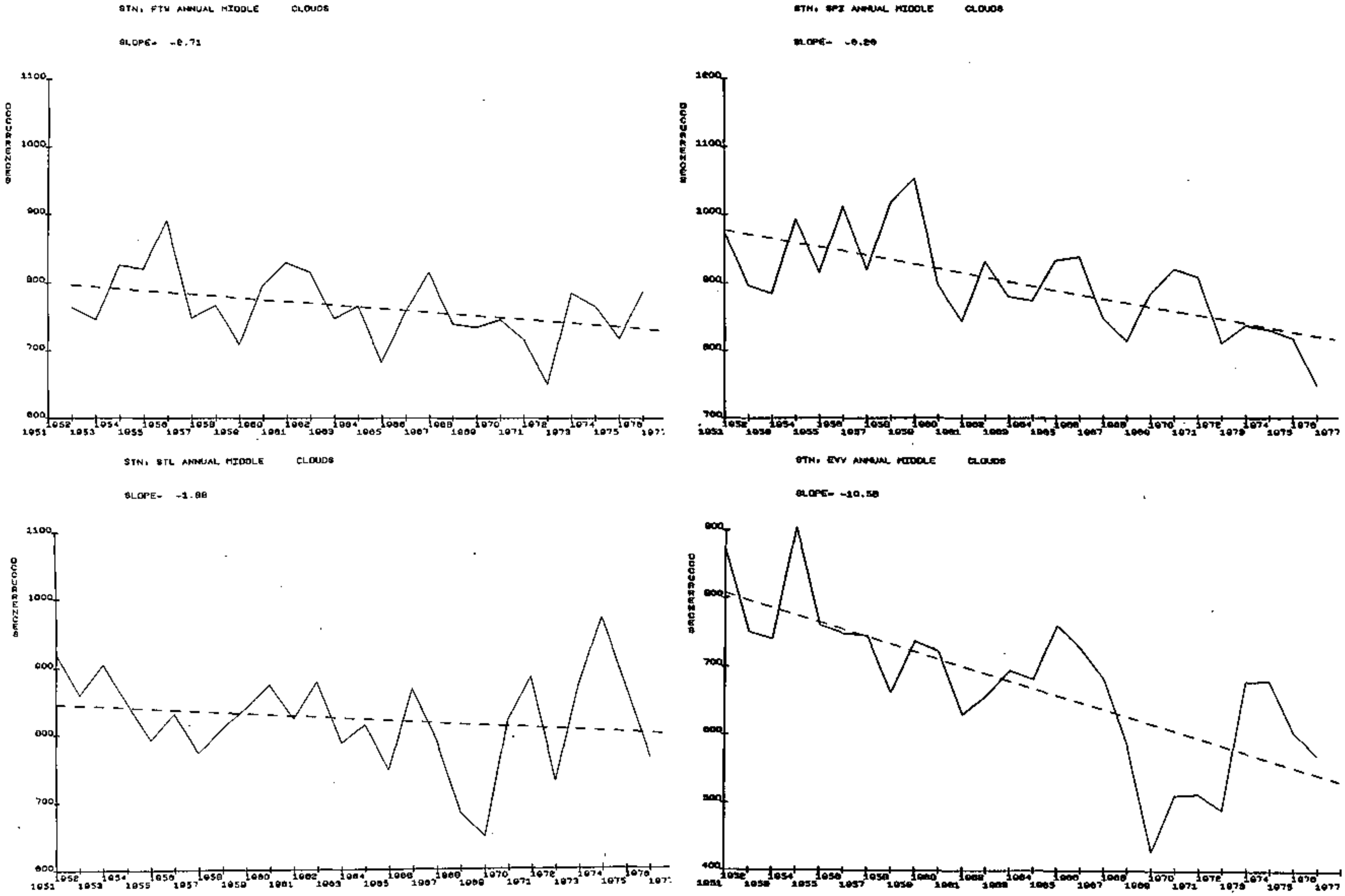


Figure 26. The annual frequency of middle clouds during 1951-1976 at Ft. Wayne, Springfield, St. Louis, and Evansville.

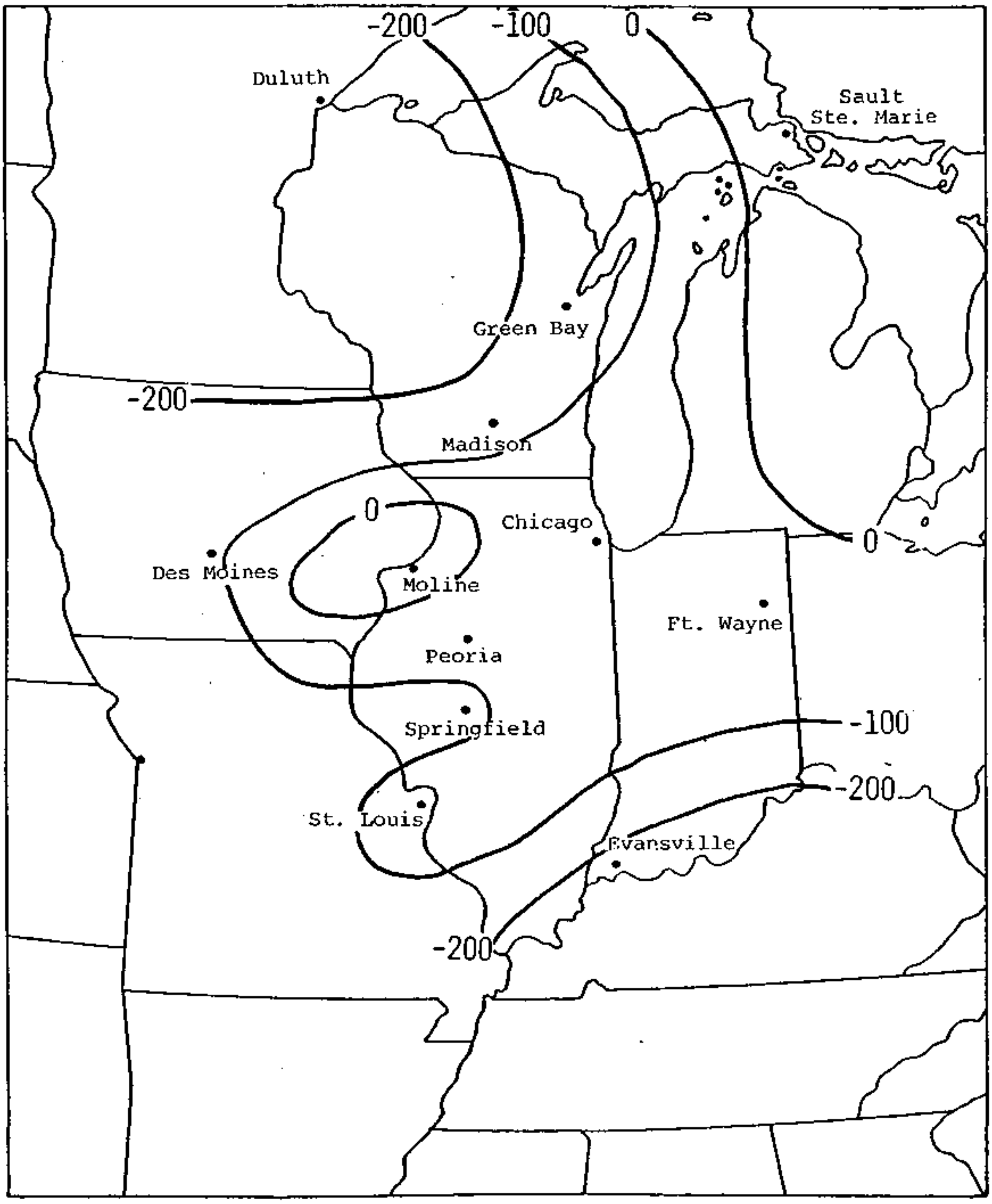


Figure 27 The 26-year change in middle clouds obtained from the difference between the 1951 and 1976 frequencies.

of the frequencies are somewhat lower than at Duluth at the western most tip of Lake Superior. Thus, the Lake does not appear to be responsible for the increase at Sault Ste. Marie.

The spatial pattern of the trend line slope is shown in Figure 28. As evident from study of Figures 24-27 the pattern is not very coherent. The dominating negative slope values are interrupted only by the slight positive values at Sault Ste. Marie and Moline giving the appearance of a northwest-southeast oriented pattern of alternating positive and negative trend lines. The middle cloudiness is obviously somewhat paradoxical and actually raises several questions since these clouds are strongly controlled by cyclonic systems traversing the upper middle west. It is important to recognize that the frequency of middle cloudiness is an important feature to be reckoned with in attempting to discern the occurrence of high clouds.

High Cloud Frequency Trend

The high clouds, including all forms of cirrus clouds, show a positive trend during the 26-year record at all stations. With the exception of Sault Ste. Marie, the relative increase shown by Table 7 is greatest over the area of north-central Illinois through Indiana. This tendency agrees quite well with the assessment of air travel shown in Figure 2. It is interesting to note that at Moline where an increase of middle cloudiness was observed there was a very strong increase of high clouds as indicated by the trend analysis. The same feature is true of Sault Ste. Marie although the greatest increase observed in high cloud frequency was at Ft. Wayne where the middle clouds showed little change.

As seen in Figures 29-31, the high clouds increased rapidly at nearly all stations during the first half of the decade of the 50's. Little increase

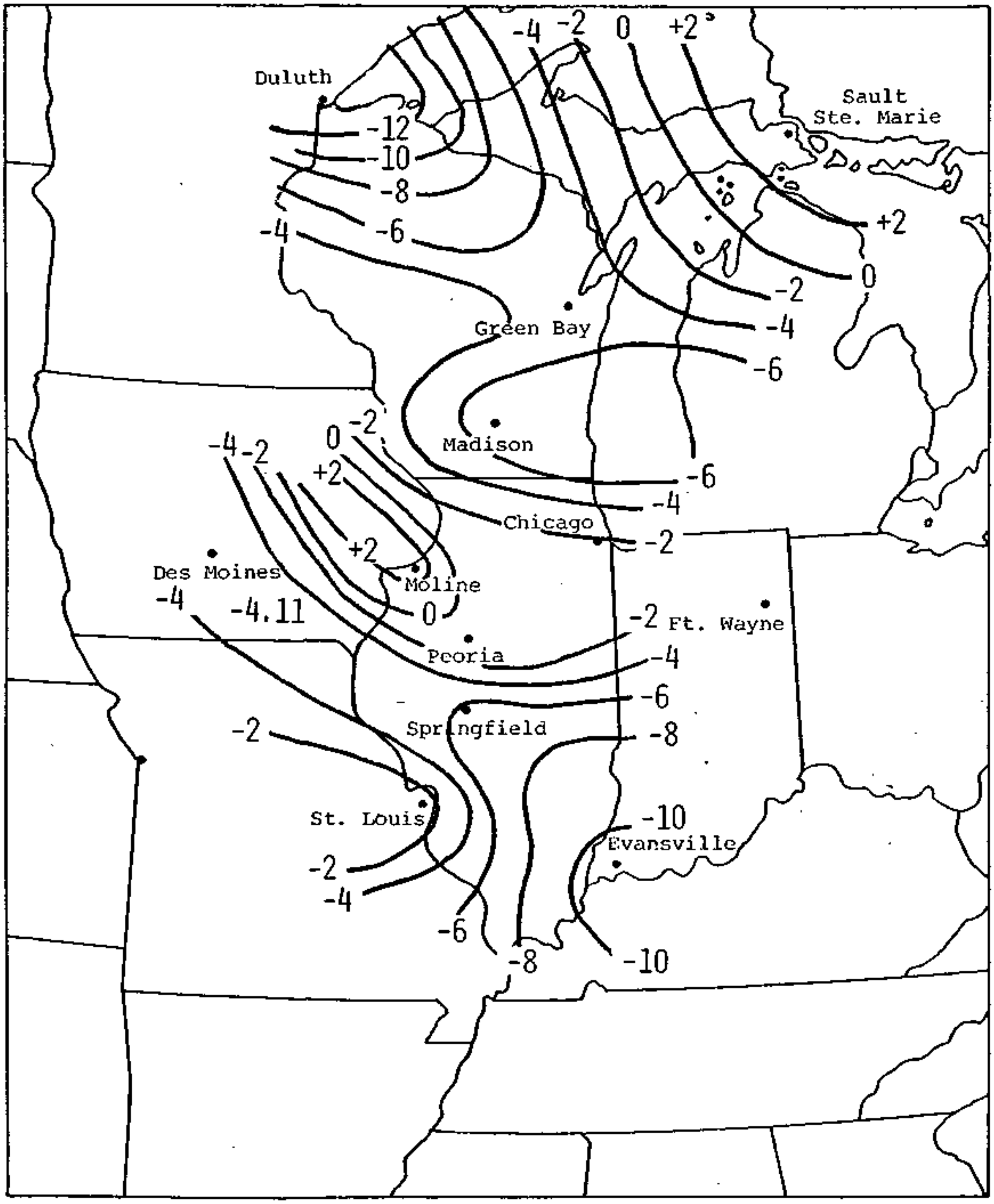


Figure 28. The variability of the slope of the 1951-1976 trend line over the Midwest for the middle cloud category.

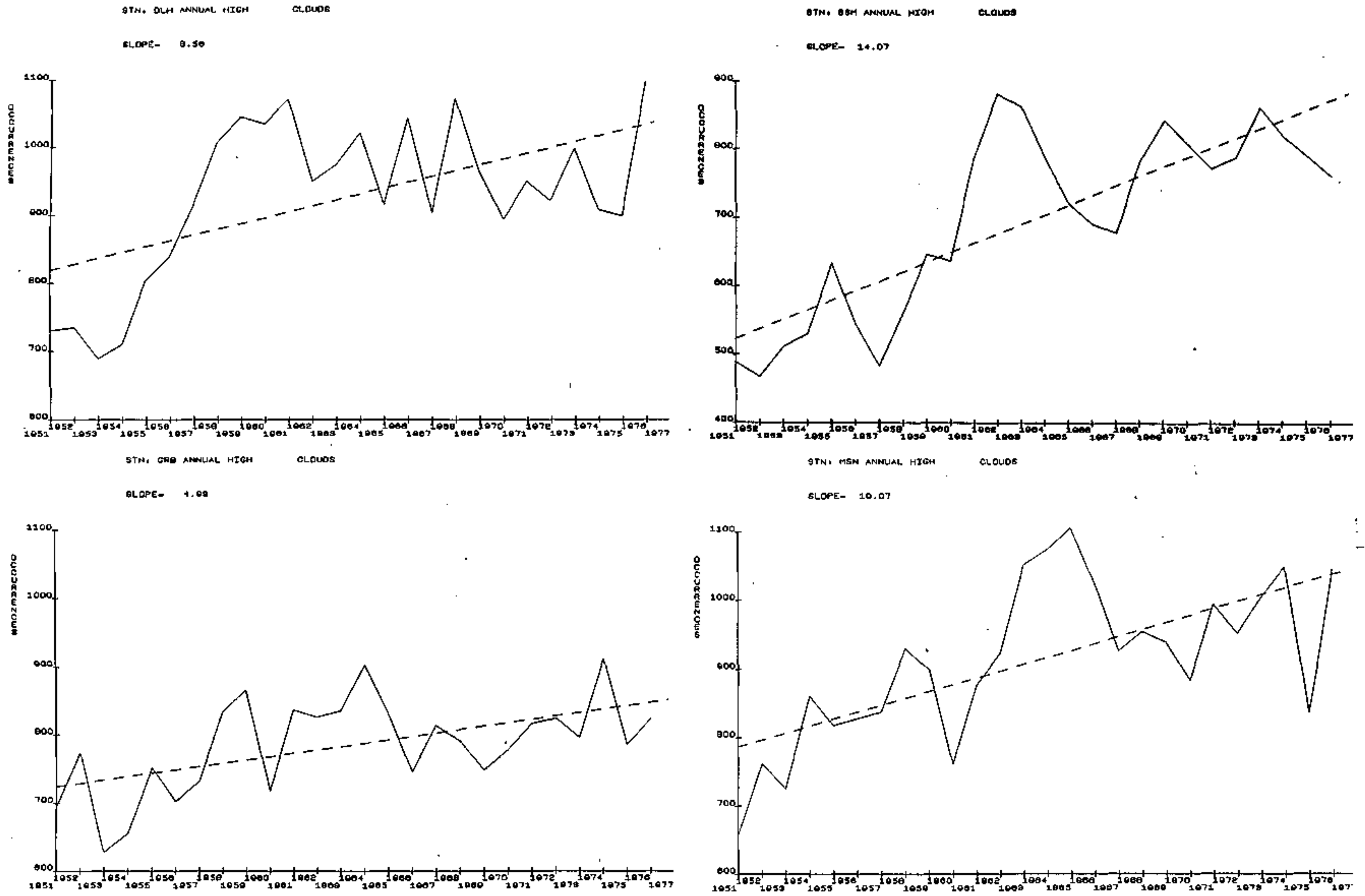


Figure 29. The annual frequency of high clouds during 1951-1976 at Duluth, Sault Ste. Marie, Green Bay, and Madison.

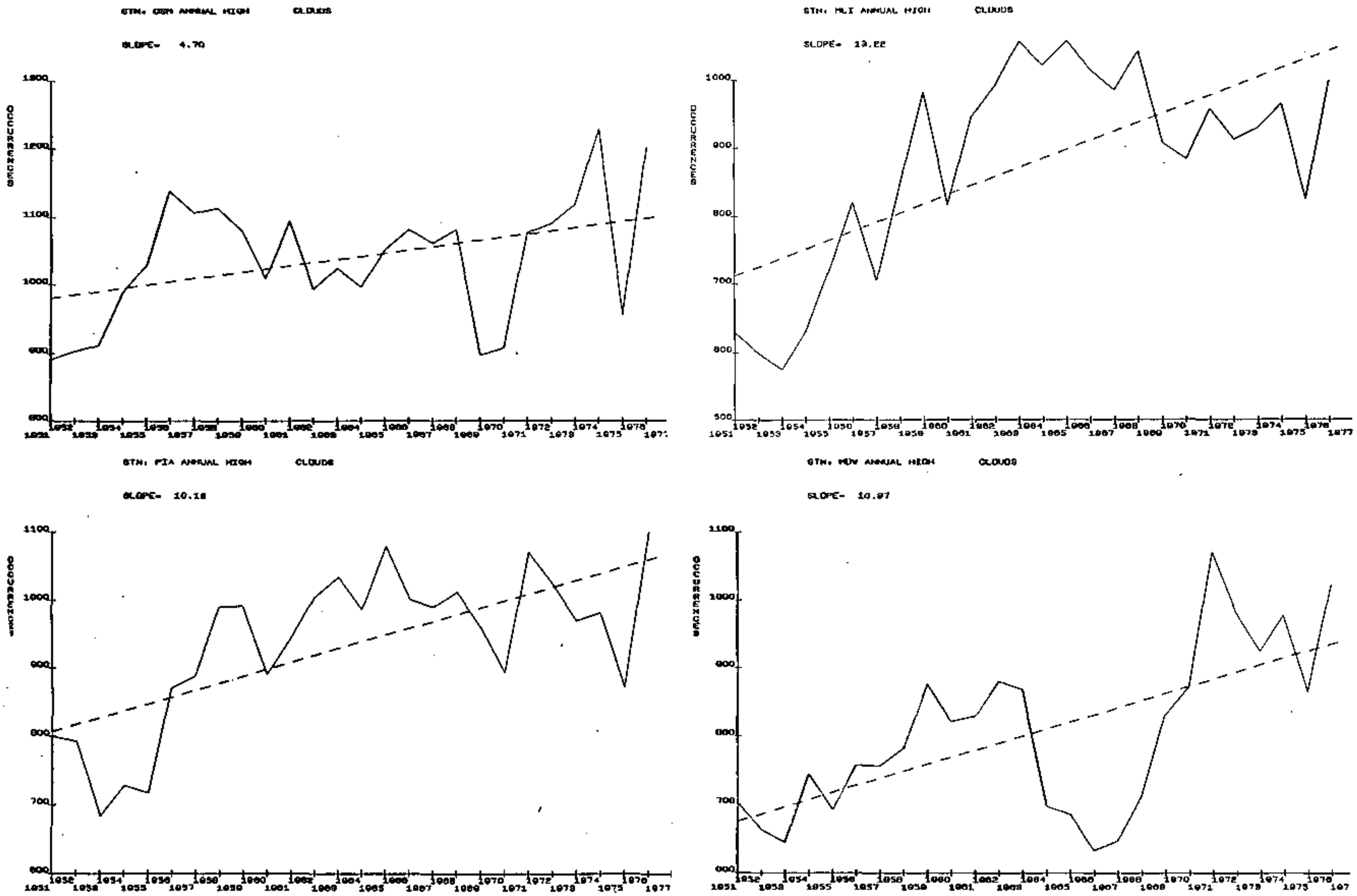


Figure 30. The annual frequency of high clouds during 1951-1976 at Des Moines, Moline, Peoria, and Chicago.

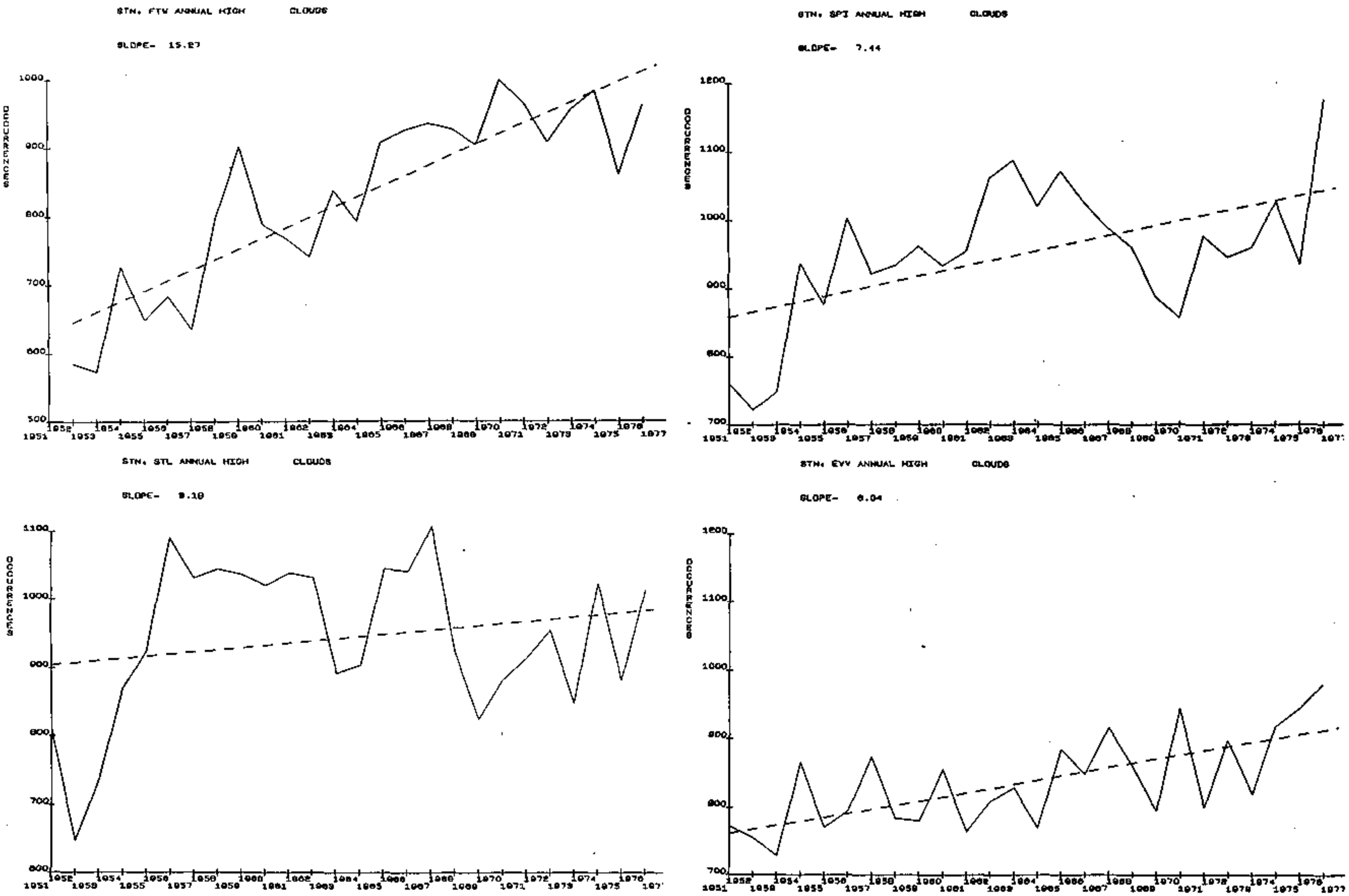


Figure 31. The annual frequency of high clouds during 1951-1976 at Ft. Wayne, Springfield, St. Louis, and Evansville.

occurred at Evansville during this period, with only moderate increases at Midway, Ft. Wayne, Green Bay and Sault Ste Marie. Following this rise in the 50's, the trend in high cloud frequency can be viewed as nearly zero (with fluctuations) for approximately the latter 20 years. This feature may be related to the drought period of the early 50's and the stabilization of the trend thereafter, may reflect a recovery to a more normal synoptic scale circulation.

Again we note that Duluth (Fig. 29) experiences greater high cloud occurrences than Sault Ste. Marie some 700 kilometers to the east. In fact, in 1951 Sault Ste. Marie had the least high cloud frequency of any of the stations and the only station with fewer high clouds in 1976 was Green Bay.

The spatial pattern of the trend line slope is shown in Figure 32. The most striking feature in this pattern is the swath of large slope values over northern Illinois extending into Indiana. A comparison between Figures 28 and 32 reveals, however, that the middle clouds apparently do not significantly affect the high cloud frequencies. The region from Duluth southeast across Green Bay showed a large negative slope for middle clouds, but weak positive slope for high clouds. Most interesting, though, is the area from Moline to Ft. Wayne with increased middle cloud frequency and yet is the same area of a maximum increase in high clouds. A suitable explanation for this phenomenon awaits further study.

Assuming that Sault Ste. Marie reflects the natural high cloud climatology including large scale changes and excluding inadvertent changes due to aircraft, the differences between the 1951 values at Sault Ste. Marie and other stations show that there is a distinct westward increase of high cloud frequency as seen in Figure 33. This may again be the reflection of the drought over the Great Plains in this time frame allowing for more frequent

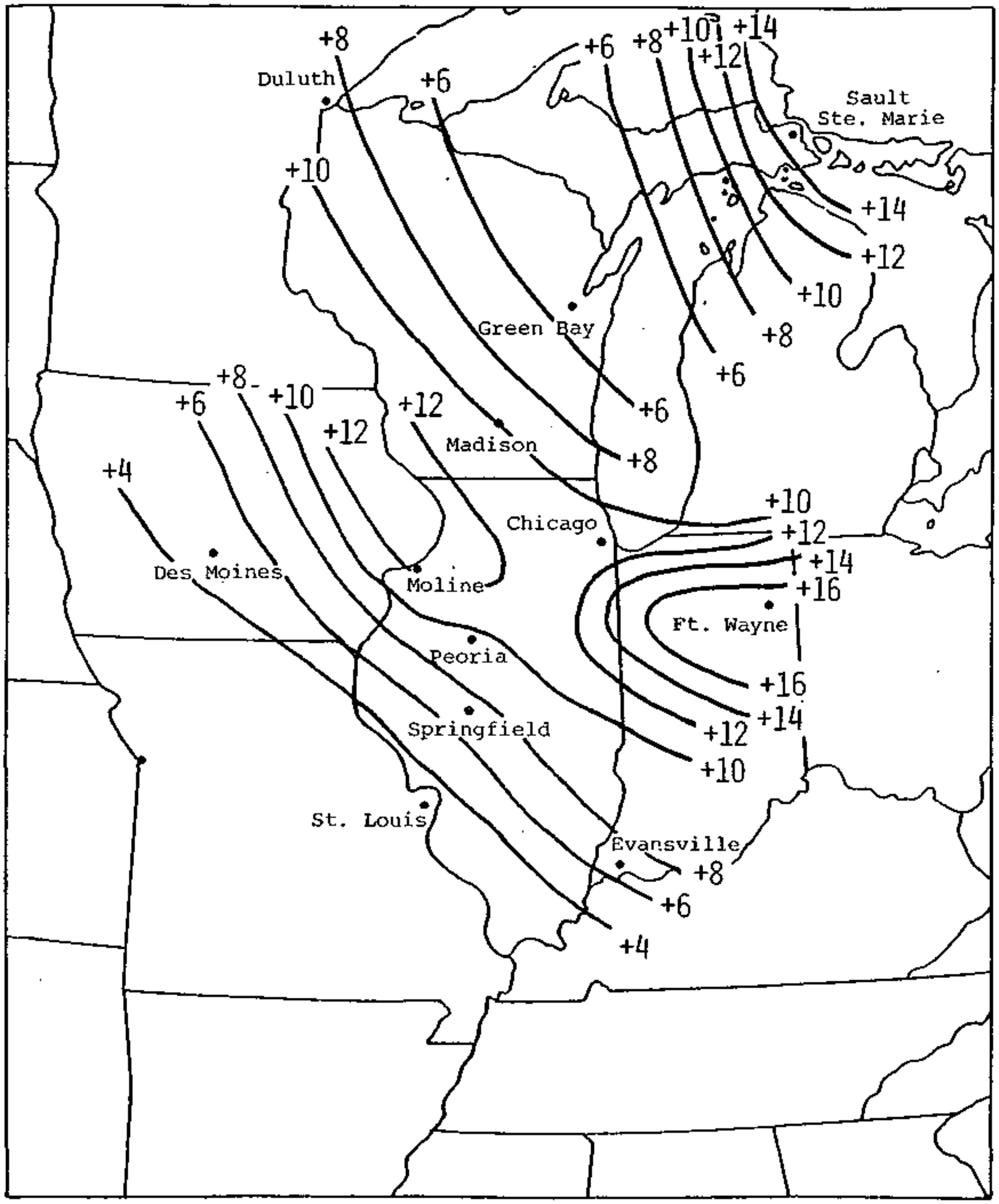


Figure 32. The spatial distribution of the 26-year trend line slope of high clouds.

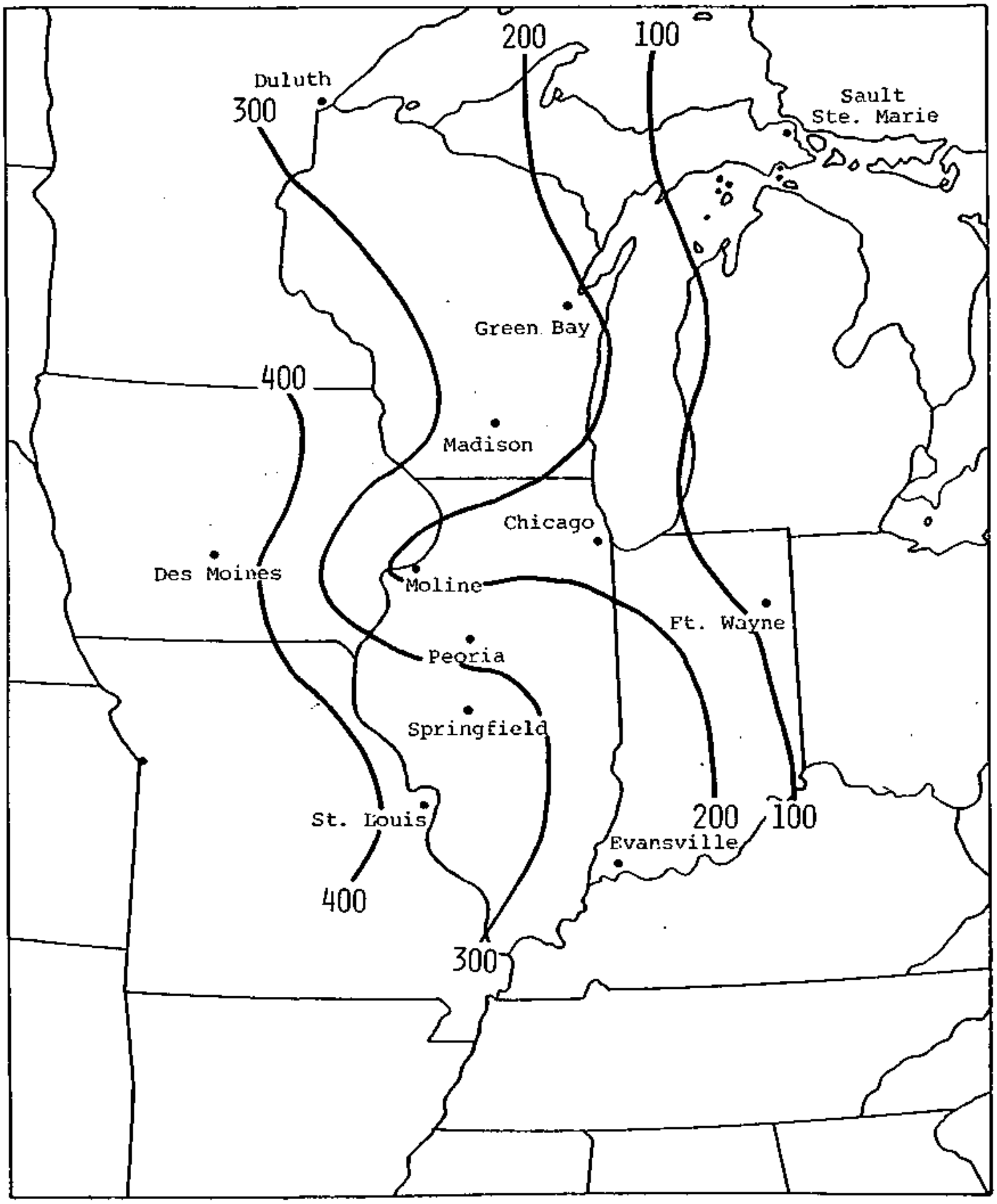


Figure 33. The high cloud frequency differences between Sault Ste. Marie and the other first order stations for 1951.

observations of high clouds. Performing the same simple calculation for the 1976 high clouds, the pattern changed significantly from that in Figure 33, as shown in Figure 34, exhibiting a relatively greater frequency of high clouds over the high frequency jet flyway. This strongly suggests the potential influence of high altitude commercial jet aircraft on cirrus clouds, but considerable detailed analysis is required to exclude large scale climatological changes over the 26-year period.

Another indication of the spatial pattern of the frequency trend was obtained from the differences between the 1976 and 1951 values at each station shown in Figure 35. A comparison between Figure 2 and Figure 35 shows excellent agreement between the relatively greater increases of high clouds through Iowa, central Illinois, and Indiana and the high frequency of commercial jet aircraft traffic.

High Cloud Frequency Trend With ≤ 0.4 Middle and Low Clouds

To increase the probability of observing contrail cirrus from conventional data the observations were stratified to exclude those observations with ≥ 0.4 cumulative low and middle clouds. Obviously, the overall frequency of events is decreased by this procedure as can be noted in Table 7. For example at Moline in 1951 the high cloud frequency was 712 and during the same year this was reduced to 566 when the low and middle clouds with ≥ 0.4 coverage of the hemisphere were excluded.

It is noteworthy that although the trend slopes are less steep after stratification, they are nonetheless all still positive, lending greater credibility to a conclusion of increasing cirriform cloud cover with time (Figs. 36-38). The greatest change in this classification of high clouds was observed at Ft. Wayne (Fig. 38) with the least change at St. Louis (Fig. 38).

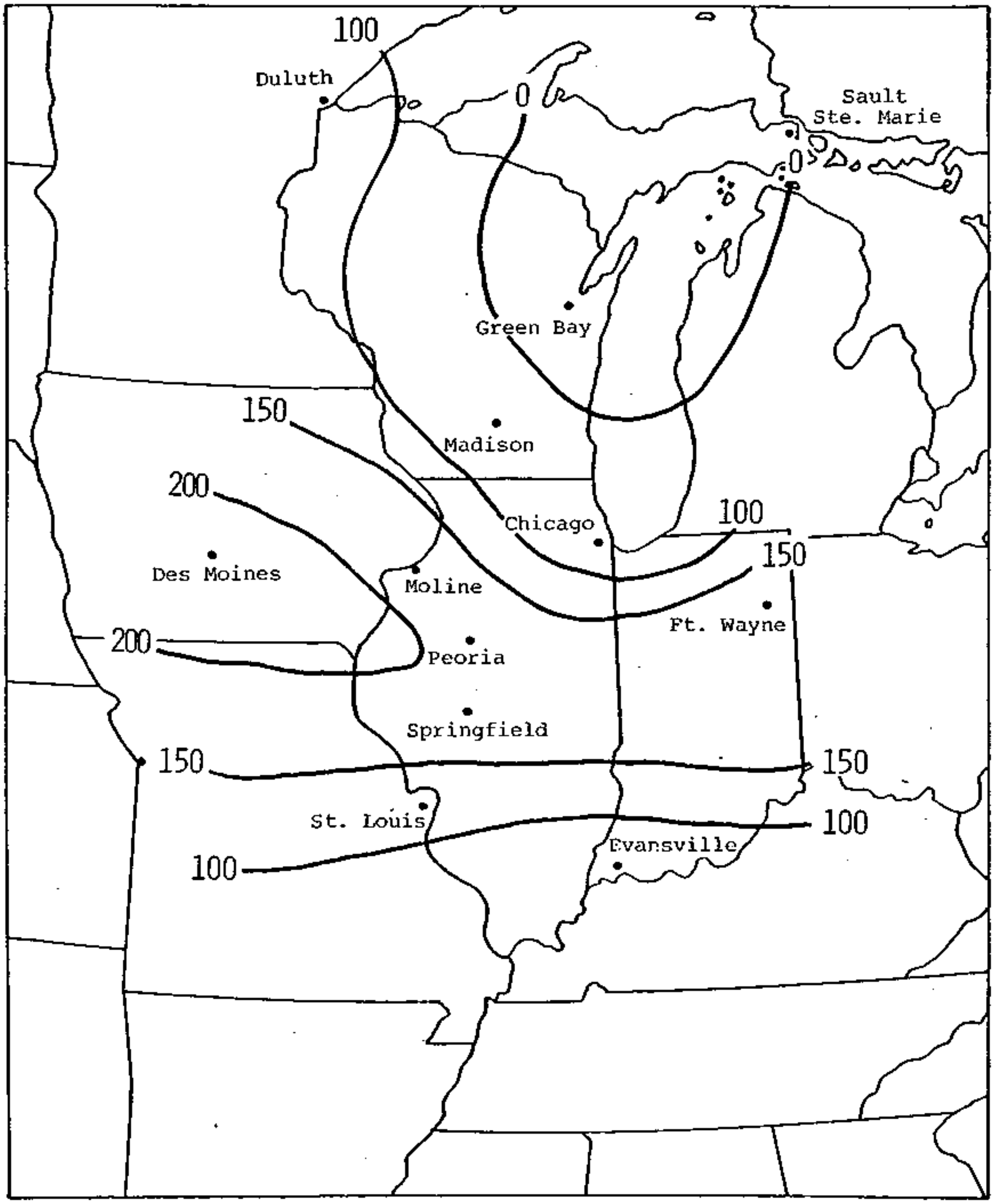


Figure 34. The high cloud frequency differences between Sault Ste. Marie and the other first order stations for 1976.

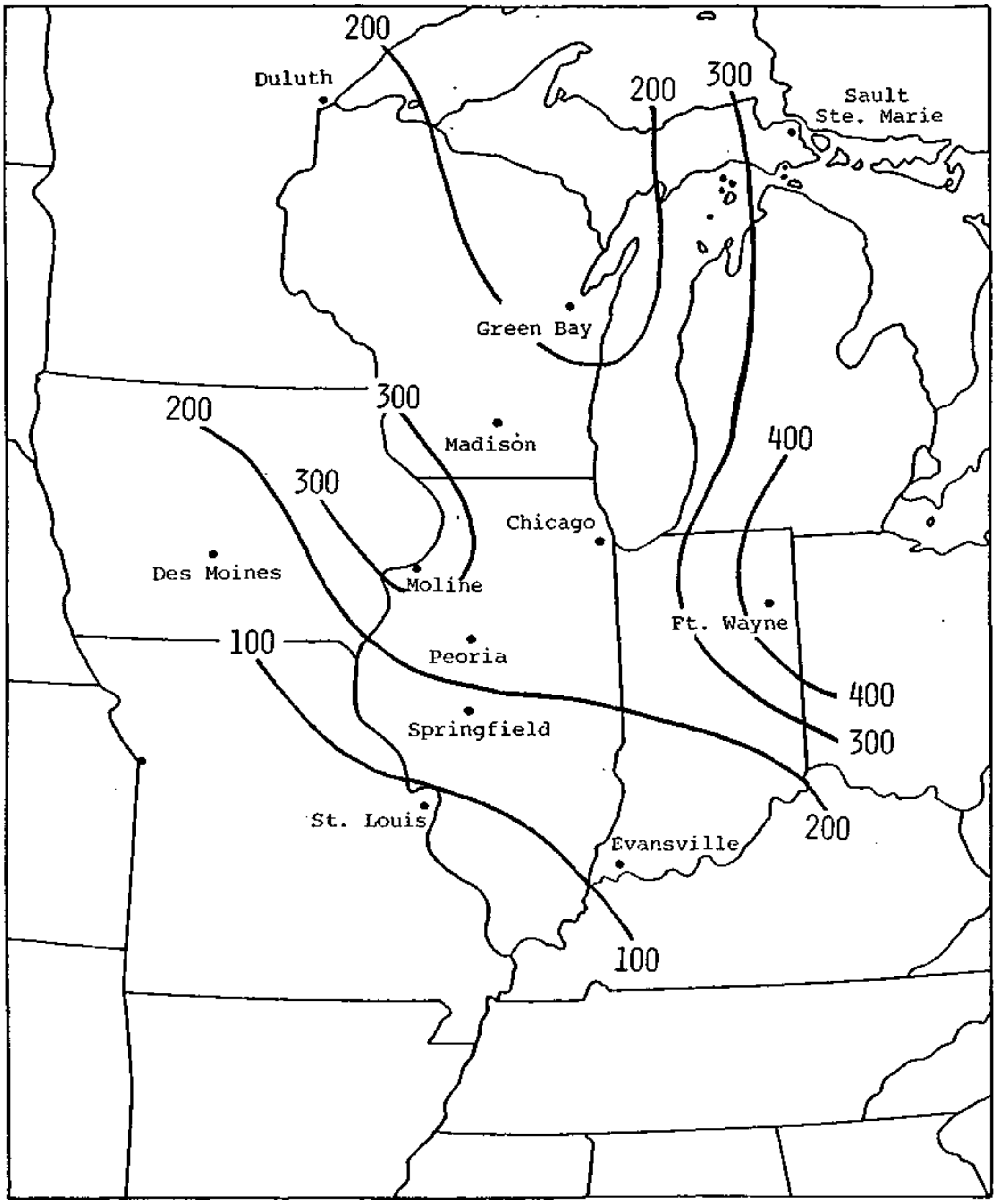


Figure 35. The 26-year change in high clouds obtained from the difference between the 1951 and 1976 frequencies.

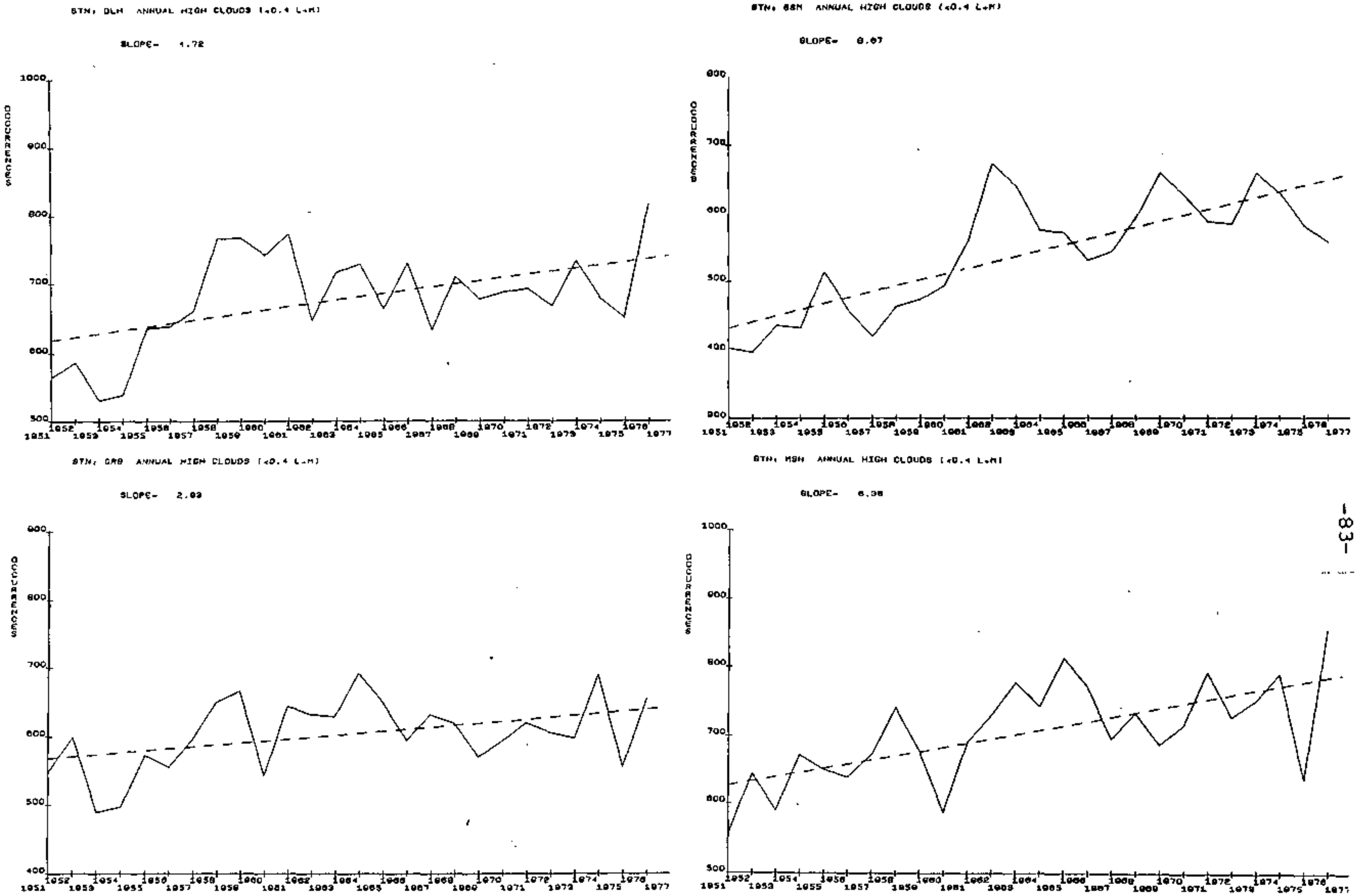


Figure 36. The annual frequency of high clouds with ≤ 0.4 intervening middle and low clouds during 1951-1976 at Duluth, Sault Ste. Marie, Green Bay, and Madison.

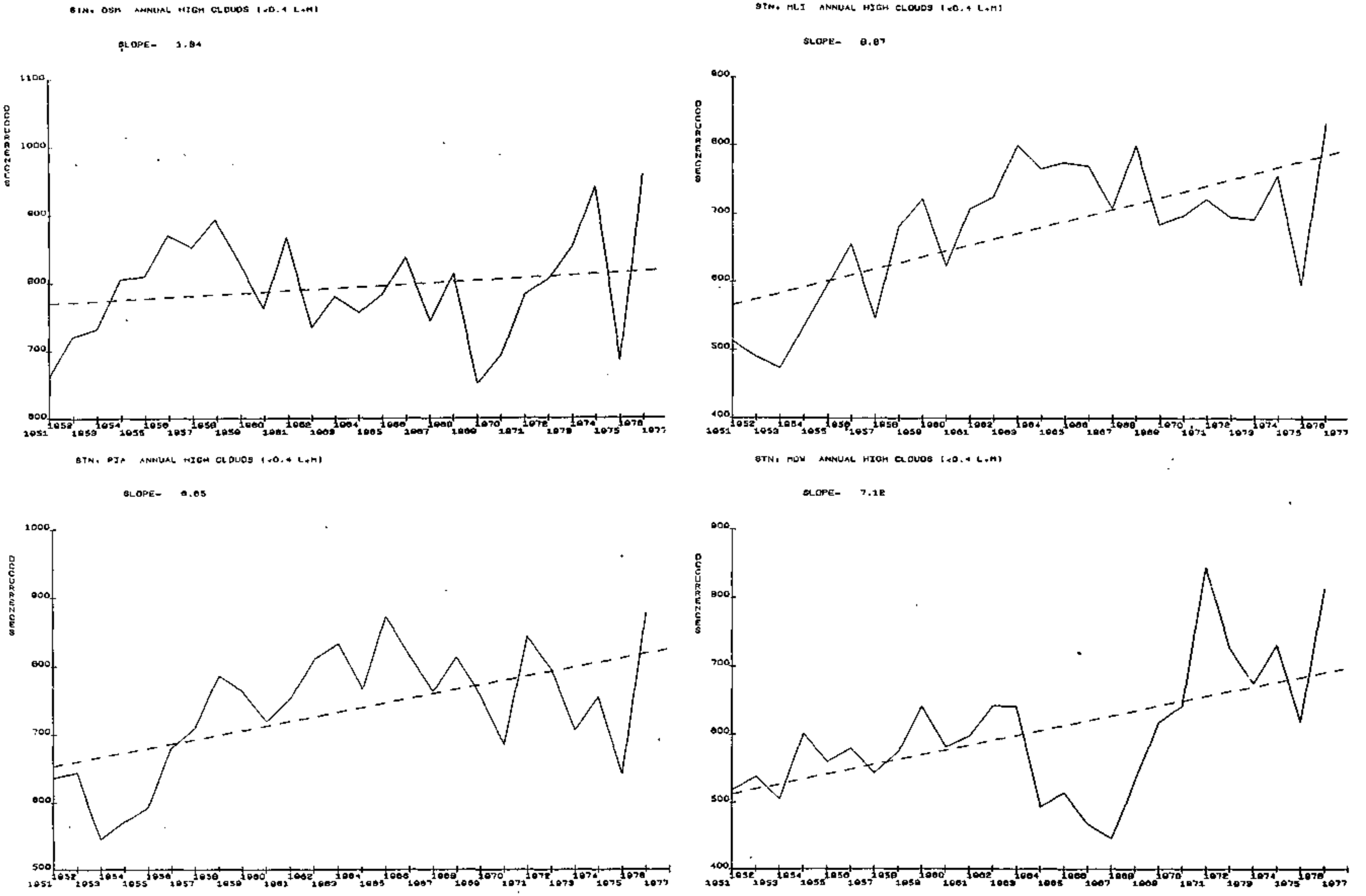


Figure 37. The annual frequency of high clouds with ≤ 0.4 intervening middle and low clouds during 1951-1976 at Des Moines, Moline, Peoria, and Chicago.

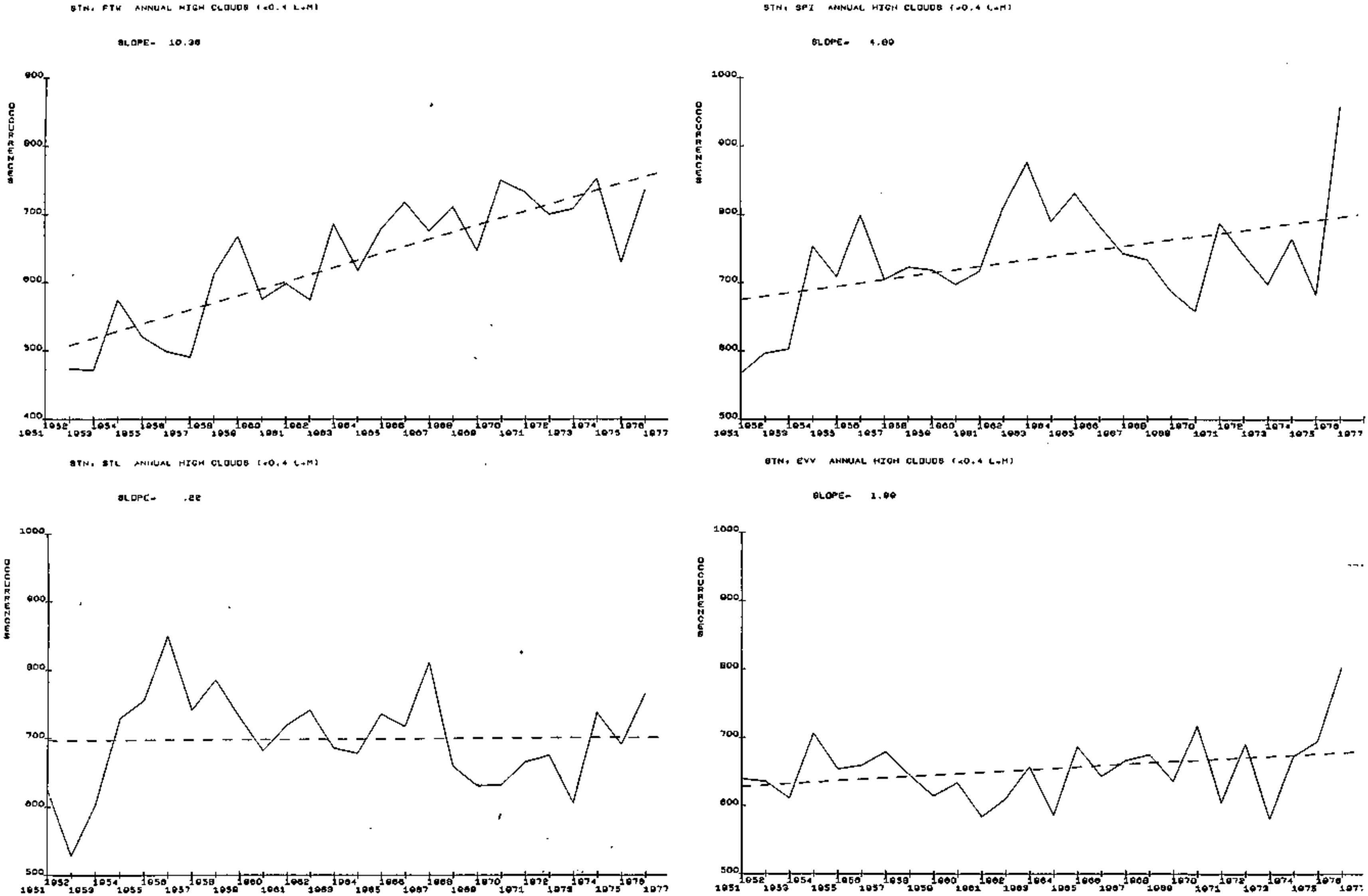


Figure 38. The annual frequency of high clouds with ≤ 0.4 intervening and low clouds during 1951-1976 at Ft. Wayne, Springfield, St. Louis, and Evansville.

The yearly data reflect similar features to those observed in the annual high clouds without consideration of the amount of low and middle clouds. There was a rapid increase in high clouds in the 1950's at Duluth (Fig. 36), Des Moines (Fig. 37), Moline (Fig. 37), Springfield (Fig. 36), Green Bay (Fig. 36), Madison (Fig. 36), Midway (Fig. 37), Ft. Wayne (Fig. 38) and Evansville (Fig. 38) observations do not show this same signature.

The overall change in cloud frequency that each station experienced is determined from the difference of the beginning and end points of the 26-year trend line is shown in Figure 39. These data certainly suggest an increase over the Illinois-Indiana area but also a comparable increase at Sault Ste. Marie. In contrast to the high cloud frequency (without regard to the intervening low and middle cloud frequency), the spatial pattern is substantially changed. The strong east-west gradient with larger frequency of high clouds to the west (Fig. 33) is no longer apparent in Figure 39. This stratification of cloud frequency suggests low values over Minnesota, northern Wisconsin, and southern Illinois with high values from Iowa southward.

Again assuming that Sault Ste. Marie (SSM) is relatively uninfluenced by contrail cirrus, the observational data were transformed to a difference from that at SSM to determine the climatological pattern for 1951 (Fig. 40) and 1976 (Fig. 41). As discussed previously there is a north-south alignment of isopleths of the relative cloud frequency with greater values to the west and lesser values to the east (Fig. 40). This may be the reflection of the 1950's drought on the Great Plains providing greater opportunity for cirrus observations. Transforming the 1976 data also to differences from SSM, the pattern of relative increase of cirrus with fewer low clouds is very similar to that described previously. The maximum values occur along the major flight-way for east-west commercial jet aircraft traffic. Equally important,

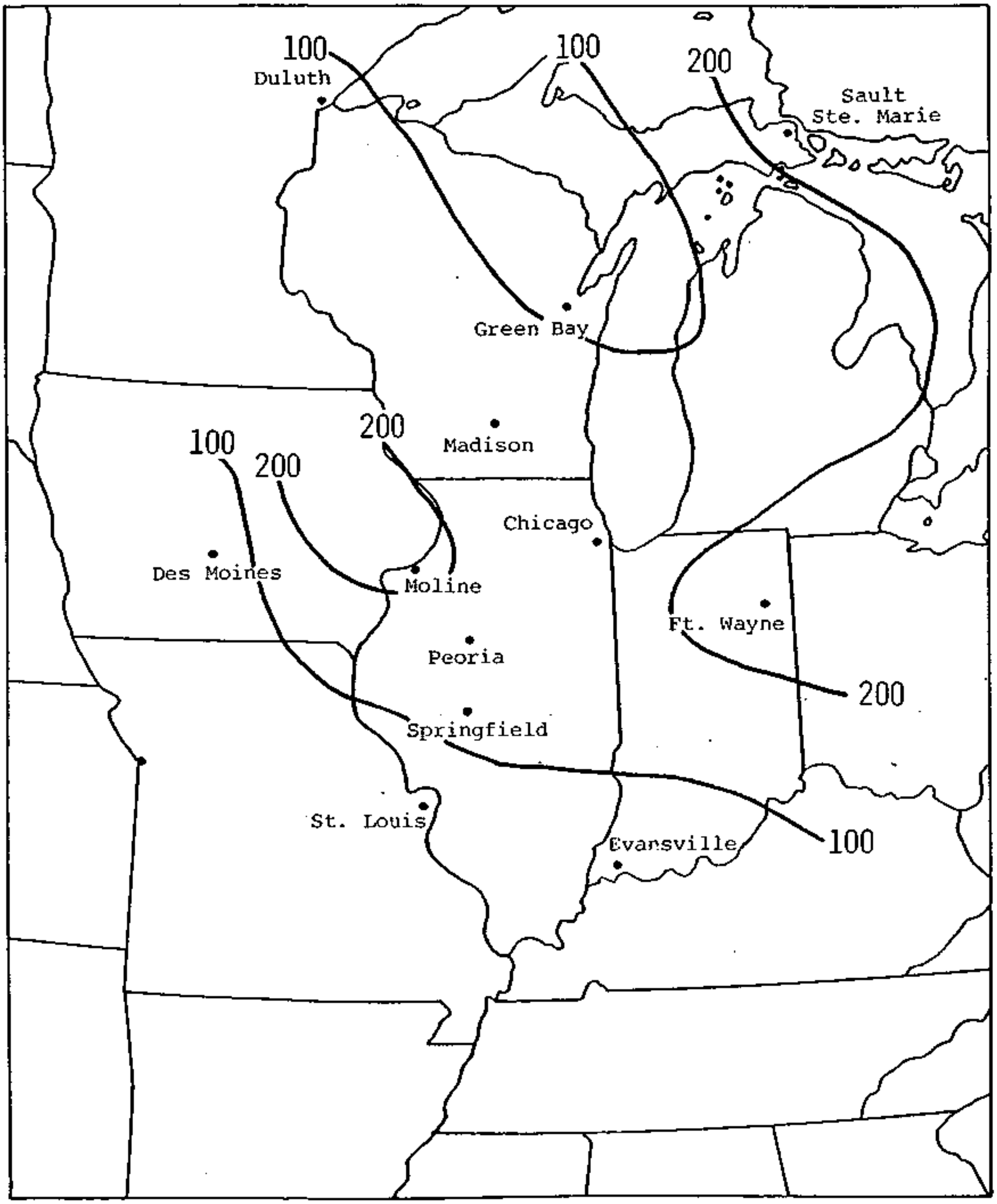


Figure 39. The 26-year change in high clouds with ≤ 0.4 intervening low and middle clouds obtained from the difference between the 1951 and 1976 frequencies.

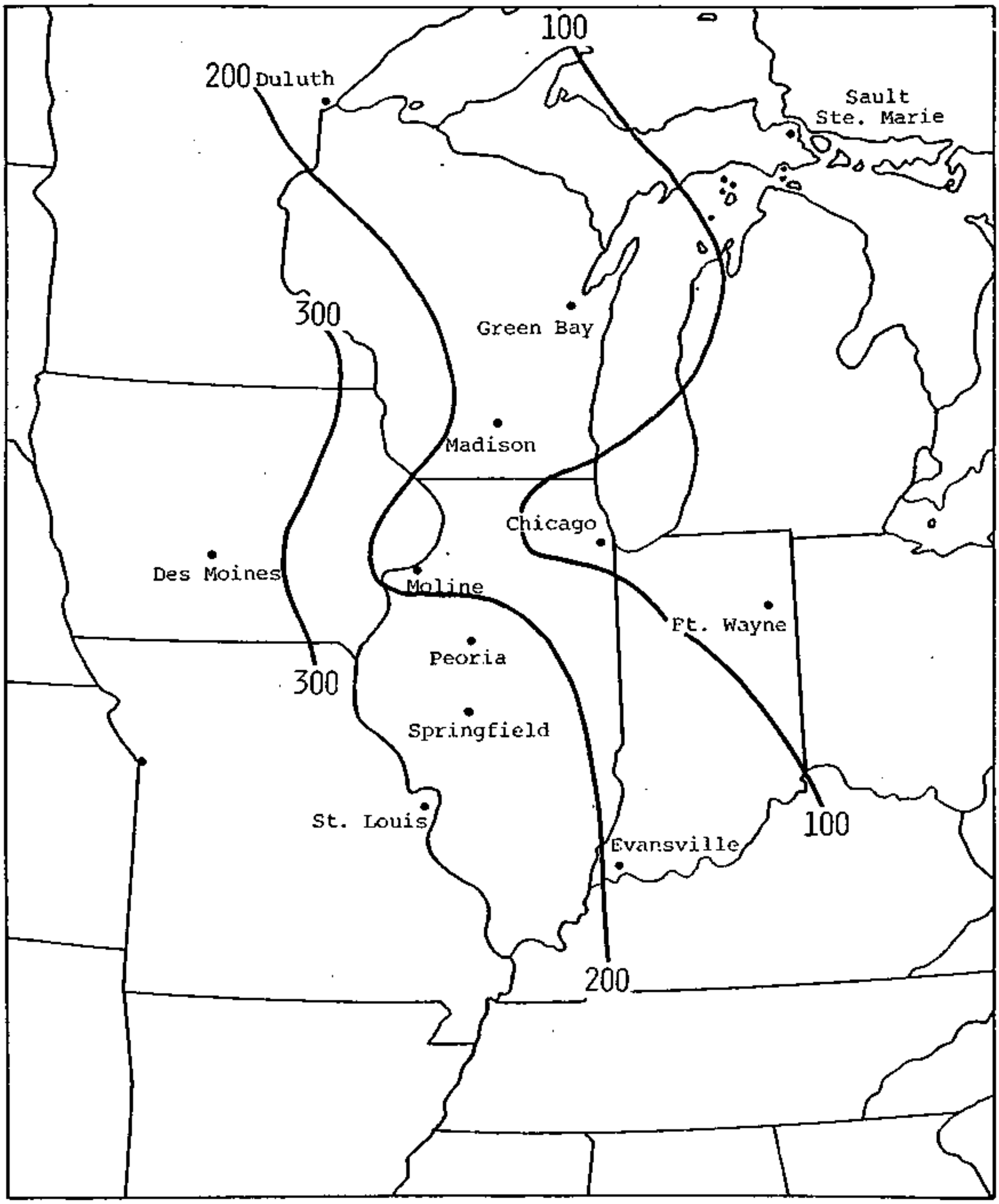


Figure 40. The 1951 frequency difference between Sault Ste. Marie and other first order stations for high clouds with ≤ 0.4 low and middle clouds.

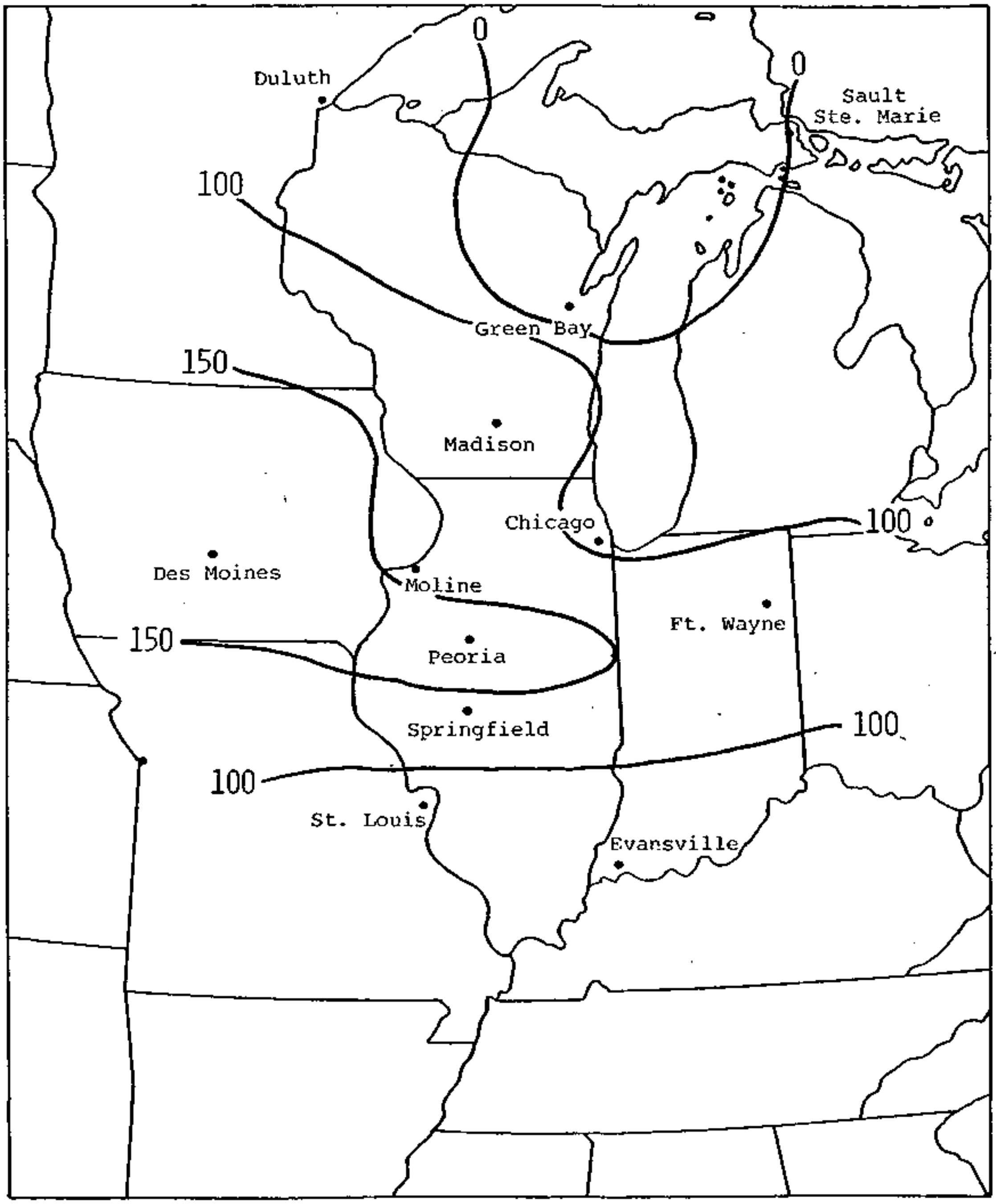


Figure 41. The 1976 frequency difference between Sault Ste. Marie and other first order stations for high clouds with ≤ 0.4 low and middle clouds.

the reduced spatial gradient in 1976 along with an increase in high clouds at SSM exhibits the general spatial increase in cirrus with the maximum increase located near the jet traffic maximum.

An analysis of the spatial distribution of the slope values is shown in Figure 42. There is little significant difference between this pattern and that in Figure 32. The clearly greater increase of cirrus from eastern Iowa across northern Illinois and Indiana with very little slope increase across southern Illinois and Indiana is evident. An area of relative low frequency is seen extending from Duluth southeastward across lower Michigan.

The results from this stratification of the high cloud frequency data did not increase or improve our interpretation of the high cloud trend. In other words, the geographical pattern of the change in cloud frequency is not particularly improved by excluding those occurrences of cirrus ≥ 0.4 with low and middle observed clouds. The underlying assumption for using this stratification was that fewer low and middle clouds increase the likelihood that contrail cirrus would be observed, and that the relative frequency of high clouds over the high frequency jet airways would be increased. However, this does not seem to be the case since the spatial analysis is rather stable for either of these high cloud stratifications.

Clear Sky Frequency Trend

The cumulative result of the cloud frequency change indicated in the foregoing sections is illustrated by examination of the trend of clear sky observations.

The slope of the trend line is shown in Figure 43 illustrating that over the area through northern Illinois eastward, a decided downward trend was observed in the clear sky frequency. The only stations indicating a positive trend were Duluth, Des Moines, and Peoria.

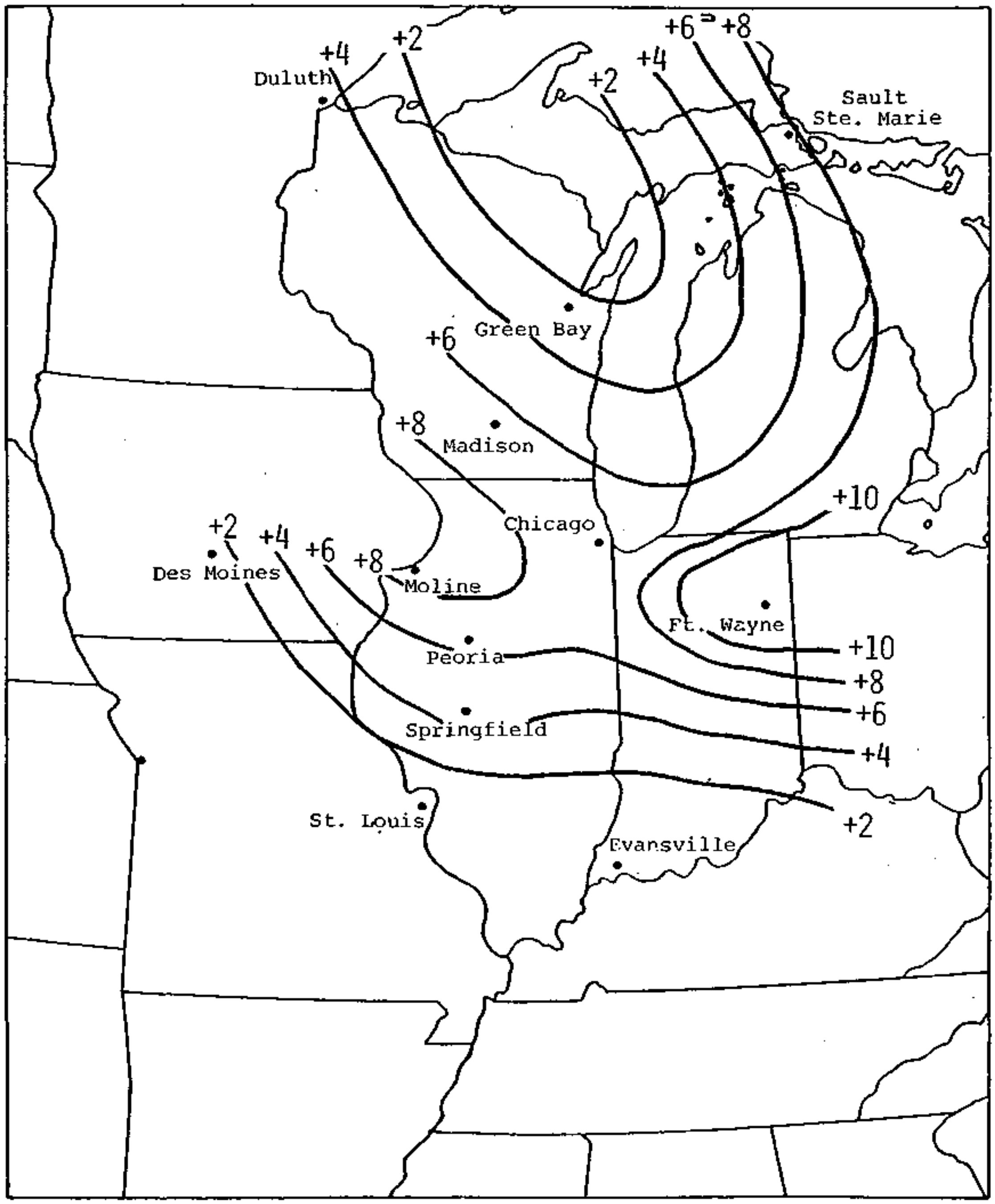
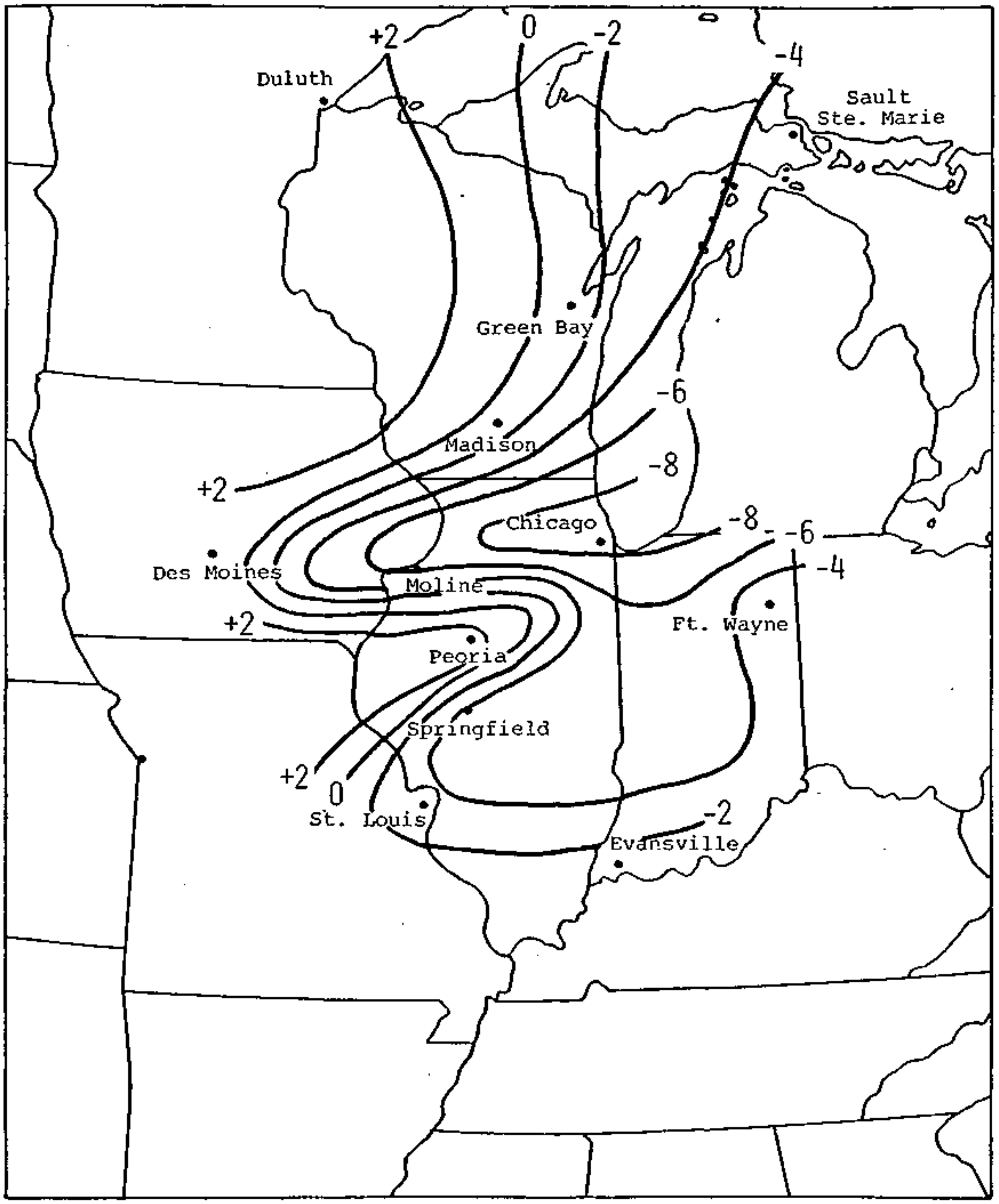


Figure 42. The 26-year trend line slope distribution for high clouds with ≤ 0.4 low and middle clouds.



Pigure 43. The spatial distribution of the 1951-1976 trend line slope of clear sky frequency.

Depicting the 1951 intercept values of the trend line at each station relative to the Sault Ste. Marie observation, the relative frequency of clear skies over the Midwest is shown in Figure 44. Interestingly, there were relatively greater numbers of clear days in 1951 through northern and southern Illinois, with Peoria somewhat of a negative anomaly. A similar analysis for 1976 (Fig. 45) shows an increase from the northeast to the southwest in the frequency of clear sky observations with the maximum number shown at Evansville. Study of these two figures reveals an increase in the relative clear sky frequency over Wisconsin and Michigan. The anomalies at Peoria and Moline were no longer evident in 1976 with a smoothly varying pattern prevailing. The frequency of clear skies (relative to Sault Ste. Marie) was little different over Indiana for the two years. In Figure 46 the 1951-1976 change in clear sky frequency is shown over the Midwest. The greatest decrease in clear skies was observed at Chicago with a tendency for a decrease over most of Illinois extending into Indiana.

Summary

From the foregoing analysis of individual cloud categories, it is extremely difficult to assign a component of the observed frequency variability of cloud observations to artificial cirrus produced by contrails. The proof of the contribution from commercial air traffic to the cirrus cloudiness is inferred from the relatively good pattern correlation between the frequency of aircraft across the research area and the decided changes in high cloud frequency.

To establish a correlation between jet aircraft in the upper troposphere and the increased occurrence of high clouds, detailed case studies including direct observation of contrails by eye or photography are needed. A careful

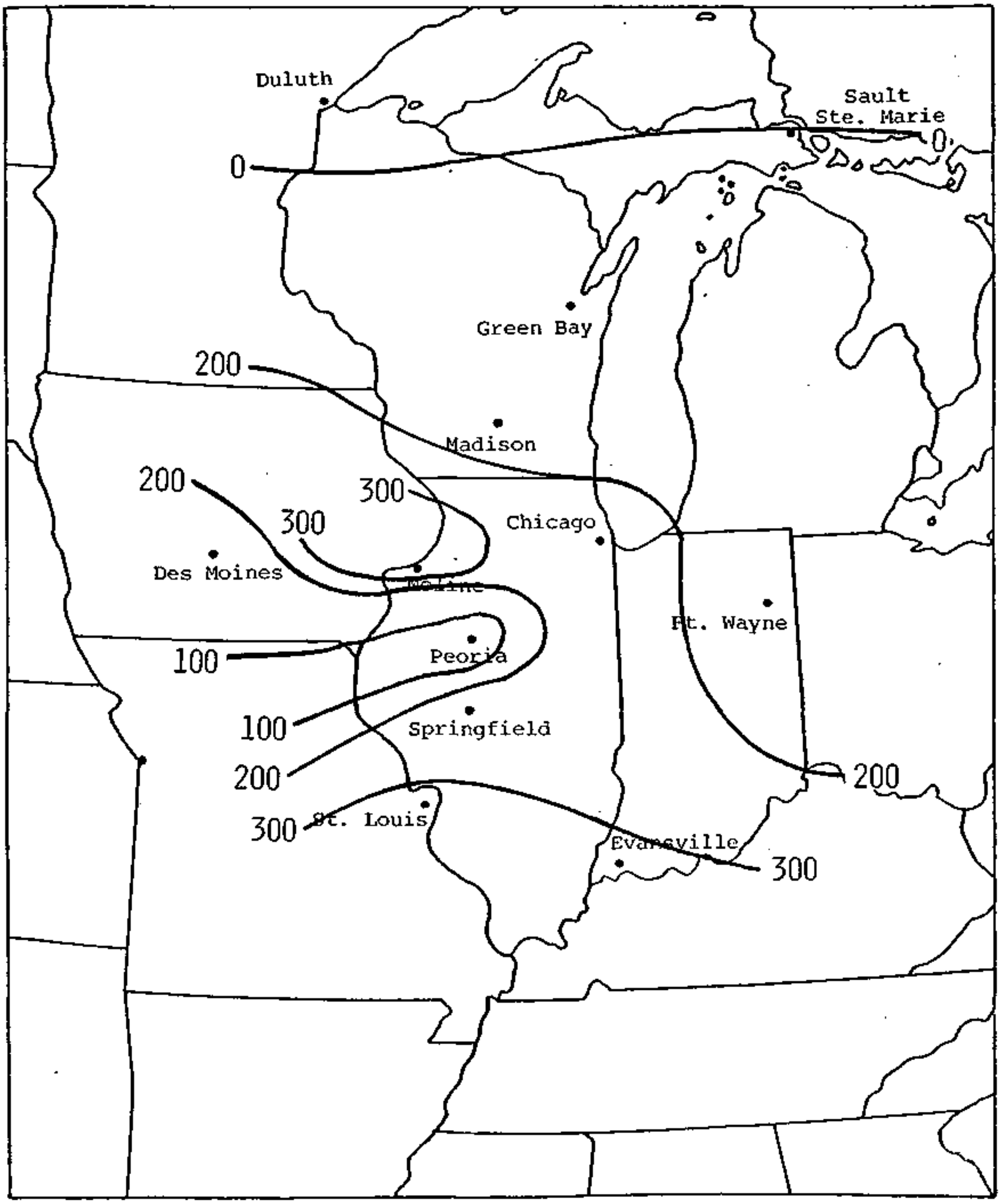


Figure 44. The clear sky frequency difference between Sault Ste. Marie and the other first order stations for 1951.

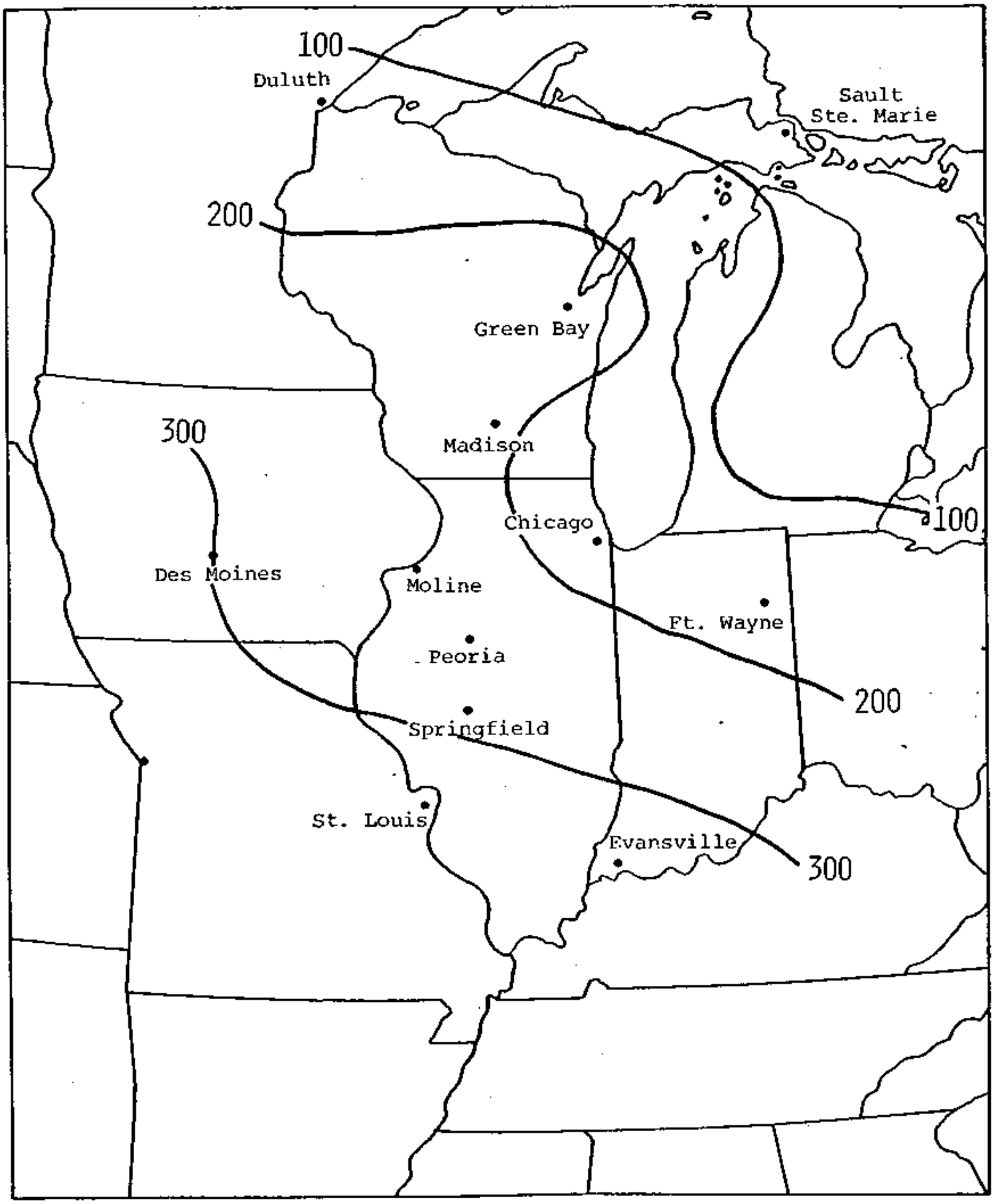


Figure 45. The clear sky frequency difference between Sault Ste. Marie and the other first order stations for 1976.

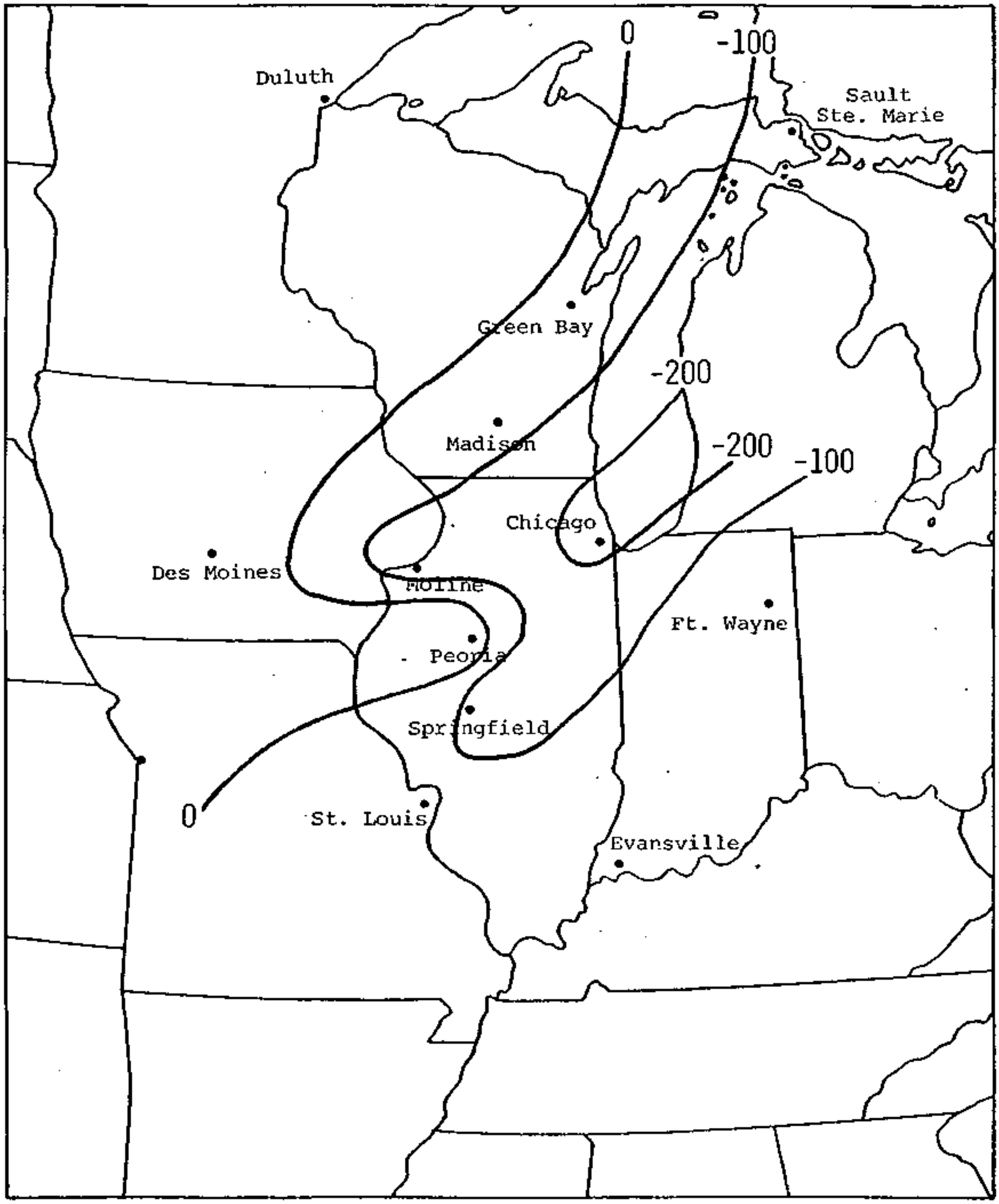


Figure 46. The 26-year change in clear skies obtained from the difference between the 1951 and 1976 frequencies.

documentation of control occurrence during a rather long period of time (such as 6 months or more) over a large area (such as Illinois) will permit development of a correlation between contrails and the commonly observed cloud types at first-order stations.

This study within the overall project has raised several questions which will be addressed in future research. In a manner analogous to determination of inadvertent effects of large cities on precipitation, the natural occurrence of high clouds must be determined to provide a baseline against which to judge the impact of artificial clouds. For example, without the spatial density and long-term precipitation records, the precipitation increases observed at many large cities would have been impossible to detect. Analogously, it is not possible to distinguish, with the current observational network, the increased high cloud frequency due to jet travel without a more dense network and longer term observation. However, as newly acquired measurements helped to elucidate the urban effects on precipitation, case studies of control formation will aid in interpretation of the available long-term cloud observations.

It is interesting that study of the trend line slopes for clear and high clouds shows that the consistent high, positive values of slope for high clouds (indicating an increase of cirrus clouds) is in contrast to the highly variable clear sky frequency trend line slope over the same area. The high cloud frequency trend over the study area is the most consistent of all cloud types studied. While this is not proof, it certainly is suggestive that these clouds are increasing at an anomalously high rate as compared to other cloud types and to the clear sky observations. Consideration of this result with the long-term cloud data and sunshine records, certainly supports the hypothesis of a non-natural influence on high cloud frequency.

CHAPTER THREE

CONTRAIL RELATIONSHPS LEARNED FROM USAF COMBAR DATA

Frequency of Jet Traffic During the Study Period and Study Area

Since the history of contrail frequency is essentially the history of jet aircraft, observations of jet traffic within the area of interest are crucial to the present study. The Federal Aviation Authority (FAA) furnished the data shown in Figure 47 which represents the total number of operations from 1957 thru 1978 for the FAA Aurora Center, which controls the air space over the Upper Midwest. The three tabulations on Figure 47 are very similar showing a constant increase in operations from 1957 through about 1970, with a rather constant number since that time to the present.

Figure 48 presents the total number of takeoffs and landings at both Lambert Field, St. Louis, and Midway and O'Hare Fields in Chicago. Again, the total number operations at Chicago increased with a doubling rate of about seven years from 1950 until the late 1960's, after which the rate of increase was much less. Little, if any trend is noticable in the short St. Louis record. The slowing of the growth rate in both Figures 47 and 48 beginning in the late 1960's is a function of the introduction of wide-bodied jets.

Jet aircraft comprised the major component of military aircraft, already in middle 1950's. Therefore, increases in jet aircraft and contrail formation, should be expected to begin about middle 1950's and continue to grow until the late 1960's and remain about constant to the present time.

The spatial distribution of jet flights over the ten state area is only partially known (see Figs. 2 and 49). Specific records of commercial jet flight tracks are not available. We found only one source of jet records

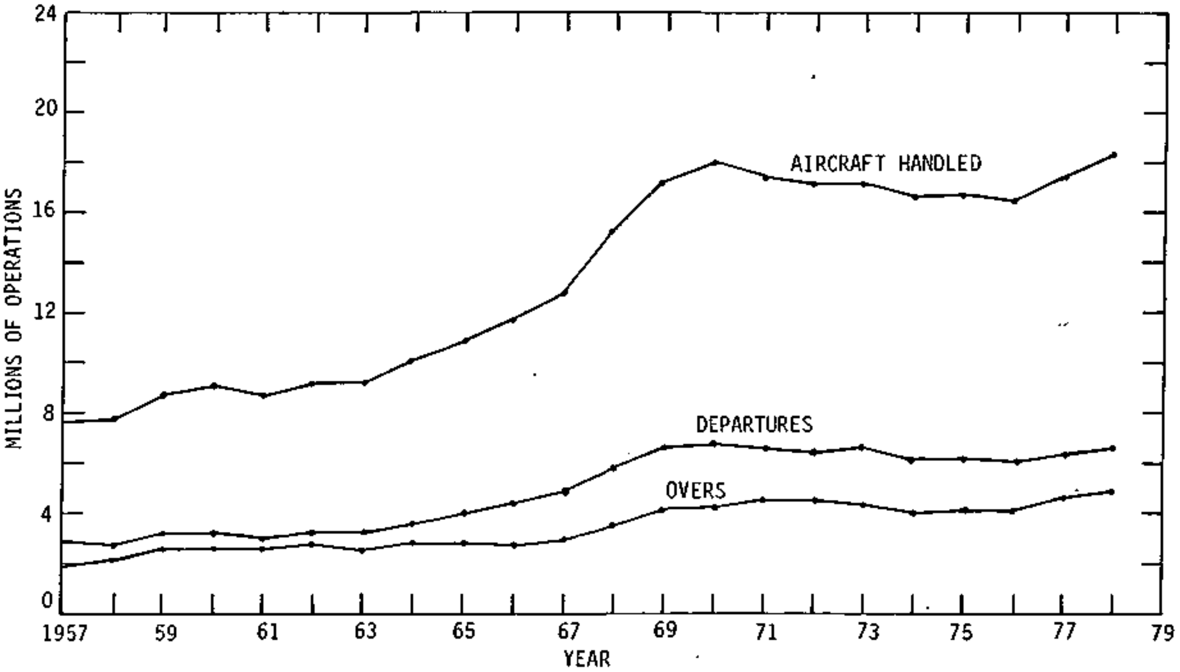


Figure 47. Total annual operations handled by FAA Aurora Center, which controls airspace over and around Chicago.

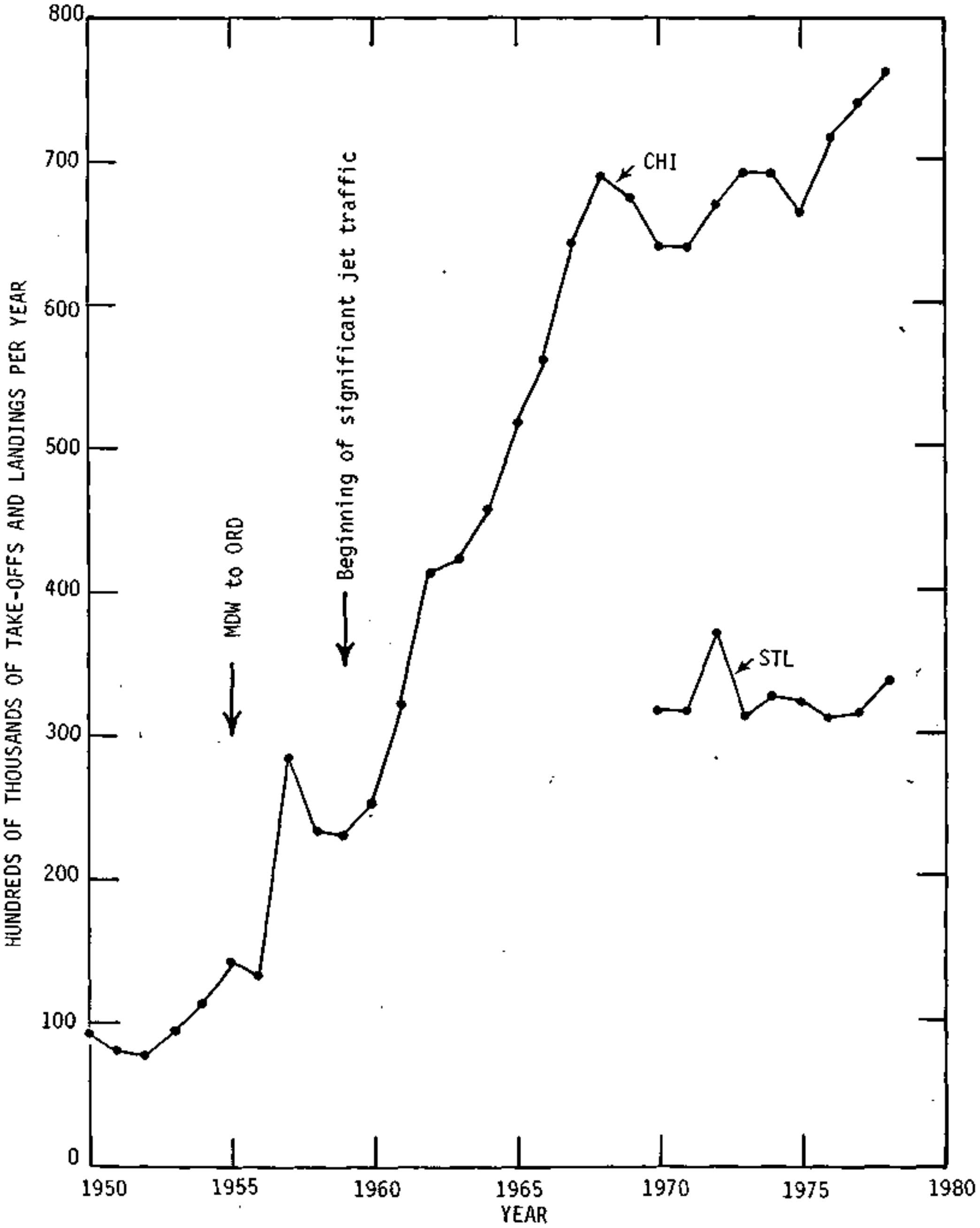
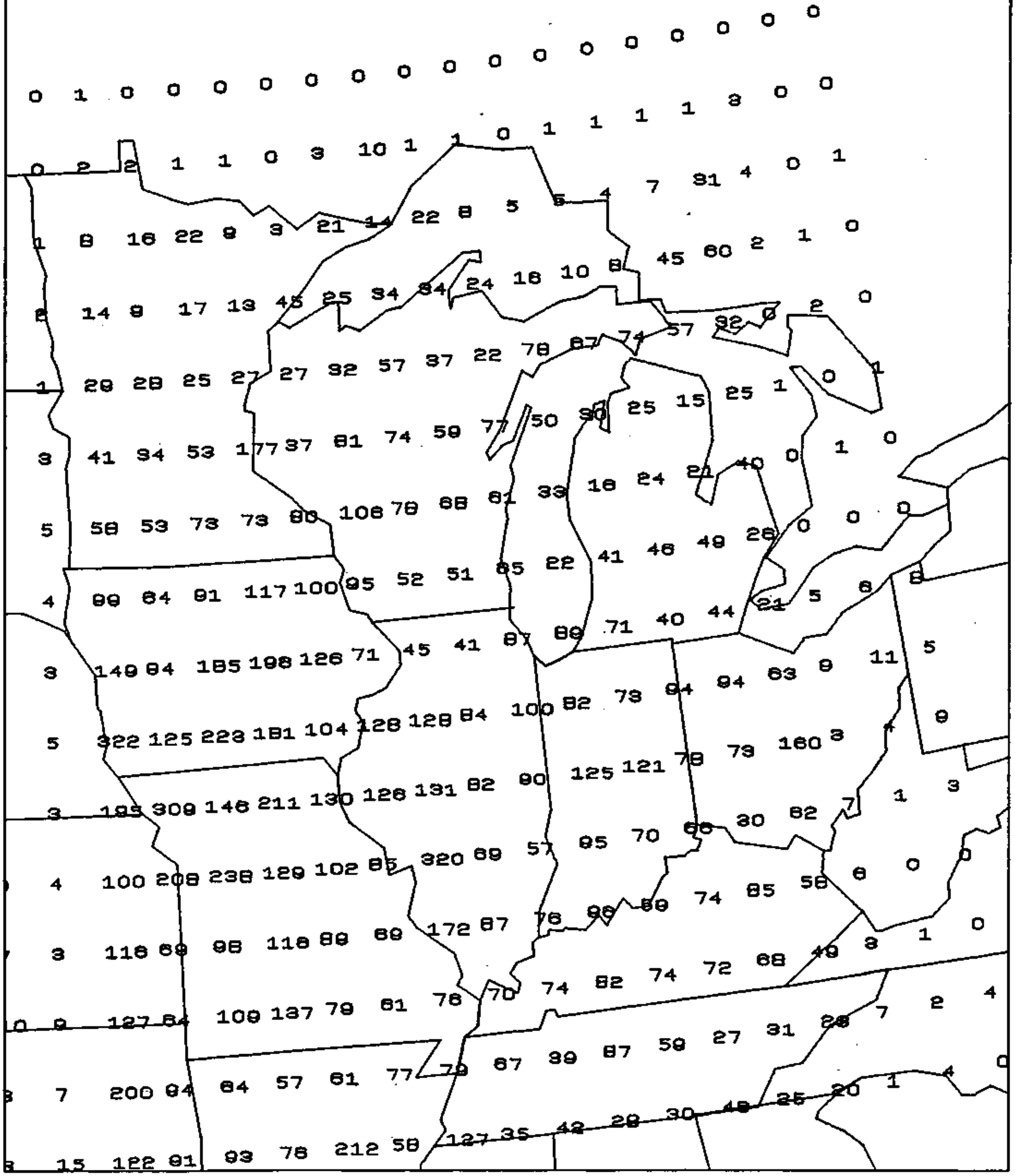


Figure 48. Total annual take-offs and landings at Chicago (Midway, MDW, and O'Hare, ORD) and St. Louis, STL.

Figure 49. Areal density of aircraft COMBAR reports, 1957-1969, used in this study.



which included the date of flight, latitude, longitude, and altitude. The one source was the U.S. Air Force Combat Meteorological Aircraft Report (COMBAR), record, and therefore represents only military traffic across the area of interest from 1957 through 1969. Figure 49 shows the total number of aircraft at each 1 latitude-longitude intersection from the total period of study. The general paucity of data near the periphery of the figure is due to instructions given to the data collectors, i.e., data were only to be copied from observations between 35 and 48 N latitude and between 82 and 96 W longitude. When Figure 49 is scanned, there is a great perponderence of observations from the Tulsa area to southeastern Nebraska, thence one branch to Minneapolis and Upper Michigan and another to central Indiana and southern Ohio. The greatest totals for any one degree latitude-longitude intersection are located in northwestern Missouri and south-western Iowa, undoubtly due to the concentration of several Air Force bases in southeastern Nebraska and northeastern Kansas. The local high density values east of St. Louis and in central Indiana and Ohio apparently reflect the location of other bases. The spatial distribution of observations with persistent contrails, non-persistent contrails and no contrails (not shown here), are essentially the same as that displayed in Figure 49. Though these data reflect military flights from 1957 through 1969, it is noteworthy that this density distribution closely resembles that for commerical jet flights for 1979 (see Fig. 2).

Observation of Contrails made Prior to the Present Study

Published information on the frequency of occurrence and the conditions necessary for contrail formation are very few in number. The information which follows is from two primary sources: Appleman (1953), and Beckwith (1972) updated to include data from 1976. The former is a review of Air Force contrail experiences from data gathered over several years, the latter is a collection of personal observations gathered over thirteen years while associated with a commercial airline.

Contrail formation appears to be essentially limited to flights within the troposphere. Since commercial airliners constitute the majority of jet traffic, and since they typically fly several thousand feet higher today as opposed to a decade ago (to conserve fuel and because they have more powerful engines), one might expect contrail formation to be less frequent today than 10 years ago, all other things being constant. In addition to the above potential trend, there is a potential annual fluctuation in contrail formation due to the fact that the height of the tropopause is typically located at about 15 km during summer, and decreases to a mean height of about 10 to 11 km in winter. Jet aircraft, flying at altitudes between 11 and 12 kilometers, fly essentially within the stratosphere from about December to April, therefore, contrail formation should be expected to be reduced during the colder half-year (Beckwith, 1972).

The following is a summary of Beckwith's personal flight log from 395 inflight observations made during about 179,000 nautical miles of flight between 1964 and 1976. The average flight altitude of the observations was 33,000 feet, although observations were made between 29,000 and 41,000 feet. He classified his observations into one of three catagories (1) no contrails, i.e., no visible plume behind the aircraft or a visible contrail extending less than 6 to 10 wing-spans behind the aircraft; (2) non-persistent contrails, i.e., contrails extending more than 6 to 10 wing-spans behind the aircraft with up to 5 minutes persistence; and (3) persistent contrails, i.e. , contrails persisting for more than 5 minutes behind the aircraft. (The authors are unaware of any widely accepted definition of "persistent" contrails, either in terms of time of persistence or spatial extent. Hence, the above defintion pertains only to this section.)

Using these criteria the following results were found. Thirty-seven percent of all observations exhibited no contrail formation, 38% of all observations experienced non-persistent contrails, and 25% of all observations experienced persistent contrails. Beckwith drew some tentative conclusions from his set of data which are applicable to our present study. He found that continuous formation of contrails for distances over about 500 miles is very infrequent. He also suggested that persistent contrails tend to form in or near natural cirrus clouds, or in advance of cirrus clouds associated with frontal activity. This topic is addressed further.

Data Sources Available to Document Contrail Location and Persistence

Contrails persist for differing lengths of time, not only from one day compared to another, but also from one part of the sky to another, or from one altitude to another on the same day. Quantified observations of the length of time that contrails persist, or of growth or contraction rates are extremely rare. Observations of these linear cirrus-like clouds may well shed light on the dynamics of the upper troposphere as well as humidity conditions, and may infer changing surface reception of insolation due to the presence of contrails.

An inventory of contrail observations could conceivably be completed from one of several possible sources, e.g., (1) standard hourly weather observations, (2) satellite imagery, (3) surface photography and (4) aircraft observations. Each of these will be discussed in order below.

Contrail Data from Surface Meteorological Observations

Although the occurrence of contrails is occasionally mentioned in the "remarks" column of a standard meteorological observation form, this source cannot provide an adequate record from which a systematic, synoptic study of contrail occurrence could be made. For example, in the middle 1950's, when jet aircraft were new but relatively few, and flights infrequent, an observer would often record the presence of contrails as a "remark" on a standard hourly observation. As time went on, however, and jet aircraft became much more common, such notations became fewer and fewer.

The above tendency precluded the use of standard meteorological observations in order to study the location and frequency of jet exhaust contrails from the mid-1950's to the present. Instead, an alternative set of observations were sought.

Contrail Data from Satellite Imagery

We investigated the possibility of using satellite imagery for studying contrail frequency over the area of interest. We studied images from GOES, LANDSAT, and DMSP satellites. The DMSP imagery showed the greatest resolution, but the interval between images was on the order of days, which precluded any possibility of studying contrail growth rates or location of contrail on a scale of hours. LANDSAT imagery has sufficient resolution, but again the interval between successive pictures of the same region is about eighteen days (nine days when two LANDSAT satellites were functional), again too long to permit growth studies and only a crude attempt at completing a contrail inventory with time. The imagery from the GOES satellite is available for every thirty minutes on a regular basis; however,the satellite is located over the equator, and our study area is very close to the image limb and, therefore, distances and locations are very difficult to specify in that region at the necessary resolution.

Contrail Observations from Surface Photography

The only source of picture images available to us to study the frequency, size characteristics, and growth rates of contrails is the record of an all-sky camera located on the roof of the Illinois State Water Survey building in Urbana. This camera has been in operation since early 1976 with only relatively few outages (due primarily to frost and very low temperatures, the former obscuring the reflective surface of the mirror and the latter slowing or stopping camera action). A portion of a silvered sphere, with a diameter of about one meter, is mounted on the roof, with a 16 mm camera mounted directly above. The camera is initiated by an intervolometer which exposes one photograph every five minutes. Each frame records the date as well as a clock image.

The 100 foot-long rolls of 16 mm film were scanned for the existence of aircraft condensation trails. About 3% of all the days of the 3 1/2 year-long record indicated the presence of contrails. This may appear to be anomalously few in light of other conclusions; however, the percent of the sky useable from an all-sky camera image is limited by the severe distortion at elevation angles less than about 45 (due to the configuration of the silvered hemisphere and lens distance). The "useable" area at 30,000 ft altitude above the camera is only about 115 mi^2, representing only a small percent of the whole sky visible by eye. In addition, contrail intensity and color seem to be enhanced with a low sun, the condition under which the all-sky camera is least effective. These two conditions may explain why contrails were only infrequently observed on the film record.

It is interesting to note that Detwiler (1980), when seeking contrail evidence on LANDSAT images, identified contrails on 355 of the ca. 13,500 images that were studied, a frequency of about 2.6%.

In order to obtain growth rates of the contrails, two observations were made from each frame for each contrail being studied: First, the altitude angle from the horizon to the lowest portion of the contrail, and second, the altitude angle from the horizon to the uppermost part of the contrail, to yield the contrail width in degrees. Observations were made on only relatively persistent contrails, i.e., those which persisted for several five-minute intervals and thus were recorded on several successive frames. The characteristics of 56 contrails were measured using this technqiue, 25 of which were expanding and 31 of which were dissipating.

Growth rates of the contrails were obtained by converting the width of the contrail in degrees into a linear measure. Although we had no record of contrail height, we arbitrarily assumed all contrails to be located at 30,000 feet. With this assumption, and trigonometry, the horizontal width of each contrail was calculated on each of the five-minute interval photographs.

Since contrails often tended to persist for a few tens of minutes, the growth rates represent the mean growth rate from several successive pictures. The mean longevity of contrails was about 25 minutes, and mean rates of change could therefore be averaged from six photos, although some were based on only two, and some on ten successive photographs. Of those contrails exhibiting expansion, the average growth rate of all observations was 18 km per hour with a standard deviation of 36 km per hour. The mean rate of contraction however, was 35 km per hour with a standard deviation of 65 km per hour. With the relatively small number of cases, it is unknown whether the slower rate for expansion should be interpreted as being significantly different from those showing contraction, although the contraction rates were about twice the magnitude of the former. It is also unknown whether "contraction" designates areal contraction (a phenomenon not frequently observed), or dissipation by evaporation, or a loss of the image due to moving lower on the hemisphere (where greater distortion occurs). The magnitudes of the standard deviations suggest a relatively large difference in growth rates from one photograph to that of five minutes later. The relatively large standard deviations may also point to the relatively crude method used to calculate the growth rates.

The discrepancy between the number of, and frequency of, contrails noted by eye from the surface of the earth as opposed to the frequency observed by either the all-sky camera or inspection of LANDSAT images requires some discussion. Beckwith (1972) found that persistent contrails were observed in about 25% of the several hundred observations he made over several years from commercial aircraft, and casual contrail observations made from the surface, also suggest a contrail frequency of between perhaps 10 and 30%. Actual counts, however, of contrail days from the ISWS all-sky camera and several thousands LANDSAT images reveal contrails only between 2 and 3% of all the days observed. Although the casual observations of contrails were not continuous nor rigorous, the discrepancy between contrail frequency obtained visually and that obtained by counting photograph images, is sufficiently large to demand attention.

Assume for a moment that the contrails in question are at an altitude of 30,000 ft. If one were to scan the sky between the angles of 45 through the zenith to 45 , the total distance between those two points at 30,000 ft is only about 19 km (12 miles), a distance traversed in about 1.2 minutes by jet aircraft. Similarly, the distance between 30 from the horizon through the zenith to 30 above the horizon is about 32 km (20 miles), a two minute jet trip. Even if one traverses the distance between 10 from the horizon through the zenith to 10 from the horizon, the distance at 30,000 ft is about 104 km (65 miles) or a 6 1/2 minute journey by jet aircraft. Essentially, a jet aircraft or one point along a contrail would only necessarily be seen in one frame of the all-sky camera since it exposes one frame every 5 minutes. However, if the contrails are persistent, existing for at least 15 minutes, and moving in the wind field at 30,000 ft at about 30 knots, they might only appear on two consecutive frames of the all-sky camera. On the other hand, contrails persisting for longer than 30 minutes, but passing through only small portions of the airdrome, may not be seen in even one frame of the all-sky camera I

Without knowing the number of trajectories of jet aircraft across the sky, nor the exact altitude or the length of time that contrails persist, a corrective factor cannot be applied to the observed camera or LANDSAT data in order to obtain a more realistic estimate of the contrail frequency.

The LANDSAT system records a continuous series of images of the surface of the earth under the satellite track, however, the same point on the earth is only photographed once every 18 days. Since the vast majority of the earth surface is not typically over-flown by jet aircraft, estimating contrail frequency with the use of LANDSAT imagery from any and all areas of the earth would seriously underestimate the frequency. On the other hand, if the frequency were to be estimated using LANDSAT imagery from only areas containing jet airways, then only 20 images per year would be available for each location to be studied, again underestimating the total frequency.

Contrail Observations from Inflight Observations

A non-pictorial source of information which proved to be very valuable for this study was information taken from observations made by U.S. Air Force pilots during the 1950's, 1960's and early 1970's. The Combat Meteorological Aircraft Report (COMBAR) was required of all USAF bomber crews, and was a standardized method to make hourly meteorological observations, or at any other time when either aircraft or environmental characteristics changed. The parameters included on the form are position (latitude and longitude), date, time, altitude, outside air temperature, wind direction and speed, occurrence of turbulence, whether contrails were being formed (and whether they were persistent or non-persistent), and cloud occurrence above, at, and below the level of the aircraft. These observations were routinely made by air crews, and after arrival at their destination, the observtions were transmitted on the meteorological teletype network. Since crews were required to make these observations hourly and at other locations along the flight plan, tens of thousands of observations were made each year. Observations appear to have been more numerous during the 1950s than during 1970s, perhaps as the number of flights declined. The teletype data are not archived to our knowledge, nor were the data from the COMBAR forms put on punch cards or magnetic tape. However, the forms themselves were archived in the Federal Records Center (FRC) at East Point, GA, which contains tens of thousands of COMBAR observations. The COMBAR observations stored at the FRC presumably include all those submitted to USAF weather stations within the United States. We should again note that the thousands of observations are not uniformly dispersed over the U.S. Rather, they frequent airspace around USAF bases, and seem to favor specific routes (see Fig. 49).

Observations were extracted and punched on computer cards. Observations within the area of interest were copied, i.e., 34 to 48 N latitude (roughly Little Rock to International Falls) and 83 to 96^0 W longitude (roughly Detroit to Sioux City). About 16,000 observations were extracted, about half of them with persistent contrails, the other half without contrail activity (see Table 8). Because of time and cost constraints, not all COMBAR data from the FRC could be copied. We therefore arbitrarily decided to about equally sample observation with and without contrails. Monthly observation density from 1956 to 1969 is shown in Table 9.

The observations were made between 1956 and 1969 and are by no means evenly spaced in time. The great majority of observations were from 1957, 1958, 1961, and 1962, with less than 450 observations taken during any other year, and no observations from 1963 and 1964 (see Table 9).

Our record of contrail observations is a function of (1) the frequency and the routes "preferred" by Air Force flying personnel during the several years of record; (2) the location of Air Force bases; and (3) the efficiency of the record saving system, i.e., the efficiency with which COMBAR forms eventually reached the Federal Records Center. Because of the above conditions, our record cannot be used to study frequent areas of contrail formation, only areas of preferred formation given the flight routes. Similarly, temporal changes in contrail frequency or associated atmospheric conditions cannot be discerned from these data.

Results from the COMBAR Study

Many of the atmospheric characteristics listed on the COMBAR form were analyzed according to the occurrence or non-occurrence of contrails. Several of the results were largely expected and/or yielded little or no insight into

Table 8. Number of COMBAR observations used in this study.

Year	w/ Contrails	w/o Contrails	Total
1956	0	2	2
1957	2574	2071	4645
1958	1643	1129	2772
1959	5	32	37
1960	1	12	13
1961	2525	1916	4441
1962	1845	1417	3262
1963	0	0	0
1964	0	0	0
1965	263	182	445
1966	76	51	127
1967	3	21	24
1968	4	17	21
1969	1	2	3
	8940	6852	i5,792

Table 9. Temporal distribution of COMBAR observations used in this study.

	J	F	M	A	M	J	J	A	S	O	N	D
1956							2					
1957		22	542	431	467	176	239	149	703	754	592	602
1958						27	242	490	394	761	192	756
1959												
1960	12					1						
1961	677	627	511	215	398	394	650	210	188	91	230	314
1962	835	210	707	715	18	312	20	53	101	109	79	121
1963												
1964												
1965	80	80	85	25	69	67		5	8	10	10	12
1966	57	36				34						
1967	2				23							
1968	5	5	2	6	2		1					
1969								1			1	1
Total:	1696	980	1847	1392	1087	1011	1153	898	1394	1728	1104	1806

the study of contrail formation, e.g., the mean latitude and longitude of the observations were found (as expected) to be about the mid- section of the area of interest; the mean wind direction (both with and without contrails through all months of the year) was westerly; and the distribution of COMBAR observations through the 24 hours of a mean day exhibited fewest observations between 0600 and 1200 Z, (0000 to 0600 CST) which only reflected the fact that most flights were made during the day or early evening. The relatively high concentration of Air Force bases in eastern Nebraska and Kansas was apparent in Figure 49.

There were some associations, however, which did yield useful information. About 72% of all observations with contrails reported persistent as opposed to non-persistent characteristics. The above percent may be somewhat uncertain since no generally accepted definition of persistence is known to exist.

Evidence from flights, both with and without contrails, shows that about 25% of all observations encountered turbulence of some magnitude (see Table 10). There is no apparent annual fluctuation in the frequency of turbulence from those flights without contrails. Of those flights which did produce contrails, turbulence is slightly more frequent than flights without contrails Turbulence is (slightly) more frequently encountered during the summer half-year. The mean frequency of turbulence for flights without contrails was 25%, that for flights with contrails was 30%, the winter half-year being about 25% and the summer half-year being about 35%. The reason for higher frequency of turbulence during the summer half-year is probably a function of typical cruising altitudes, e.g., mean altitudes during the summer were about 5000 ft. higher than those during the winter. Higher altitudes during the summer place the aircraft in the upper troposphere, near the tropopause and jet stream, with a higher probability of encountering turbulence.

Table 10. Summarized information from C0MBAR observations.
Number of observations given in parentheses.

	Turbulence Obs		Clouds Above Aircraft Level		Clouds At Aircraft Level		Cloud Below Aircraft Level		Mean Altitude w/o Contrail	Mean Altitude w/ Contrails	Mean Temperature w/o Contrail	Mean Temperature w/ Contrails
	No %	Yes %	No %	Yes %	No %	Yes %	No %	Yes %	(100s of feet)		(°C)	(°C)
J	22 (764)	23 (932)	20	10	11	7	42	57	296	338	-39	-46
F	25 (461)	31 (519)	21	8	14	8	55	62	292	350	-36	-50
M	25 (834)	27 (1016)	18	7	9	10	51	66	314	328	-41	-49
A	22 (601)	30 (794)	18	11	15	14	58	69	311	350	-41	-49
M	26 (462)	41 (633)	20	11	13	16	53	69	313	366	-36	-52
J	25 (494)	32 (517)	27	15	18	16	57	73	299	383	-33	-48
J	29 (568)	35 (589)	25	14	16	19	65	77	328	386	-36	-49
A	26 (419)	36 (491)	20	11	11	14	59	79	329	389	-35	-50
S	22 (641)	30 (754)	18	9	11	13	62	79	326	377	-36	-49
0	22 (800)	30 (928)	12	7	10	10	49	63	325	367	-43	-49
N	28 (518)	25 (586)	21	8	12	10	57	68	324	358	-41	-50
D	21 (799)	25 (1007)	15	9	8	10	52	74	319	340	-42	-47
Mean:	25	30	20	10	12	13	55	70	314	361	-38	-49

NOTE: "NO" indicates observations with no contrails. "YES" indicates observations with contrails.

The number and density of contrails is undoubtedly greater than that observed from the ground because clouds below the aircraft often obscure a surface observation of the total sky. The COMBAR observations support that claim, in that about 70% of flights observing contrails also observed natural clouds below the flight level of the aircraft (see Table 10) . According to these data, only about one-third of all contrails can be seen from the ground. In contrast, aircraft not observing contrails did observe clouds below the aircraft flight level 55% of the time. There is an annual fluctuation in the frequency of clouds below the aircraft, i.e., there tend to be more clouds below the aircraft flight level during summer than during the winter, the values being about 78% during the summer, and about 60% during the winter.

Observations of the frequency of clouds <u>at</u> flight level show essentially no difference between observations with or without contrails. For both contrail and non-contrail observations, about 13% of all observations included clouds at the flight level with a slight increase in frequency during the summer half-year. The average frequency of cloud encounters at flight altitude may be less meaningful than other observations, since pilots may opt for a different flight altitude if visibility is impaired by existing cirrus clouds.

Clouds <u>above</u> the aircraft flight level were observed in about 15% of all cases. The mean frequency for flights without contrails was 20%, whereas the mean frequency for observations with contrails was only 10%. Again, this is undoubtedly related to the mean flight altitude of contrail vs no contrail observations, i.e., 38,000 ft. for the former and 31,000 ft. for the latter (see Table 10). At these altitudes, an increase of just a few thousand feet places the aircraft in the upper extremes of the troposphere or even in the lower stratosphere.

Clouds above aircraft flight level are typically a few percent more frequent during the summer half-year in both contrail and non-contrail situations. It is unknown why this is the case. The fact that observations without contrails (see Table 10) have more frequent clouds above the aircraft level, is probably because observations without contrails were made from about 5000 ft below those with contrails.

A small sampling was made to estimate the frequency of contrails during the various months of a year. About the first 300 observations for each month of 1961, encountered in the assemblage of COMBAR cards at the Federal Records Center were collected, and the number of contrail and no contrail observations were counted. The results of that "grab" sample are shown in Figure 50. According to this limited sample, contrails occur in about 26% of observations from all months, and were more frequent in February, March and October than the remainder of the months.

As mentioned above, there was a significant difference between the mean altitude of flights with and without contrails, the mean altitude of the former being 36,100 ft. and the mean altitude of the latter 31,400 ft. In both "with" and "without" contrail instances, mean altitudes in summer are a three to five thousand feet higher than mean winter altitudes. The annual variation in flight altitude may merely reflect the fact that pilots tend to seek altitudes where aircraft attain higher efficiency in colder temperatures. The higher mean altitude for observations with contrails supports the findings of Appleman (1953), who suggested that contrail frequency was inversely related to temperature, and hence directly related to altitude. The annual mean altitude for observations with non-persistent contrails was about 1,400 ft below those with persistent contrails.

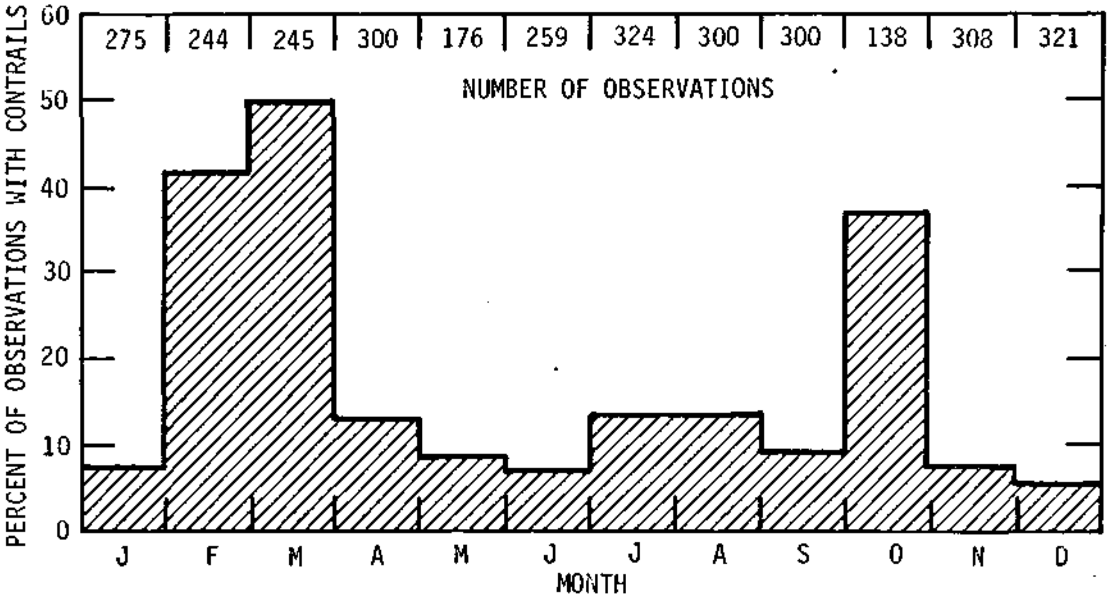


Figure 50. Percent of COMBAR observations with contrails from each month of a subsample of 1961 data. Numbers across top show monthly sample size from which percent was calculated.

Again, as mentioned earlier, mean air temperature at flight altitude was about 11 C colder for observations with contrails than those without, the former being -49 C and the latter -38 C (see Table 10). This is clearly related to the differences in mean altitude between observations with and without contrails.

Similar parameters were calculated for observations with persistent contrails, and for non-persistent contrails. The results of these two separate data sets were essentially the same as the data presented in the above discussion (which included both persistent and non-persistent contrails).

Identification of Daily Contrail Areas

The several thousand COMBAR observations from aircraft both with and without contrails gave us the opportunity to identify areas with contrails from those without on any given day. On any one of the few thousand days with COMBAR observations from 1956 to 1969 there were typically ten to twenty COMBAR observations somewhere within the area of the Upper Midwest, although the actual number for any day varied from 1 to at least 100.

Daily maps showing the location of COMBAR observations both with and without contrails were plotted by computer for 1957, 1958, 1961, 1962 and 1965. The plottings were limited to these years because of the relatively fewer data available for other years. About 500 days from those 5 years exhibited in excess of about 20 observations for each day, sufficient to allow contrail areas to be identified from those areas where contrails were not forming. These maps form the foundation of a contrail inventory for the Upper Midwest from 1956 through 1969. The use of these maps will be discussed in the section "Future Research."

Spatial Relationship between Contrails and Synoptic Circulation Features

Using the data supplied from the COMBAR records, relationships between contrail areas and large-scale synoptic circulation features were assessed. A total of 1,242 days were identified within the 13 years (4,745 days), with contrails. This cannot be interpreted as a reasonable estimate of the temporal frequency of contrails, since the COMBAR frequency was primarily a function of flight time and area during the years with observation.

To assess a relationship between the location of contrail areas and the synoptic circulation features, twelve different surface synoptic circulation features were defined, and each of the contrail areas of the 1,242 days with contrails were counted as being related to one of the 12 major features. The features of circulation which were used in the study include the features mentioned in Table 11. If any of the first 8 features were within 400 km of the contrail area, the contrail was associated with that feature. If the contrail area was not within 400 km of any of the first 8 categories, then it was arbitrarily assigned one of the last four features, i.e., north, east, south, or west flow. About 21% of total contrail days were not categorized with any of the 8 principal circulation features, but were categorized according to the local direction of flow.

Results of this study are found in Table 12. First, note that the percent of cases associated with the circulation feature to the west of the contrail area is essentially the same as the number of cases associated with the same circulation feature located to the east of the contrail area. This relationship holds for high pressure centers or ridges, low-pressure centers or troughs, cold fronts and warm fronts. Therefore, from these data, it appears that the proximity to a certain circulation feature is more important

Table 11. Features of the general circulation which were studied for spatial association with contrail areas.

1. High pressure center or ridge to the west of the area
2. High pressure center or ridge to the east of the area
3. Low pressure center or trough to the west of the area
4. Low pressure center or trough to the east of the area
5. Cold front to the west of the area
6. Cold front to the east of the area
7. Warm front to the southwest of the area
8. Warm front to the northeast of the area
9. Contrail area in northerly flow
10. Contrail area in easterly flow
11. Contrail area in southerly flow
12. Contrail area in westerly flow

Table 12. Percent of cases when contrail area is within 20 nm of given circulation feature of the 1200z surface weather map for the day in question.

	High Pressure		Total Anti-clonic	Low Pressure		Cold Front		Warm Front		Total Cyclonic	NLY	ELY	SLY	WLY
	to W	to E		to W	to E	to W	to E	to SW	to NE					
Jan & Feb	26	12	38	5	8	7	13	3	5	41	5	7	6	3
July & Aug	17	28	45	11	3	12	9	2	1	38	12	2	1	2
Year	18	18	36	9	6	11	11	3	3	43	9	5	3	4

than whether the circulation feature is advancing toward or receding from the contrail area (remembering that all associations were within 400 km of the contrail area)

Contrails were most frequently associated with a low pressure center or a trough of low pressure at the surface. Thirty-six percent (see Table 12) were associated with high centers or ridges, whereas forty-three percent (43%) of the contrail areas were within 400 km of one of the following: Either a low pressure center, a trough, a cold front, or a warm front, with the cold front being the most frequent individual feature, i.e., 22%.

There is a slight preference for contrails to be associated with surface cyclonic features throughout the year, although that preference is reversed during July and August when most contrail areas are associated with anti-cyclonic situations. The reason why contrail areas tend to be primarily associated with anticyclonic systems during July and August is not understood.

For those cases where no major circulation feature was within 400 km of the contrail area, the area was categorized according to the direction of surface flow. From Table 12 one can see that the most frequent direction was northerly (i.e., northwest through north to northeast), sponsoring cold air advection. Also note that there is essentially no difference in the association with contrail areas and the direction of surface flow from yearly data to that of winter or summer, with the exception that easterly flow is the most frequent observed direction in the winter season.

The location of contrail areas was also studied in relation to pressure systems and the maximum wind belt and the direction of flow in the middle-troposphere. Contrail areas for each day were located in relation to the trough and ridges of the 500 mb surface. The contrail areas were categorized according to one of the following five situations: Within 800 km either to the east or the west of a ridge, or 800 km east or west of a trough, or not related to either a ridge or a trough. Data from 1957, 1958, 1961, and 1962 were used in this study. For all months of the year, and for December, January, and February, and for June, July, and August, the results were essentially the same, i.e., about 60% of all contrail areas were located within 800 km either to the east or west of a trough, and about 1/3 of all the contrail areas were located within 800 km to the west of a trough (see Table 13). There was no seasonal variation.

The persistent relationship between contrails and troughs at 500 mb is as expected. However, the fact that most of the contrail areas were located to the west of the trough line, i.e., the area of decreasing convergence, is perhaps not expected, although contrails were earlier found to be associated with cold air advection, a feature associated with the west side of a trough. One might expect the most frequent contrails to be located to the east of trough lines, i.e., the area with increasing cyclonic activity and increasing convergence. This may actually, in fact, be the case in this instance. Contrails are typically located near the 300 or 250 mb surface, whereas the trough and ridge lines in this study were identified from the 500 mb surface, 10,000 to 15,000 feet lower than the typical contrail altitude. Since virtually all troughs slope toward the northwest with increased altitude, the troughs of 500 mb would be located some distance to the west at 300 or 250 mb, and would place some of the contrails located to the west of the 500 mb trough line either on or to the east of the trough lines at 300 or 250 mb. We are unable to determine whether most contrail areas would in fact be relocated east of the 300 or 250 mb trough line, however, since the percentages to the east and west of 500 mb trough lines were very close (see Table 13) we may safely conclude that the contrail areas are located within the trough area at 300 or 250 mb.

Table 13. Percent of observations of contrails associated with various features of 500 mb pressure surface. Number of observations in parentheses.

	500 mb RIDGE		500 mb TROUGH		500 mb MAXIMUM WIND BAND			
	East	West	East	West	North	East	South	West
Annual	22	20	32	26	50	15	21	15
	(277)	(263)	(402)	(334)	(571)	(171)	(238)	(170)
Winter	16	20	36	28	47	14	29	10
(D,J,F,)	(49)	(60)	(110)	(87)	(136)	(39)	(83)	(30)
Summer	19	24	33	24	60	18	8	14
(J,J,A)	(60)	(73)	(102)	(73)	(165)	(48)	(23)	(37)

The relationship between the contrail areas and the maximum wind band was again determined using a 500 mb chart. The contrail areas were categorized into one of the following four situations: To the north, to the east, to the south, or to the west of the maximum wind band as indicated at the 500 mb surface. About half of all contrail areas were located within 800 km to the south of the maximum wind core at 500 mb. Again, as with the pressure relationships, there was no seasonal change (see Table 13). About 20% of all contrail areas were located within 800 km to the north, and about 15% were located within 800 km either east or west of the maximum winds. The greatest seasonal percentage variation occurred with those contrail areas located to the north of the maximum winds, 21% for the year, 29% for the winter months, and 8% for the summer. This may be due to the rather small sample size available for the summer season (see Table 13).

The relationship of contrail areas to the 500 mb wind flow direction yielded essentially the same results as the relationship determined earlier between wind direction reported on the COMBAR reports with contrail , occurrence. Because of the predominance of westerly winds in the Upper Midwest during all seasons, about half of all contrail areas were associated with westerly flow, 12 to 30% were associated with northwesterly or southwesterly flow.

In summary, contrail areas are best correlated with low pressure features at the surface and in the middle-and upper-troposphere.

Contrails-Daytime or Nighttime Phenomenon?

Prior to 25 years ago, there was a general consensus among forecasters that cirrus clouds more frequently occurred during the daytime. This conclusion evolved, not so much from a definitive study, but from routine meteorological observations which exhibited greater observations of cirrus during the day. The advent of jet traffic in the middle 1950's rekindled an interest in cirrus frequency because pilots of high altitude jets frequently reported restrictions to visibility at nighttime although no cirrus were visible, nor reported from nearby weather stations.

The diurnal frequency of contrails, too, has been questioned. They, like cirrus clouds, are thin and often transluscent, therefore making detection difficult. In addition, the areal coverage of contrails is typically much less than that of cirrus clouds making them particularly difficult to see at night.

Although COMBAR observations were collected with the purpose of obtaining about the same number of contrail/no contrail observations per day, no care was taken to ensure equal numbers of contrail/no contrail observations for day- and night-time hours. The observations for each 24 hr period were divided into day and night observations, and the following results represent those data.

Contrail frequency during the day during the summer half- year, i.e., April through September, included all observations between 1100 Z and 0100 Z (0500 CST to 1900 CST). Daytime observations during the winter half year (October through March) were limited to 1300 Z to 2300 Z (0700 CST to 1700 CST). Nighttime observations during the summer half-year included those between 0300 Z and 0900 Z (2100 CST to 0300 CST), and nighttime observations during the winter half year included all observations between the hours of 0100 Z and 1100 Z (1900 CST to 0500 CST).

About 7600 of all COMBAR observations fell into the aforementioned time catagories. Daytime observations were 3 to 4 times more numerous than those taken during the night, and winter observations are about 1/3 more numerous than those from the summer oeriod.

During summers, 56 percent of daytime observations and 45 percent of nighttime observations experienced contrails. In winter, the percent of total observations with contrails was 61 percent during the day and 41 percent at night. In both seasons, contrails tend to be slightly more frequent during daylight hours than during the night, although the difference in percent is small. The small size of the difference may only be due to the ease with which contrails may be seen during daylight as opposed to night.

It is difficult to determine whether the differences noted above are significant. The slight difference may only be indicative of the difficulty of seeing contrails at night, particularly during flights with no moon. From the results of the study above and attending discussion, it is difficult to claim more than: Contrails appear to form with the same relative frequency, during daylight hours as during hours of darkness.

Summary of COMBAR Observations

The above discussion may be summarized as follows. Turbulence is more frequently encounted on flights with contrails than without contrails, and turbulence is somewhat more frequent in summer than in winter. Natural clouds (other than high level cirrus) are more frequently encountered with contrail occurrence than without. High level cirrus (clouds above aircraft level) were more frequently noted when contrail were not produced.

All forms of natural clouds were more frequently observed during the summer half-year.

Since flights with contrails encountered clouds below aircraft level about 70% of the time, it appears that contrails are significantly underestimated from ground observations, i.e., only about one-third of all contrails may be seen from the ground.

Suggestions for Future Research

We recognize that this research only begins to answer some of the more apparent and unanswered questions concerning contrails and their effect on surface climate. The data set which we compiled is only partial, i.e., only including COMBARS from the Midwest and archived at the FRC in East Point. At some later date, additional data should be collected and put on magnetic tape so that spatial differences of effects may be identified for different spatial and time scales. Our present data set of 15,000+ observations was adequate to the present objectives.

We have prepared a preliminary day-by-day inventory of contrail occurrences for most days from 1956 through 1969. The inventory is not all-inclusive, i.e., contrail areas can only be defined for areas with observations. A more complete inventory may be prepared as more observations become available.

The above inventory clearly identifies several score of days from 1956 to 1969 with contrail areas with well-marked boundaries. Rawinsonde observations within three hours of the time of contrail observation, both for contrail and near by non-contrail areas, will form the data base from which pressure, temperature and vertical motion characteristics for each of both areas can be determined. This analysis should enhance the capability of forecasting contrail occurrence.

In addition, those days of this study identified with frequent and dense coverage of observations, will be used to study the contrail effects to surface temperature, percent possible sun and cloud cover, from an individual case study analysis rather than using monthly mean data.

Whenever the possible effect of a forcing function (contrail) on a response function (clouds, sunshine, moderated temperature) are studied using parallel spatial and temporal records to discover coincident trends or discontinuities (as we are), a more complete and finer-resolution data base may increase the information learned from the study. Therefore, studies of (low, middle and high) cloud amount over an area larger than the Midwest will strengthen the conclusions reported herein. A most obvious extension of this type of work is to investigate cloud amount trends over other areas within the US with frequent jet traffic (metropolitan airports and high-altitude airways), and contrast those results with those from areas with little jet traffic.

With the results of this case study analysis, contrail frequencies of the recent 25 yrs over the US may be reconstructed, to ascertain the increase in cloud cover of increased jet traffic on natural cloud cover.

There are obvious problems in attempting to non-physically study "forcing" and "response" functions, i.e., study by coincidence of trend or discontinuity in the two record, rather than by fine resolution observations of contrails, and sensing changes in radiation components, both above and beneath the contrail. Physical observation of the contrail and its environs require a jet aircraft, appropriately instrumented to measure short- and long-wave fluxes, both up and down; and on-board collectors to determine the size distribution of particulates and crystals within the cloud. At some future date, a concerted effort will be made to collect these data.

CHAPTER FOUR

CONCLUSIONS

The following statements recapitulate specific findings of this research. Detail may be found in the summary portions of each of Chapters 1, 2, and 3.

Casual observations suggest that contrails produced by jet aircraft often persist and spread into cirrus veils, thus increasing the total cloud cover at least at cirrus altitudes. This research addressed the question: Is the increase to natural cloud cover due to jet contrails of significant magnitude (1) to be seen in cloud cover observations from National Weather Service stations in the Upper Midwest and (2) to modify temperature and insolation received at the earth's surface.

The first objective was to identify areas and times with jet traffic and areas and times with observed contrails. Simultaneously, cloud cover, surface temperature and insolation were studied over the ten state area to identify areal and temporal patterns in these records which may be coincident with aircraft flight and contrail records.

The results of this research, fully described within the final report, are summarized in abbreviated form, without explanation in the following statements:

1. Jet air traffic began in the mid-1950's, grew at a rapid, steady pace until about 1970, continued to grow but at a slower rate until the present.
2. The area with the most frequent jet traffic within the ten state area of interest includes central and northern Ohio, Indiana, and Illinois; southern Iowa, central Missouri, and the area about eastern Tennessee.

The results of our research, listing changes in cloud cover surface temperature and insolation at the surface, do not <u>prove</u> a cause-affect relationship between contrails and the atmospheric environment. We show changes in the numbers of aircraft operations with time, the spacial distribution of those operations, and a time series of several meteorological parameters over coincident times, and suggest that the latter effects, being synchronous with aircraft operations may be causally related to the aircraft operations. Physical relationships between aircraft operations, contrails, and the surface environment cannot be developed until substantial observations are made in, above, and below contrails, to measure the physical conditions including attenuation to the insolation.

3. In all the states with data, the area roughly including northeastern Oklahoma to eastern Illinois, with one branch to Michigan and another extending into eastern Tennessee experienced decreased numbers of clear days (increased number of cloudy days) with time. This area is very similar to the area experiencing the most frequent jet traffic.
4. The percent possible sunshine from stations within the area of interest trends downward with time from Iowa along a broad path to eastern Tennessee. The trend in percent possible sunshine is either up or exhibits no change elsewhere within the area of interest. This result is also areally similar to our findings of jet traffic density distribution.
5. Autumn, the season with minimal cloud cover in the Upper Midwest, experiences the greatest change in possible sunshine with time (see #4 above).
6. In all sectors of the midwestern study area, the number of clear days decrease from about 1935 to about 1950, decreasing more slowly thereafter.

7. The frequency of moderated temperatures (a decreased difference between daily maximum and minimum) increases beginning during the late 1940's or 1950's. A particularly pronounced increase is noted over northern Illinois and Indiana, again an area with with high jet traffic density. For Urbana, although the number of smoke-haze days decreased since about 1950, the number of cloudy days and days with moderated temperature increased since about the same time!
8. Middle clouds became less frequent over the study area from 1951 to 1976 at all stations except SSM and MLI. The greatest decline was noted over DLH, southeastern Wisconsin and southern Illinois.
9. The frequency of high clouds increased from 1951 to 1976 at all 12, stations studied. When the observations with high clouds were stratified to include only those with 0.4 or less low and/or middle cloud, the amount of high cloud still was found to increase over the 26 years.
10. The frequency of days with clear skies decreased over the 26 years at all stations except Duluth and Peoria. The greatest decline was noted from Chicago to southern Iowa, and another branch from Chicago to southern Illinois.

The figures showing frequency or temporal trends in cloudiness, percent possible sunshine, etc., exhibit trends and discontinuities of varying magnitudes over the 40 to 70 years of record. In addition, several of the significant changes in trend are not associated with either the areal or temporal distribution of jet traffic. this should not be an unexpected finding, since jet traffic is likely only one of several causal mechanisms which may be effecting response functions at the surface. According to an earlier study by Beckwith (1972), during about 180,000 miles of flight during which about 400 observations were taken, 37% of those observations exhibited no contrail formation, 38% exhibited non-persistent contrails and 25% exhibited persistent contrails. In contrast, contrails were only noted on about 3% of the total observations both from a 2 1/2 year reocrd of an all-sky camera at Urbana, and from several thousand LANDSAT images studied by others. Even casual experience suggests that this frequency is lower than actual. The low frequency from LANDSAT imagery may be expected due to the lapsed time between successive photographs of the same region, i.e., 14 days. The analysis of the all-sky camera imagery may also be biased because of distortion of contrails or clouds when located in the area between the horizon and an altitude angle of 45 , and because of the short time that an aircraft or non-persistent contrail remains in the field of view.

11. Of 25 cases of spreading contrails which continued for at least 20 minutes, the average rate of spread was about 18 kilometers per hour. The average dissipation rate of 31 such contrails was about 35 kilometers per hour.

The following information (#12 through #21) represent findings summarized from USAF pilot reports.

12. Of all the pilot reports during which contrails were being formed, 72% were persistent contrails.
13. Turbulence was encountered between one-quarter and about one-third of all observations, being slightly more frequent with contrails than without (30% vs 25%).
14. About 70% of all contrail observations occurred with some cloud cover below the aircraft altitude. Therefore, only about one-third of all contrails can be seen from the gournd due to intervention from natural cloud cover. Of those aircraft observations without contrails, natural

clouds were observed below aircraft altitude about 55% of the time. Clouds below the aircraft flight altitude are about 10% more frequent during the summer than during the winter half-year.

15. Clouds were observed at aircraft level about 13% of all observations, both with and without contrails. Again, there is a slight increase in frequency during the summer half-year.

16. Natural clouds located above aircraft altitude were observed only 10% of the time when contrails were being formed, and only 20% of the time when no contrails were formed. Again, there is a slight frequency maximum during the summer half-year. Mean flight altitude of all observations with contrails was 36,000 ft, and 31,400 ft for those observations without contrails. The mean altitude of summer observations is about 5,000 ft higher than those during winter.

17. Mean outside air temperature for those observations with contrails was -49 C, and -38 C for those observations without contrails, a function of altitude.

18. For a small sample of cases (about 300 observations per month), contrails (non-persistent or persistent) were observed on between 10% and 15% of all the flights during all months except February, March and October during which the contrail frequency was between 40 and 50%.

19. There may be a slight preference for contrails to be observed during daylight hours as opposed to during times of darkness. About 56% of all daylight observations in summer reported contrail formation, whereas only 45% of summer nights reported contrails. Similarly in winter, 61% of all daytime observations reported contrails whereas only 41% of winter nights observed contrails. These findings are somewhat uncertain since about equal numbers of contrail/no contrails observations were obtained for each day during the several years of record.

No effect was made to obtain equal numbers of observations from daylight and nighttime periods, however, the fact that the percent frequency of contrails is close to 50%, suggests that the numbers are strongly biased by the collection method. However, it is interesing and perhaps significant that there was a 10% difference in the frequency of contrail observations between summer nights and summer days, and a 20% difference between winter nights and winter days. Although the absolute percent frequencies may not be reliable, the diurnal differences in frequency may indeed be significant.

20. There was a slight preference for contrail areas to be located closer to surface troughs than ridges. A stronger relationship was found between contrail areas and mid- and upper-tropospheric pressure features, i.e., pressure troughs and the location of the maximum wind belt. Contrails were much more frequently found associated with a 500 mb trough (58%) than with a ridges (42%). There was essentially no seasonal variation.

21. Half of all contrail areas were located within 800 km to the south of the maximum wind belt at 500 mb. In summer, the frequency increased to 60%, in winter 47%.

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