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TEMPORAL DISTRIBUTIONS OF GLOBAL THUNDER DAYS

By

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CONTENTS

INTRODUCTION

Thunder-day frequencies during the 1901-1980 period from 90 weather stations throughout North America, and 131 other stations scattered around the world were studied to describe the statistical properties and climatological rationale of their seasonal and annual fluctuations.

Earlier studies of the 1901-1970 data from a limited number of stations indicated that the stations in the central and eastern United States had their lowest frequencies of thunder days in the 1951-1970 period, ranging from 10% to 30% below their 70-year averages (Changnon, 1977). Mackerras (1977) had found similar decreases in Australia. Minima found in these areas during the 1951-1970 period were a result of a general downward trend in the frequencies of days with thunder that began at many U.S. locations in the 1930's. Upward trends in thunderstorm days, comparable to the downward trends for 1935-1970, were found at more northerly stations, those in Canada. These results were interpreted to reflect possible shifts in atmospheric circulation patterns leading to the displacement of mean frontal positions, and to suggest the possibility that inadvertent atmospheric alterations produced by humans may have helped cause the change in thunderstorm frequencies, at least in some parts of North America.

Regardless of the causes, study of such thunderstorm changes offered the opportunity to gain a better understanding of atmospheric electricity and of the severe storm climatology of the world, and to provide guidance for properly interpreting climatic records.

The proposed study sought data for a study period of 1901-1980. Particular attention was given to a definitive statistical analysis of the thunder-day frequencies over North America (the United States and Canada). The analytical emphasis was on statistical treatment of the data, basically in a descriptive format. Temporal characteristics of the North American stations were used to define regions of similarity. Regionality so defined, was compared with various climatic and geographical regions. Through both spatial and temporal analyses we tried to infer some of the causes of the fluctuations found. Primary causation of trends or changing variability included a) natural (non man-induced) fluctuations, b) observational errors or problems, and c) effects related to man's accidental influence on the atmosphere.

The overall goal of the study was to provide data and information useful in obtaining a better understanding of conditions in two important topical areas of the atmospheric sciences: atmospheric electricity and climatic change. Efforts to better understand the global atmospheric electric circuit in which thunderstorms play a fundamental role can benefit by having readily available data and information on the spatial and temporal frequencies of thunderstorm activity. The earth and thunderstorms are two current sources of equal strength but opposite polarity.

Furthermore, the number of thunderstorms is critical since they play such an important role as an element, or generator, in the global air-electric circuit (Muhleisen, 1977).

The results of the project also help address the issues of climatic fluctuations and their causes. For example, man-generated aerosols have been noted to affect the electrical conductivity of the atmosphere (Gunn, 1964; Cobb and Wells, 1970), and Boeck (1977) indicates that gases released from nuclear plants (e.g., Krypton 85) will cause an increase in the ionization rate of the atmosphere. Natural and human-made aerosols not only affect the conductivity of the atmosphere with the degree depending on meteorological conditions, but they also have an effect on cloud electrification processes including the thunderstorm charging mechanism (Vonnegut, 1963; Paluch and Sartor, 1973). Indirectly, shifts in thunderstorm activity, either up or down, in the more settled and highly industrialized parts of the world, as compared to activity in other less populated areas, may suggest selective and regional scale influences on atmospheric electricity, partially realized through effects on thunderstorm electrification.

Goal and Objectives

The initial objective of this climatological study was to obtain and evaluate quality long-term historical data on thunderstorm-day frequencies. The second objective was to describe their seasonal and annual fluctuations during 1901-1980. The third objective was to study the fluctuations including major trends and changes in variability at individual stations and over regions (groups of stations). This regional analysis then focused on various climatological zones to help infer possible causation for noted temporal shifts, a fourth objective.

The edited data for the 221 stations have been entered on computer tapes and are available to any user at cost. The availability in computer compatible format of not readily available thunderstorm-day statistics will be helpful in broader efforts to model and to understand climatic change.

This report is organized around four chapters. Chapter 1 addresses the data obtained, the data evaluation methods, and the final data base. Chapter 2 focuses on results from several studies of the North American data. Chapter 3 addresses the global (non-North American) data and results, and Chapter 4 interprets and summarizes the key results.

THUNDER-DAY DATA AND THEIR EVALUATION

The major emphasis of this study, although worldwide in scope, included a focus on the data from North America. North America was chosen for a mesoclimatic analysis because of the greater density of records available and of high quality, at least over a long period of time. To this end, data for the 1901-1980 period (or major portions thereof) were obtained for 65 stations in the mainland United States, 1 in Puerto Rico, 2 in Mexico, and 22 in Canada. Most stations had complete records for the 80-year period under investigation, although a few had records that began a few years after 1901 or that ended a few years before 1980. The U.S. data were from the first-order stations of the U.S. Weather Bureau, stations manned 24 hours per day by trained observers. The Canadian stations were also manned by trained observers.

These data and those for other stations around the world were all received in a tabulated paper format. Once received, the data were entered on computer tapes for a variety of evaluation analyses that were to ensue.

Potential Data Quality Problems

Any study seeking to discern temporal fluctuations in weather/climate events over extended periods of time must have quality data. All possible sources of incorrect values or changes in values related to a variety of observational circumstances must be investigated.

Observational Techniques. One possible source of problems involves the changes in observing rules or techniques during the 1901-80 period. Examination of rules relating to the reporting of thunder days in the U.S. and Canadian records revealed no change in observing rules during 1901-80. The definition for recording a thunder day in use today was established in 1893. A thunder day was reported when observers heard, at any time between midnight and midnight, thunder with or without rain. One or more peals of thunder at the station were used to indicate a thunder day in 1901 as well as in 1980.

However, certain other observational changes had to be considered. Certain first-order stations were manned 24 hours a day for many years and then at discrete times, often due to budget reductions, observations were not made during the entire day. This resulted in no observers on duty during the early morning hours (often midnight to about 0500). This brings on a potential for "missing" early morning thunder events and a false lowering of thunder day frequencies. Thus, the hours of operation of all stations had to be examined.

Other observational rules can influence the point frequency of thunderstorms. For example, there is a well recognized nocturnal maximum of thunderstorm activity in the central United States (Court and Griffiths, 1982). At stations in this area, which record thunder days on the basis of midnight-to-midnight, one can get a count of two thunderstorm days based on a single thunderstorm occurring before and after midnight. This inflates the number of thunderstorm days reported in that area.

Another possible influence on the process of recording thunder relates to the advent and growth of commercial aviation. Beginning with the growth of commercial aviation in the late 1930s, pilots have been briefed about weather conditions at the weather stations. They also had the opportunity to report to observers occurrence of thunderstorms. The possibility exists that occurrences of thunder could be entered in the logs because of the pilot report when indeed the actual weather observer did not hear the thunder. This is not believed to be a serious issue, but it is one that has a potential for influence on thunder-day frequencies.

Station Locations. A second general area of unnatural influence on thunder-day data relates to station locations. Many of the U.S. first-order stations were located in central business districts at the start of the Century, and then during the 1930s or early 1940s, were relocated to rural airport sites to serve the needs of aviation. These shifts of station locations from downtown to rural airport sites have potential for producing differences in thunder-day frequencies. One potential influence might be viewed as natural spatial differences. For example, in Chicago the influence of Lake Michigan on thunderstorm activity may suppress activity and produce a real difference from conditions at Midway Airport located many miles from the lake; hence the shift of the station from the downtown, or the near lakeshore area, to the area west of the lake might produce a difference just because the thunderstorm climatology differs locally. This type of difference could also exist in stations located close to major mountain ranges such as Denver.

Another potential problem related to station relocations concerns audibility and changes in the noise level. Since a thunder day is measured by audibility, one has to be concerned about noise levels, particularly for instances of distant thunder. One can hypothesize that downtown business sites were generally noisier than comparable rural sites and hence caused certain distant thunder events to be missed more often than at rural airports. Conversely, due to the noise of commercial aircraft, particularly at busy urban airports, distant thunder events might be missed. This factor is not easily evaluated quantitatively.

Another problem possibly affecting thunder reporting is the advent in recent years in the use of air conditioning at the weather stations. With windows closed, there is the potential for reducing the ability to hear distant thunder, and hence a reduced thunder frequency. These influences, if they existed, presumably developed in the 1950's and 1960's (depending on city and airport size and on aircraft frequency). The basic possibility exists that the influence of additional aircraft traffic and air conditioning would lead to a decrease in recorded thunderstorm activity.

Court and Griffiths (1982) have cited another factor affecting thunderstorm reporting in the high mountains of the western United States. It has been noted that stations at higher elevations report considerably more thunderstorms than those stations at lower elevations or in valleys. The number of thunderstorm days reported at stations increases by about 20 days per kilometer of elevation. Reasons for this effect offered by Court and Griffiths include a) possibly storms on distant mountains can be observed more readily at higher places and their thunder carefully awaited; or b) sound may be attenuated less than at lower atmospheric densities; or c) the ambient noise may decrease with elevation. Whatever the reason, certain high elevation stations in the western U.S. such as Sante Fe, New Mexico, Colorado Springs, and Flagstaff, Arizona, have very high thunder-day averages. For these reasons, their data were not included in the study. As much as possible, we chose lower elevation stations from the western 11 states for this study.

Evaluation and Testing Procedures

The influences on thunder frequencies due to the above identified problems are not easily identified. Basically, the potential shifts in thunder-day frequencies due to non-climatic causes, if sizable, were investigated by a series of three tests. First, all station data were plotted by 5-year and 10-year totals. These were then compared with dates of known station relocations. If sizable shifts in frequencies, up or down, occurred immediately after the station relocation, the station was put on a questionable list for further checking.

The second evaluation test involved a series of paired station comparisons. Since many of the possible influences relate to potential activities in the larger cities and at busy airport stations, comparisons were made between data of first-order stations located at adjacent big and small cities. Examples of these are Springfield, Missouri, compared with Kansas City; Cheyenne, Wyoming, with Denver; Cairo, Illinois, with St. Louis, etc. The list of 16 paired stations undergoing this "big and little" station test is shown in Table 1. This approach helped to assess further whether there were major differences between stations largely related to problems or influences at the large city stations, with the assumption that the small city or town stations were largely uninfluenced. The process of evaluation involved a comparison of the sixteen 5-year values plotted on graphs, as shown in figure 1. Comparisons involved data of the large station and its adjacent control station. In figure 1, the St. Louis, MO and Cairo, IL values are shown. These stations are 75 miles apart and although Cairo has a higher frequency due to latitudinal differences, the variations are similar. Hence, the St. Louis station values were considered satisfactory based on this comparison.

The final evaluation of the stations, including the ones that were labeled as questionable because of frequency changes at times of station relocations, was done through regional intercomparisons. The 5- and 10-year distributions of annual thunderstorm frequencies at stations in

Table 1. Pairs of North American Stations Assessed for Differences between Large Cities with Busy Airports and Nearby Small Communities

Large Station Evaluated	Control (Small) Station	Assessment
Washington	Harrisburg, PA	Satisfactory
Philadelphia	Harrisburg, PA	Satisfactory
Baltimore	Harrisburg, PA	Satisfactory
Portland	Eastport, ME	Questionable
Boston	Eastport, ME	Satisfactory
Atlanta	Augusta, GA	Questionable
Cleveland	Sandusky, OH	Satisfactory
Houston	Corpus Christi, TX	Satisfactory
Kansas City	Springfield, MO	Questionable
Chicago	Moline, IL	Satisfactory
Denver	Cheyenne, WY	Questionable
Vancouver	Victoria, BC	Satisfactory
Toronto	London, BC	Questionable
Montreal	Ottawa, Ont.	Satisfactory
New York	Albany, NY	Satisfactory
Dallas	Abilene, TX	Satisfactory

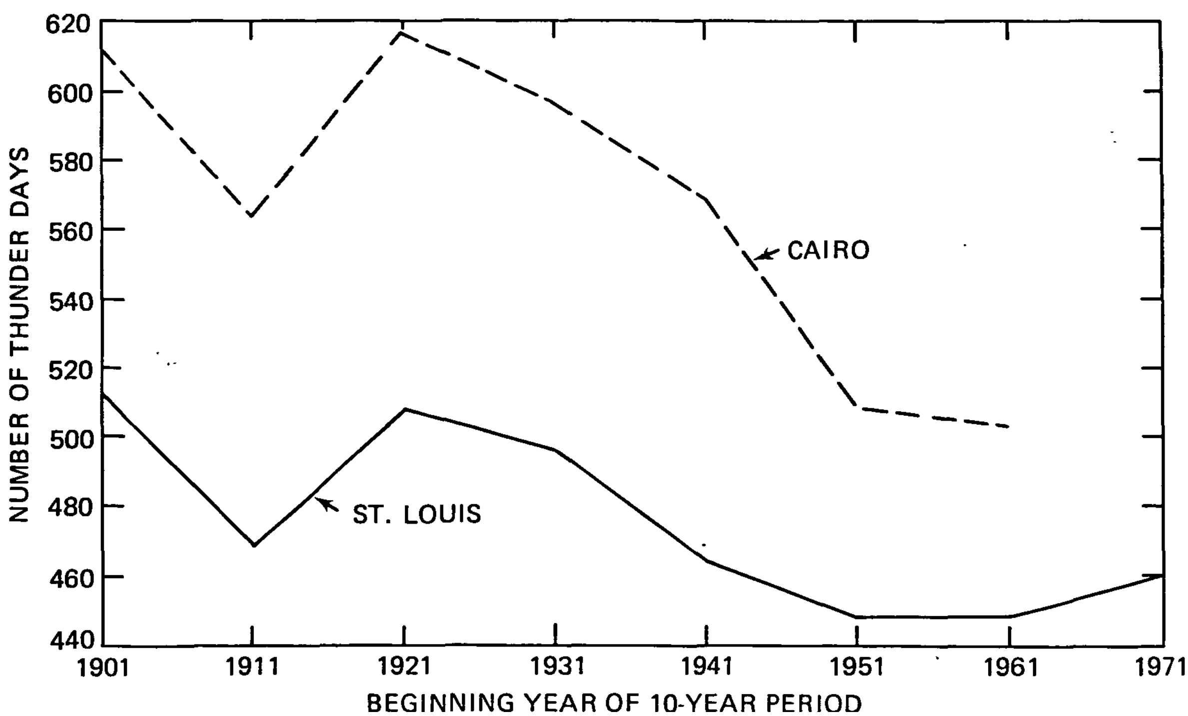

Figure 1. Comparison of thunder-day frequencies at St. Louis and Cairo

regions were compared. These were always grouped by regions of expected climate homogeneity. For example, stations along the Gulf Coast were compared, as were all stations in the southern Great Plains, northern Great Plains, Midwest, and those around the Great Lakes, etc. This final evaluation helped assess whether certain questionable stations fit or did not fit within the distributions found in adjacent stations.

Results of Evaluation: Data Used

North America. The examination of the temporal distributions of all stations against dates of their relocations, indicated that two stations (Denver and Kansas City) appeared questionable (figure 2). After further regional evaluation, it was concluded that only the data at Kansas City had been unduly affected by a 1934 station relocation. This station was eliminated from analysis. Regional comparisons of Denver data indicated the values after 1934 were satisfactory.

The "target-control," or paired station tests, compared 16 large city stations with nearby small city stations (Table 1). It suggested that Atlanta, Toronto, and Portland, ME had questionable records. Figure 3 presents the 5-year curves of these stations and their controls. Portland appeared to have increases to values that were relatively too high, in relation to those at Eastport in the 1926-45 period. The comparison of Toronto data with London, Ontario, data shows closely related values up through 1930, but then dramatically lower values occur at Toronto after 1950. Comparison of Atlanta and Augusta shows the station values varied around each other from 1901 through 1940, but during the 1941-45 period, the Atlanta values reduced. The final evaluation involving regional comparisons for all stations resulted in the conclusion that Toronto had frequencies that were very questionable.

Importantly, none of the station pair comparisons showed unusual shifts at large cities in the late 1950's, 1960's or 1970's when aircraft traffic including jets increased dramatically at the major U.S. airports. Furthermore, the questionable records were not found at the largest cities and busiest airports such as those at New York, Chicago, Boston, Philadelphia, or Washington. The conclusion about questionability of records is that local influences, when they have occurred, were infrequent and were largely associated with urban-to-airport relocations. They were not related to aircraft frequency at airport stations nor to urban size. They appeared to be random and related to uniqueness of some airport facilities.

Table 2 presents a list of the quality North American thunder stations for all or most of the 1901-80 period. The station locations in North America are shown in figure 4.

Elsewhere. Data were acquired from all other continents. Often it was less than the desired 1901-80 study period. Table 3 lists the 131

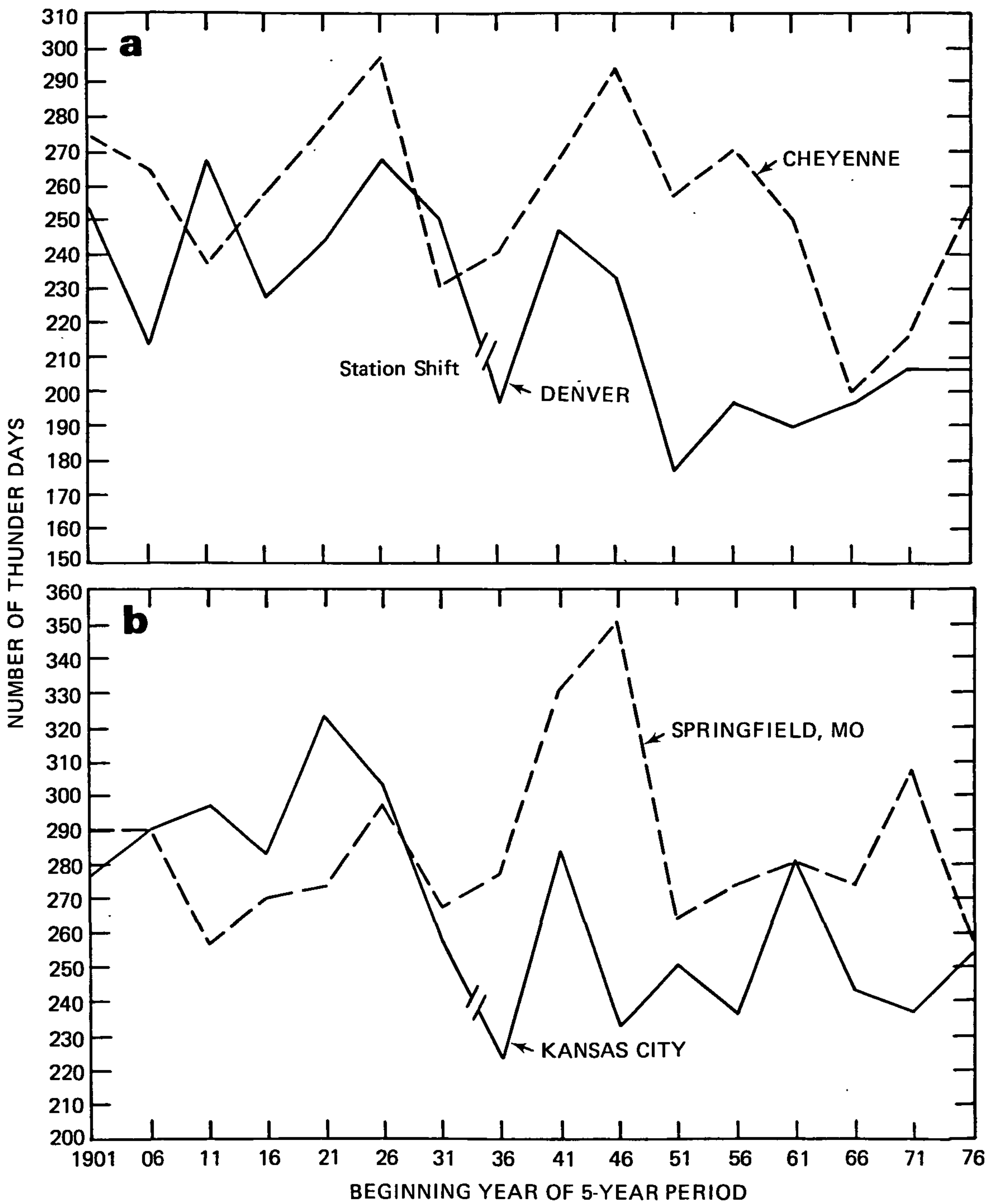

Figure 2. Evaluation of thunder-day frequencies at Denver and Kansas City

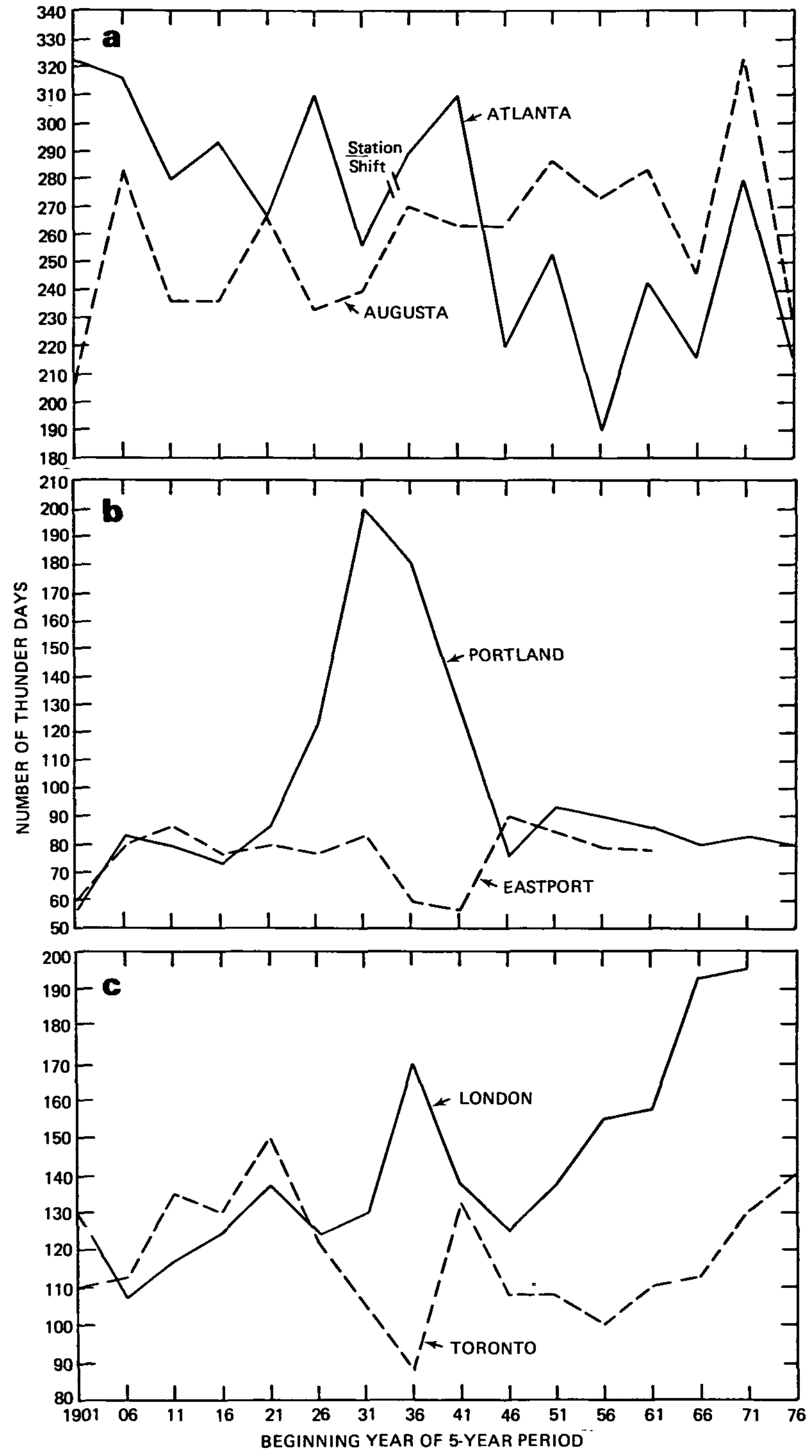

Figure 3. Evaluation of thunder-day frequencies at Atlanta, Portland, and Toronto

Table 2. Thunder-Day Data for North America
(The Period of Record is 1901-1980 Unless Shown Otherwise)

ID	Station, State (Province)	ID	Station, State (Province)
MIA	Miami, FL (1912-1980)	CIR	Cairo, IL
TPA	Tampa, FL	HOU	Houston, TX
AGS	Augusta, GA	HAR	Harrisburg, PA
ATL	Atlanta, GA	SKY	Sandusky, OH
MGM	Montgomery, AL	EPM	Eastport, ME
MSY	New Orleans, LA	LEX	Lexington, KY
GLS	Galveston, TX	SLC	Salt Lake City, UT
CRP	Corpus Christi, TX	YQI	Yarmouth, NS
DFW	Dallas-Fort Worth, TX	PWM	Portland, ME
ABI	Abilene, TX	YXU	London, Ont.
ROW	Roswell, NM (1905-68, 75-80)	YUL	Montreal, Que.
ELP	El Paso, TX	YOW	Ottawa, Ont.
PHX	Phoenix, AZ	GRB	Green Bay, WS
LAX	Los Angeles, CA	MIC	Minneapolis, MN
RDU	Raleigh, NC	RAP	Rapid City, SD
CAE	Columbia, SC	SHR	Sheridan, WY
BNA	Nashville, TN	BOI	Boise, ID
LIT	Little Rock, AR	PDX	Portland, OR
AMA	Amarillo, TX	YFC	Fredericton, NB
DCA	Washington, DC	YQM	Moncton, NB
BAL	Baltimore, MD	YQY	Sydney, NS
PHL	Philadelphia, PA	SSM	Sault Sainte Marie, MI
STL	St. Louis/Lambert, MO	YWR	White River, Ont.
SPI	Springfield, IL	DLH	Duluth, MN
IND	Indianapolis, IN	YQT	Thunder Bay, Ont.
SGF	Springfield, MO	BIS	Bismarck, ND
DDC	Dodge City, KS	ISN	Willston, ND
DEN	Denver, CO	HLN	Helena, MT
RNO	Reno, NV (1906-1980)	SKA	Spokane, WA
SFO	San Francisco, CA	YYJ	Victoria, BC
LGA	New York, NY	YYT	St. John's, NFLD (1901-20, 35-80)
BOS	Boston, MA	YWG	Winnipeg, MAN
ALB	Albany, NY	YMJ	Moose Jaw, SASK
CLE	Cleveland, OH	YYN	Swift Current, SASK
ROC	Rochester, NY	YXH	Medicine Hat, ALTA
PIA	Peoria, IL	YYC	Calgary, ALTA
MDW	Chicago/Midway, IL	YEG	Edmonton, ALTA
LAN	Lansing, MI	YHZ	Halifax, NS
MLI	Moline, IL	YYG	Charlottetown, PEI
OMA	Omaha, NE	YQB	Quebec, Que.
SUX	Sioux City, IA	YEA	Banff, ALTA
LBF	North Platte, NE	YVR	Vancouver, BC
CYS	Cheyenne, WY	SIG	San Juan, Puerto Rico
SAN	San Diego, CA		Guadalajara, Mexico (1921-1980)
DET	Detroit, MI		Tacubay, Mexico (1921-1980)

Figure 4. Stations with quality thunder-day data in North America

stations, and length of thunder-day record, acquired from all parts of the world excluding North America. Evaluation of these data was limited to inspection of the year-to-year values to discern any abrupt shifts that appeared suspect. Locations of the stations are shown in figure 5.

Table 3. Sites with Thunderstorm-Day Data Outside North America

Station Name	Period of Record
Pacific	
Taipei, Taiwan	1901-1970, 1973-1980
Tainan, Taiwan	1901-1970, 1973-1980
Lihue, Kauai Isi, Ha	1951-1980
Honolulu, Hawaii	1905-1980
Wake Isi	1950-1980
Johnston Isl	1960-1961, 1963-1971, 1973-1980
Hilo, Hawaii	1950-1980
Truk Isl	1952-1980
Ponape, Caroline Isl	1952-1980
Koror Isl	1952-1980
Yap Isl	1952-1980
Guam Isl	1958-1980
Majuro Isl	1956-1980
Kwajalein Isl	1961-1980
Eniwetok Isl	1960-1965
Canton Isl	1950-1964
Hong Kong	1947-1982
Singapore	1961-1980
Korea	
Seoul	1907-1982
Daegu	1907-1982
Japan	
Kofu	1901-1980
Tokyo	1901-1980
Fukuoka	1901-1980
Malaysia	
Kota Bharu	1945-1980
Kuala Lumpur	1954-1980
Kota Kinabalu	1970-1980
Kuching	1974-1980

Station Name	Period of Record
Thailand	
Bangkok	1951-1980
Chiang Mai	1951-1980
Australia	
Townsvilie	1941-1981
Broken Hill	1957-1978
Ceduna	1940-1981
Cairns	1942-1981
Kalgoorlie	1940-1980
Mount Isa	1967-1981
Brisbane Regional	1951-1981
Parafield Aero	1940-1954, 1973-1980
Melbourne	1955-1981
Geraldton	1942-1980
Perth Airport	1945-1980
Sydney Regional	1955-1981
Forrest	1941-1980
Oodnadatta	1940-1981
Mount Gambier	1942-1981
Adelaide	1955-1979
Darwin	1942-1981
Alice Springs	1942-1981
Perth Regional	1942-1980
Carnarvon	1945-1980
Port Hedland	1943-1980
Broome	1941-1980
Launceston	1940-1981
Canberra	1940-1981
Sale East	1944-1981
Mildura	1947-1981
Laverton	1941-1981
Wagga	1942-1981
Richmond	1940-1945, 1954-1980
Brisbane	1950-1981
Rockhampton	1940-1981
Amberley	1942-1981
Sydney Airport	1940-1981
Charleville	1943-1981
Coffs Harbor	1952-1981

Table 3. Continued

Station Name	Period of Record	Station Name	Period of Record
Greece		Zambia	
Athens	1931-1980	Chipata	1955-1969
Chania (Crete)	1931-1940,	Choma	1956-1968
	1945-1974,	Kaoma	1963-1969
	1976-1980	Kabompo	1962-1968
		Kabwe	1955-1969
W. Germany		Kafus Polder	1958-1968
		Kassmo	1958-1969
Hamburg	1898-1977	Kasempa	1956-1969
Karlsruke	1901-1970	Kawambwa	1959-1969
		Livingstone	1954-1969
E. Germany		Ludazi	1957-1969
		Lusaka	1952-1969
Kremsmunsta	1901-1980	Mansa	1955-1969
Wien	1901-1980	Mbala	1955-1969
		Mount Makulu	1962-1966
Portugal		Mongu	1956-1969
		Mpika	1955-1969
Lisbon	1901-1980	Mwinilunga	1954-1969
Porto	1901-1980	Naola	1958-1969
		Petauke	1952-1969
England		Samfya	1958-1968
		Serenje	1957-1969
Lerwick	1916-1980	Sesheke	1956-1969
Shoeburyness	1916-1980	Solwezi	1961-1968
London	1901-1980	Zambezi	1955-1968
France		Switzerland	
Paris	1901-1980	Basel	1901-1979
		Bern	1901-1979
Carribean		Santis	1901-1979
		Sion	1901-1979
Manley, Jamaica	1949-1980	Lugano	1901-1979
Sangsta, Jamaica	1960-1980		
		Turkey	
S. Africa			
		Kars	1931-1980
Kimberly	1939-1977	Antalya	1930-1980
Escourt	1939-1977	Ankara	1926-1980
		Florya	1937-1980
Kenya		Diyarbakir	1929-1980
		Trabzon	1929-1980
Kisumu	1934-1980	Izmir	1938-1980

Table 3. Concluded

Station Name	Period of Record	Station Name	Period of Record
Chile		New Zealand	
Puerto Montt	1914-1980	Wellington	1928-1980
Santiago	1901-1980	New Plymouth	1944-1980
		Hokitika	1964-1980
Argentina		Westport	1955-1980
		Christchurch	1955-1980
Mendoza	1903-1980	Napier	1955-1980
Buenos Aires	1902-1913, 1918-1924, 1930-1980	Gisborne	1955-1980
		Auckland	1928-1980

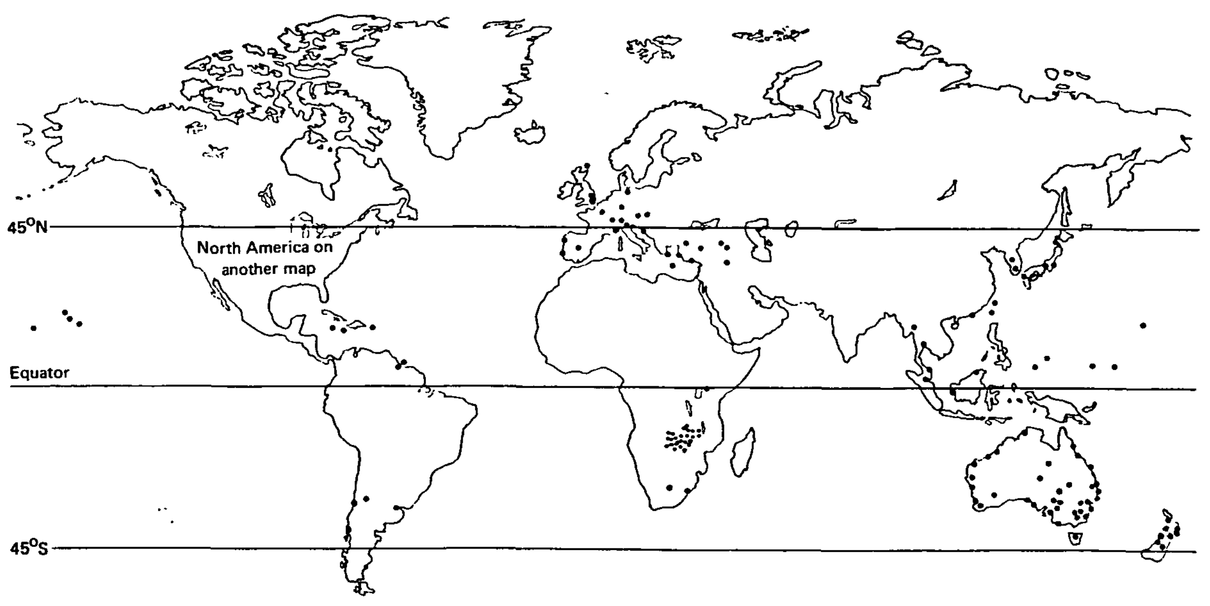

Figure 5. Stations with thunder-day data.in non-North American locales

NORTH AMERICAN RESULTS

CONTINENTAL ANALYSIS

Figure 6 presents the pattern of the average annual thunder days for North America, showing the maximum in the southeastern United States with more than 80 days per year at Tampa, and the minimum along the West Coast where San Francisco averages only 2 thunder days per year. Consideration of this pattern is important in interpreting the results on trends emanating from the study. Most of the data available varies from latitudes of 25°N latitude to 55°N latitude. The number of thunderstorms north of 55°N is essentially zero. The sparcity of Mexican data for 1901-80 does not allow assessment of the frequencies over that nation.

One might expect that a land mass of the size of North America should have a rather constant number of thunderstorm days over time. Figure 7 indicates this is not the case. This is based on the frequency of the number of thunderstorm days per 5-year period from 1901-80. The mean point frequency is lowest in 1901-05 (155 thunder days for 5 years) and increases rather steadily to a peak in 1941-45. This upward trend is similar to that found in the temperatures of North America. Following the peak in 1941-45, the North American frequency of thunder days decreases rather steadily through 1970, followed by a 5-year peak in 1971-75.

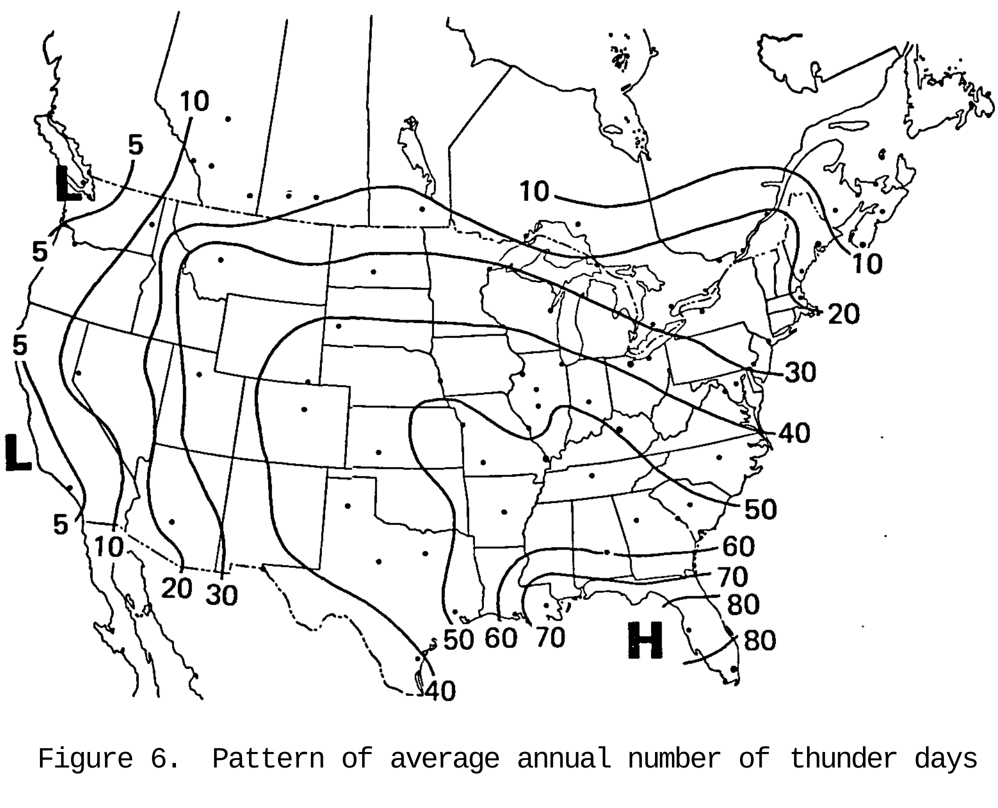

Figure 6. Pattern of average annual number of thunder days

Again, this decrease over the last 35 years is in agreement with the downward temperature trends for North America. Importantly, the frequency of thunder days of North America has not been relatively constant.

Also shown on figure *1* are the standard deviations for the 5-year periods. These show a general decrease of variability with time. The highest standard deviations (greatest variability) existed in the first 30 years of the Century, and then decreased to 1980 except for a minor peak in 1971-75.

The distribution of the annual mean thunder-day values calculated for North America for each year in the 1901-80 period was examined. The lowest 1-year value was 28 days, and the highest was 37 days with a mean of 33.27 days. The median was 33 days, the mode at 32 days, and the standard deviation was 1.87 days. Table 4 presents the stem and leaf display of the 80 values. Their distribution was tested and found to be normal.

The North American thunder-day frequencies for the spring (Mar-May) and summer (Jun-Aug) seasons are shown in figure 8. Both distributions reflect the annual distribution (figure 6). Spring shows a general increase in thunder days from 1901 through 1945, followed by a general

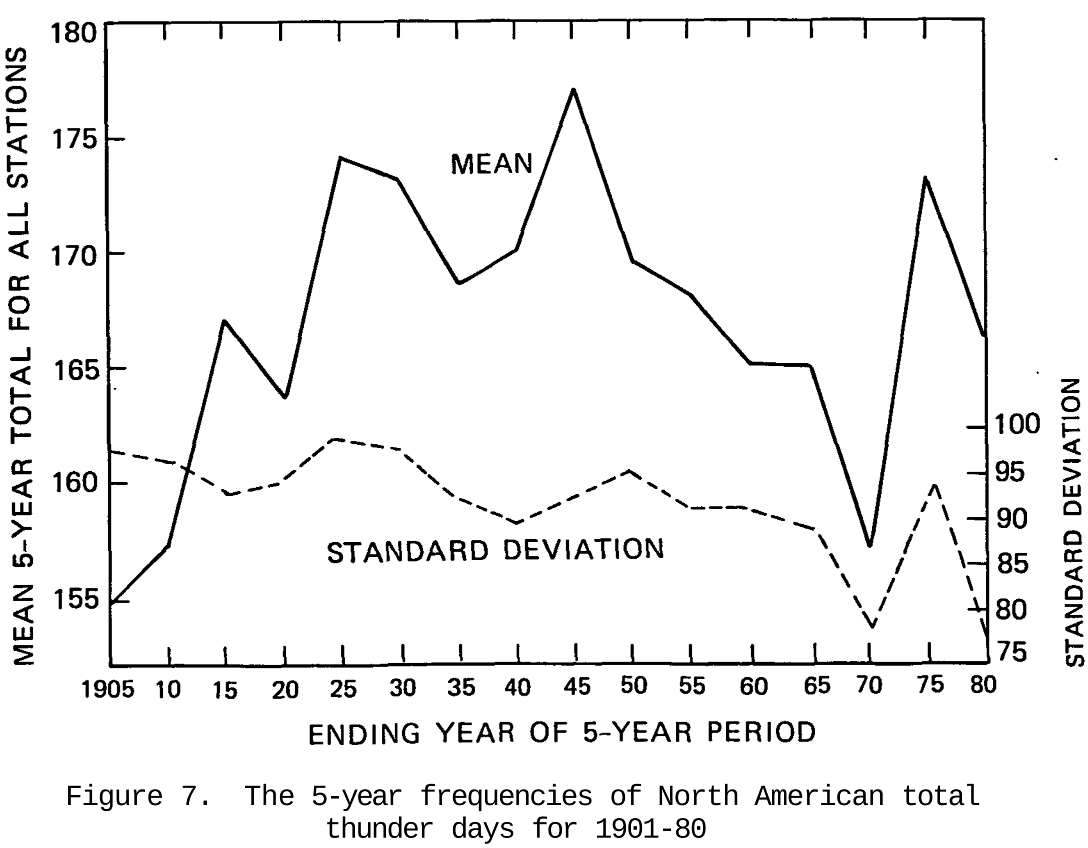

Figure 7. The 5-year frequencies of North American total thunder days for 1901-80

Table 4. Stem and Leaf Display for Annual Mean Thunder-Day Values of North America

Mean Value Range	Number of Years	Sum
37.0-37.4	X	1
36.5-36.9	X	1
36.0-36.4	XXX	3
35.5-35.9	XXXXXX	6
35.0-35.4	XXXXX	5
34.5-34.9	XXXXXXX	7
34.0-34.4	XXXXXXX	7
33.5-33.9	XXXXX	5
33.0-33.4	XXXXXXXXXX	10
32.5-32.9	XXXXXXX	7
32.0-32.4	XXXXXXXXXXX	11
31.5-31.9	XXXXX	5
31.0-31.4	XXX	3
30.5-30.9	XXXX	4
30.0-30.4	X	1
29.5-29.9		0
29.0-29.4	XXX	3
28.5-28.9		0
28.0-28.4	X	1

decrease. The summer distribution is similar but has important differences. After very low values in 1901-10, the 5-year values from 1911-15 through 1965 are generally comparable, other than the peak in 1941-45. The 1966-70 value is the lowest in the 80-year period. In general, the summer season values show the basic increase from 1901 to 1945, followed by a general decrease.

REGIONAL ANALYSES OF TEMPORAL CHARACTERISTICS

Introduction

Data from 86 quality first-order stations in the United States mainland, Mexico, and Canada were used to study the temporal variations of thunderstorm frequencies over the 1901-80 period. The density of stations in the North American continent, excluding Mexico, is considered sufficient to investigate adequately the spatial aspects of the temporal fluctuations in thunder-day distributions. Hence 84 stations in the U.S. and Canada were used. Spatial analyses were based on two temporal distributions: 1) the general trend at each station from 1901 through 1980 (which recognized decadal aberrations during the 80-year period), and 2) the temporal changes in the variability around mean 5- and 10-year thunder-day values.

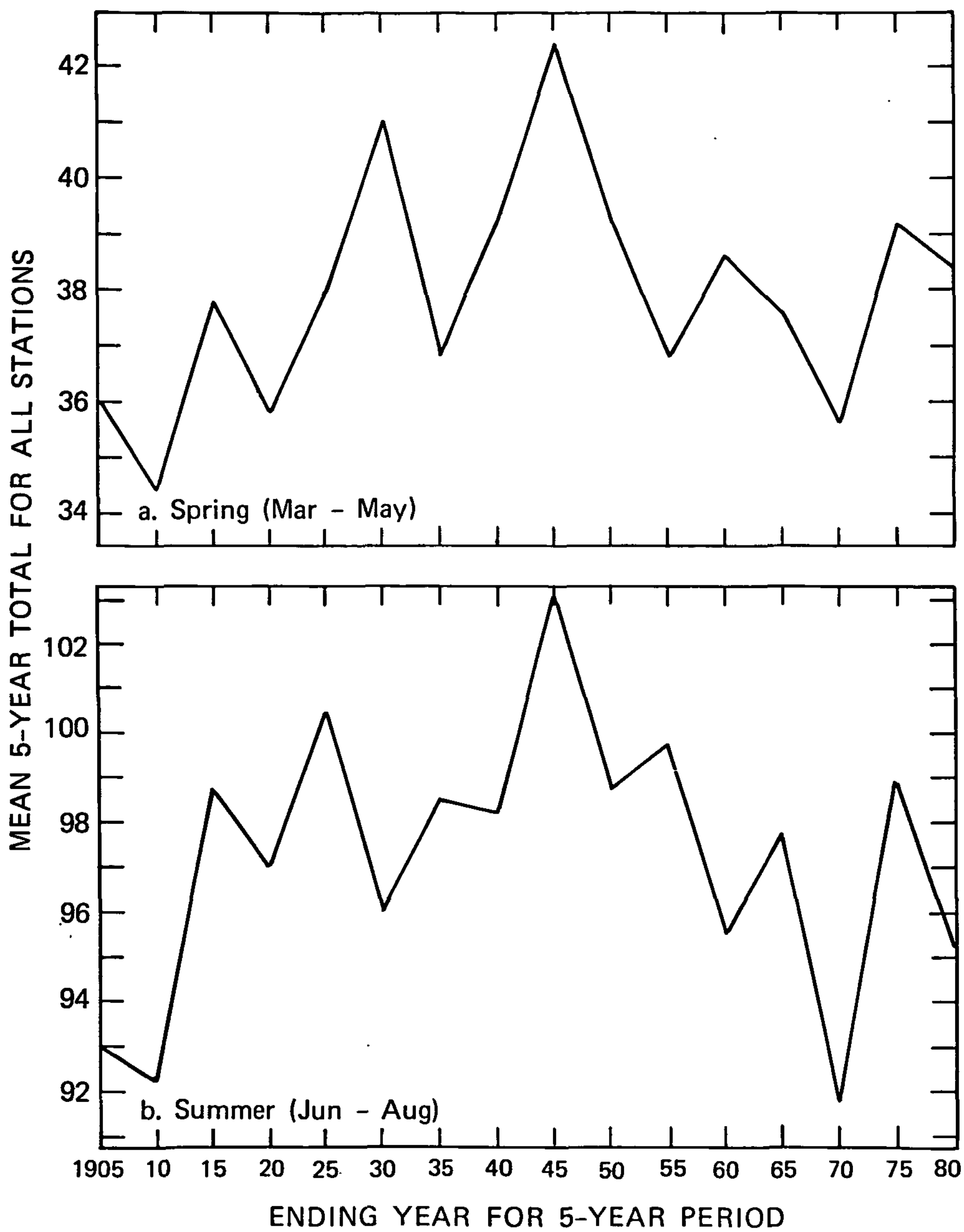

Figure 8. The 5-year frequencies of North American thunder days for spring and summer, 1901-80

One hypothesis investigated considered that there are very apt to be very different temporal distributions of thunder days across North America, and that it was likely that regions of similar distributions existed. If such regions existed, it would be informative to study their locations since causation of shifts might be inferred from the geographical distribution of the region, and the reality of regions defined could be checked against regional differences in climatic conditions related to thunderstorms.

Continental Divisions

Regional analysis of the North American thunder-day data took on several forms. For a first look, the continent was divided into four regions of approximately equal size based on an east-west separation at 100°W longitude, and a north-south separation at 40°N latitude. The stations in each of the four areas were used to calculate regional average frequencies, as shown in figure 9. The numbers of stations in the areas were not comparable (13 in the SW, 17 in NW, 29 in NE, and 22 in SE), but this probably did not seriously affect the results. The northwest area (figure 9a) shows a flat distribution from 1901-35, a rapid increase through 1945 followed by a marked decrease through 1970, and then a marked increase in the last 10 years. However, the overall trend is an increase from 1901 to 1980.

The northeast area (figure 9b) also shows a general uptrend over the 80-year period. However, after two very low values in 1901-10, the values of the last 70 years are essentially comparable. Most of the highest values occur in the last 15 years.

For the southwest area (figure 9c), a general uptrend exists for 1901-45, followed by a sharp downward trend to very low values through 1970, and then an upward trend in the last 10 years. The SW area curve resembles that of the NW but with a greater decrease after 1950.

The fourth continental section, the southeast area (figure 9d), shows a generally uniform distribution from 1901 through 1953. Thereafter, a decrease occurs through 1970 followed by a singular anomalous peak in 1971-75. The 80-year trend of the SE area was one of decrease. Since 1925, there is a general and continuing decrease through 1980. In summary, we find both of the two northern areas exhibiting upward trends over the 80-year period; the SW showing an upward trend to 1945, followed by a decrease until the minor increase of the recent years; and the SE showing a general decrease with time over the 80-year period.

The trends found in figure 9a-d for the four regions were also studied on a seasonal basis. The area trends were found in both the spring and sunnier seasons in all four areas, and were particularly similar in the NW and NE areas. In the SW, the spring distribution showed a flat trend over the 80-year period, whereas the summer season showed the

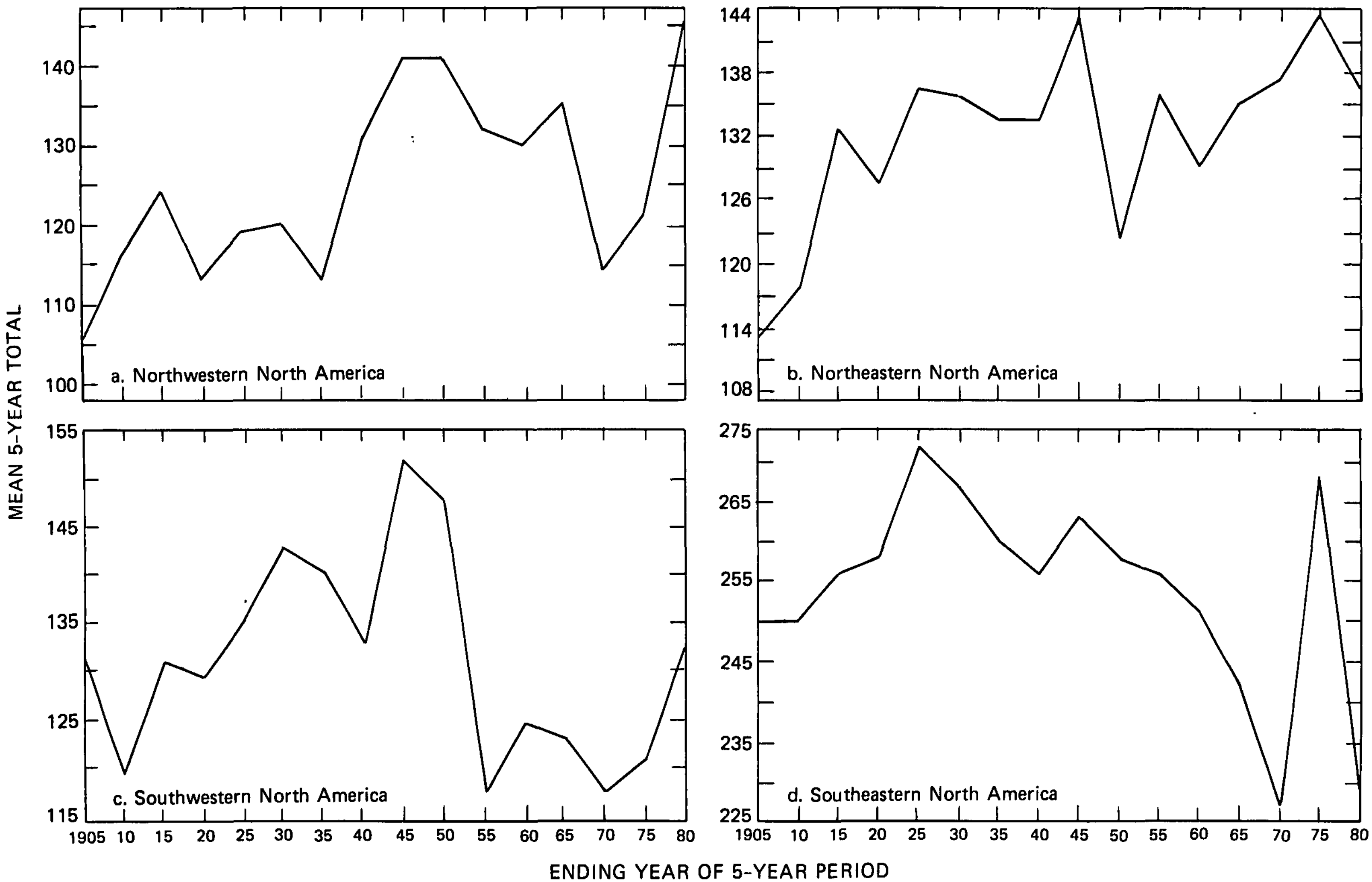

Figure 9. The 5-year frequencies of thunder days in four areas of North America

distinctive downward trend since 1945 (figure 9c). In the SE area, which has a major downward trend with time (figure 9d), this trend was very marked in the summer season values, but only a slight downward trend existed in spring. In general, stations north of 40°N latitude exhibit an upward trend for the 1901-80 period in both seasons, whereas the stations south of 40°N show a downward trend in the summer but not in the spring when 1901-80 trends were essentially flat.

Regions Based on Trends

A qualitative assessment of the temporal characteristics of the 80-year records in North America was then pursued to delineate specific regions of similarity, if any. The annual values of thunder days at the stations were calculated for fixed, or non-overlapping, 5-year and 10-year periods, and then graphed. One analytical approach involved examination of the temporal distribution of the eight decadal values (1901-10, 1911-20, etc.) to discern stations with similar temporal distributions.

Regional Criteria. As noted above, the 10-year temporal distributions of the 84 first-order stations were selected as a basis for comparisons and possible regional grouping. Certain criteria were chosen to specify regional definitions. First, an area could not be defined on the basis of a single station. If a single point had a temporal distribution that did not relate well to those of any of the surrounding stations, it was discarded. This process caused elimination of 3 stations from this analysis (Vancouver, Quebec, and Houston), leaving 81 for study.

Secondly, the basis for grouping stations was that a) a similar general shape of the 10-year values distributions had to exist, b) the decades of maximum and minimum decadal values had to agree, and c) any major secondary maximums or minimums had to be in close temporal agreement. Given these criteria, the station-to-station comparison and regional definition were accomplished.

Regionality. Based on the above stated criteria, 14 regions were defined in North America. The pattern based on these 14 regions is depicted in figure 10 which also shows the station within each region. Table 5 presents a description of the trends in each region, labeled A through N. Shown in figure lla-d are the 80-year thunder-day distributions for each region developed as a mean of all stations in each region.

From a climatic and physiographic standpoint, there are certain interesting observations. First, there is a large area in the northern portion of North America, including most of Canada and the north central U.S. (Region D) that experienced a continuing increase in thunderstorm days from 1901 through 1980.

The second largest region of similarity (Region F) incorporates all the southeastern one-fourth of the United States, south of a line running

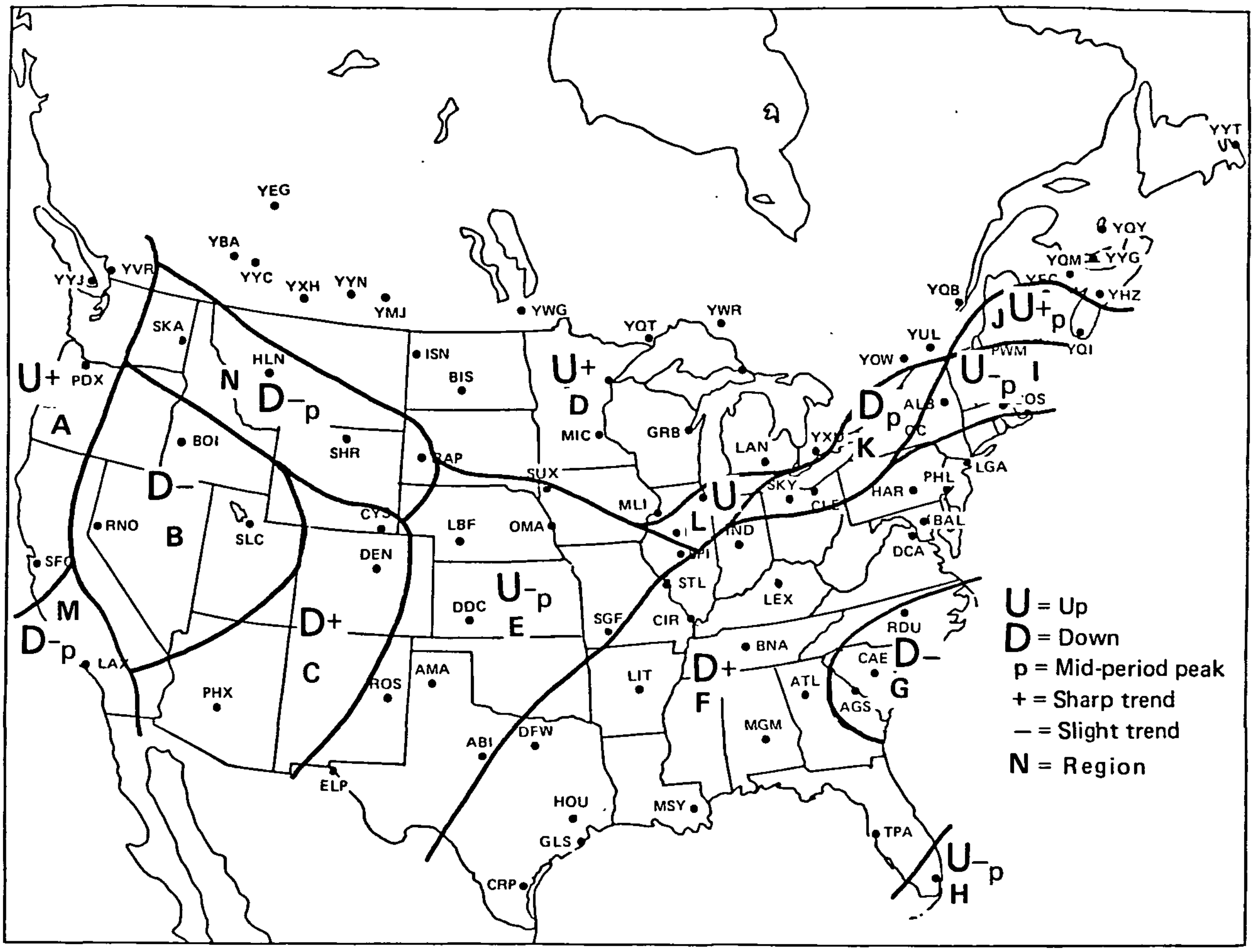

Figure 10. Regions defined by 1901-80 annual thunder day values at individual stations

from central Texas northeastward to New York. This area of general decrease (figure llc) over the 1930-80 period incorporates the major population and industrial sectors of the United States. It is also the most warm and humid climate zone of the United States and has more thunderstorms than any other region (see figure 6).

Region A is confined to the northern Pacific Coast of the U.S. in a maritime climatic regime. Region B is basically an intermontane climatic zone. Region C, which incorporates much of the central and southern Rocky Mountains, is a mountain climate area. Region E incorporates the central and southern Great Plains and extends eastward into the western sections of the Midwest. This is an area of frequent thunderstorm activity and frequent droughts. Region G is along the southeastern coast of the Atlantic Ocean and may reflect tropical storm and marine influences. Its

Table 5. Trends in Regional Frequencies in Thunder Days and Standard Deviations 1901-1980

	Frequency of Thunder Days			Standard Deviation		
Region	Trend	Max.	Min.	Trend	Max.	Min.
A	Up	1941-50	1901-10	Flat	1941-50	1911-20
B	Down (slight)	21-30	51-60	Down	01-10	51-60
C	Down	21-30	61-70	Down (slight)	21-30	11-20
D	Up	71-80	01-10	Down	11-21	71-80
E	Up (slight)	41-50	31-40	Down	01-10	31-40
F	Down	21-30	61-70	Up (slight)	71-80	31-40
G	Down (slight)	51-60	61-70	Down (slight)	21-30	61-70
H	Up (slight)	41-50	01-10	Up	51-60	31-40
I	Up (slight)	31-40	01-10	Flat	31-40	51-60
J	Up	71-80	21-30	Down	11-20	51-60
K	Down	41-50	61-70	Flat	31-40	61-70
L	Up	71-80	01-10	Flat	51-60	71-80
M	Down (slight)	31-40	51-60	Down (slight)	01-10	71-80
N	Down (slight)	41-50	61-70	Flat	11-20	21-30

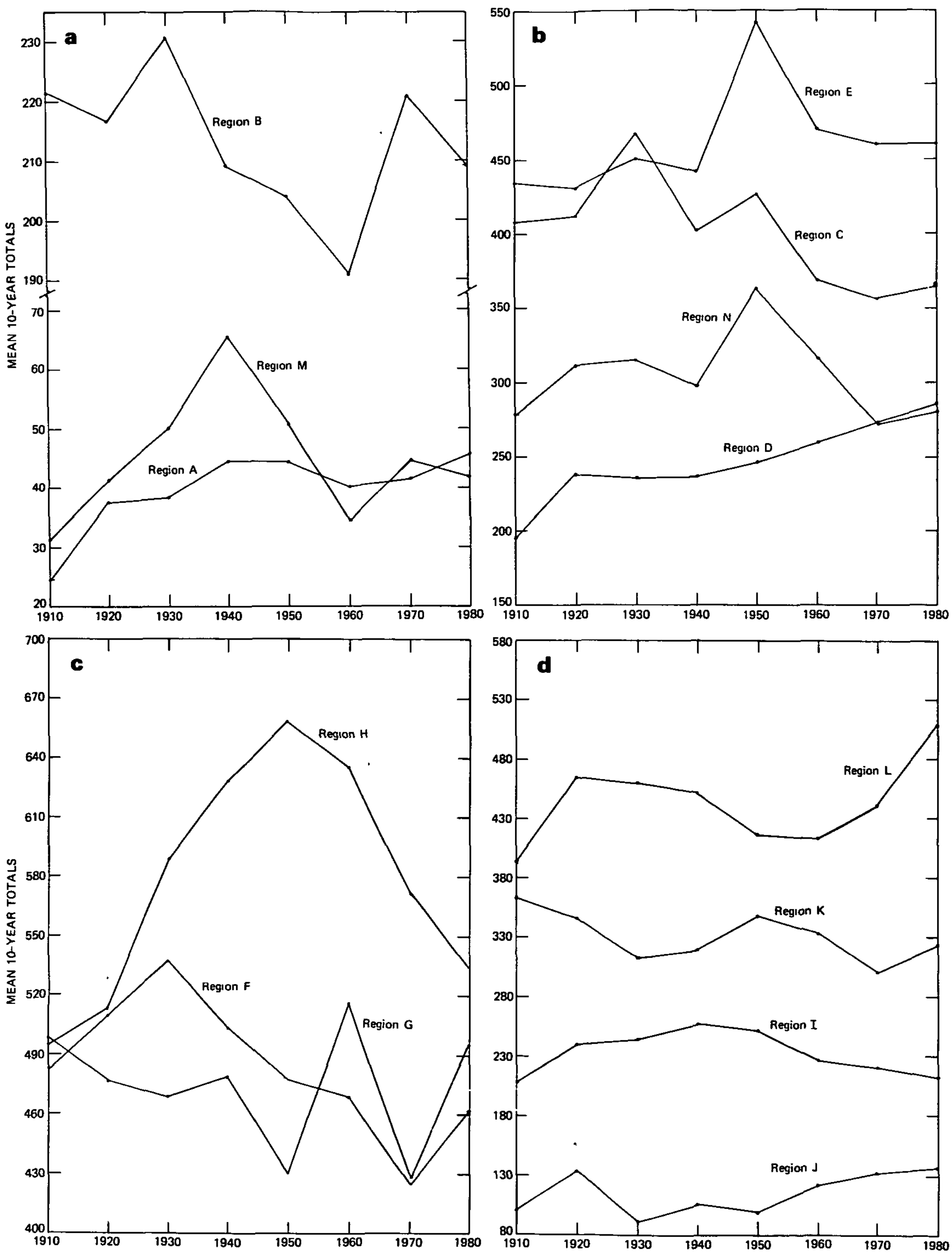

Figure 11. The 5-year frequencies of thunder days for 14 regions of North America, 1901-80

temporal distribution resembles that of surrounding Region F, but stations in Region G had a secondary peak in 1961-70. Region H is a tropical climate including Miami and San Juan, Puerto Rico.

Region I is the New England Coastal area, and Region J incorporates two stations north of Region I along the North Atlantic Coast. Region K is along and downwind of the eastern Great Lakes, and Region L extends across northern Illinois and lower Michigan. Regions I, J, K, and L are small areas lying between the two large regions of opposite trends. Region D is the region of increase and Region F is the large region of decrease. The area where Regions I, J, K, and L exist is traditionally a transitional climate zone between the C and D climates of Koeppen's climate classification. It is an area of frequent cyclonic activity.

Region M incorporates the southern California coastal climate area with its own unique thunder climate. Region N incorporates the northern Rocky Mountains of the United States.

In essence, the 14 regions defined on figure 10 appear to relate to several known major climatic zones in the United States and Canada. In most instances, a climatic, marine, and/or topographic reason for their location is evident. This is explored more fully in a later section of this report.

Various characteristics relating to the 80-year trends in thunder-day frequencies and the 80-year trends and characteristics of the standard deviations of the thunder days appear in Table 5. These classifications were studied further using map analyses. The degree of up and down trend over the 80-year period was classified as quite marked or slight, as indicated in Table 5. The 80-year trends in thunder-day frequencies are depicted in figure 11. Also the presence during the 80-year period of a mid-period peak or valley can be determined.

Figure 12 depicts the broad areas of general upward and downward trends in the 80-year thunder-day frequencies. This reveals four major zones in North America. There is a broad area of upward trend, including the northwestern U.S., the northern sections of the U.S. and all of Canada, and the central Great Plains in the United States. Two large areas with downward trends are shown. One incorporates much of the western third of the United States, and the other incorporates the south-eastern third of the United States. The fourth region, one of uptrends, is the small tropical area of the extreme southern U.S.

Figure 13 depicts those areas where a singular mid-period maximum occurred. Many of the transition regions including Regions E, I, J, K, M, and N experienced a major singular peak during the middle of the 80-year time span.

Table 6 presents the decadal characteristics based upon examination of the maximum and minimum decadal values. For example, in 1901-10 no

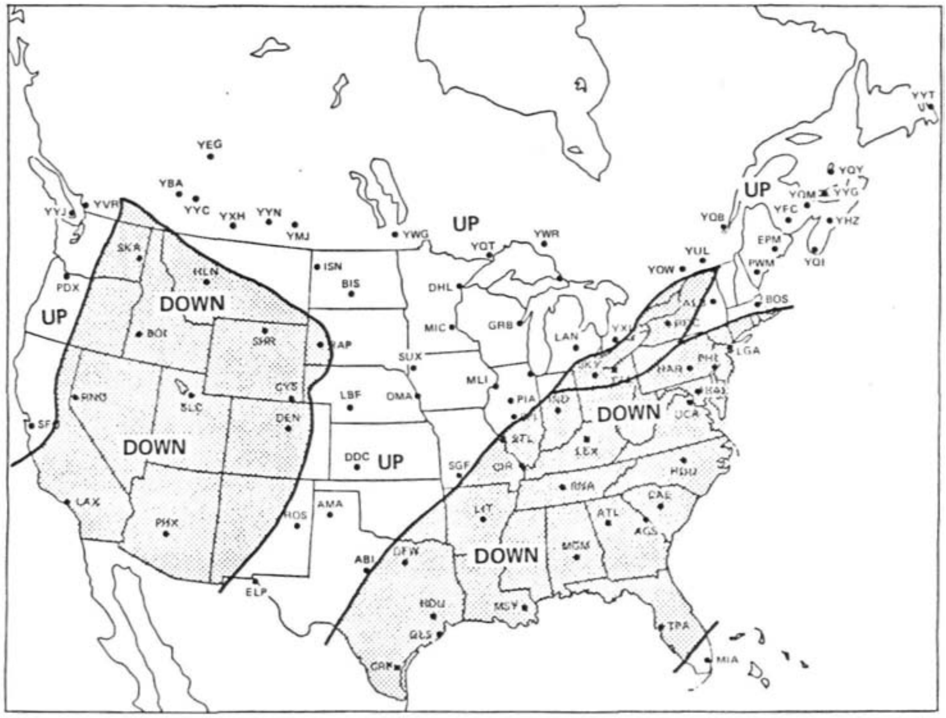

Figure 12. Major areas of up and down trends
in total thunder-day frequencies

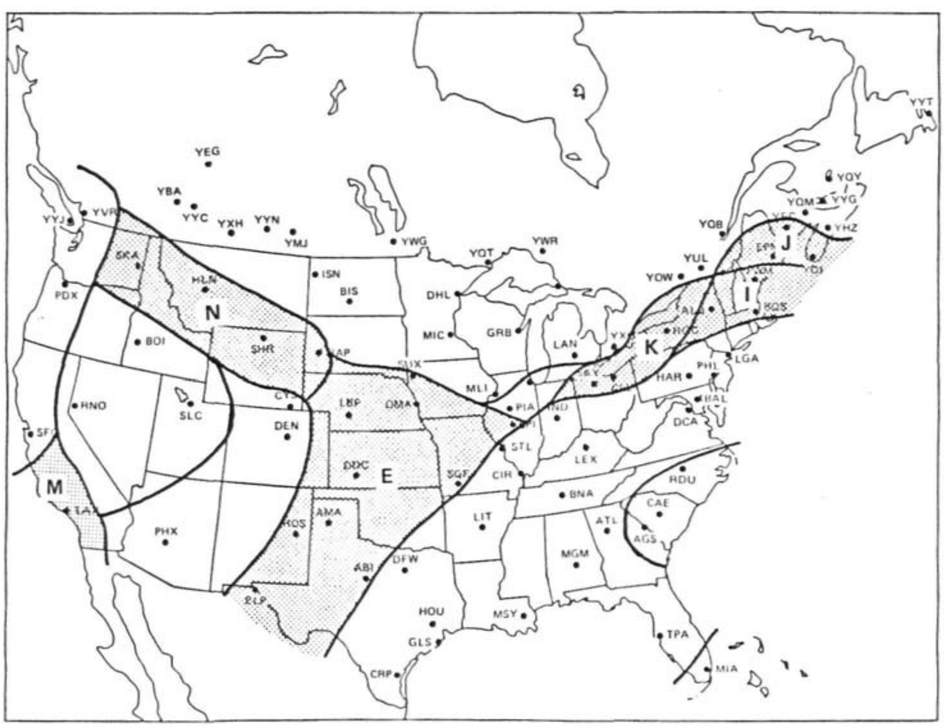

Figure 13. Regions with mid-period (1921-60) decadal maximums

Table 6. Decadal Characteristics of Trends in
Thunder Days in North America

1901-10:	No maximum; major northern minimum and in tropics
1911-20:	No maximum; no minimum
1921-30:	Maximum in mountains and south central USA; minimum in NE Canada
1931-40:	Maximum in California and N. England; minimum in SW Central
1941-50:	Maximum in NW, SW-Central, Great Lakes, and tropics; no minimums
1951-60:	Maximum in SE Coast; minimum in West U.S.
1961-70:	No maximum; major minimum in Rockies and SE-east U.S.
1971-80:	Maximum in north; no minimum anywhere

regions in North America achieved their maximum decadal value, although a major minimum occurred in the north and in the tropics. The values of the decade of 1911-20 did not achieve a rating as a maximum or a minimum in any of the 14 regions.

The decade when the peak decadal value for each of the 14 regions occurred is shown in figure 14. This reveals, as expected, that the northern region (Region D) and adjacent Regions L and J reached a peak in thunder days in 1971-80. The major areas of long-term decrease in the western U.S. and southeastern U.S. achieved their decadal maximum in 1921-30. Other isolated regions achieved their peaks in the 1930's, 1940's, or 1950's, as shown in figure 14.

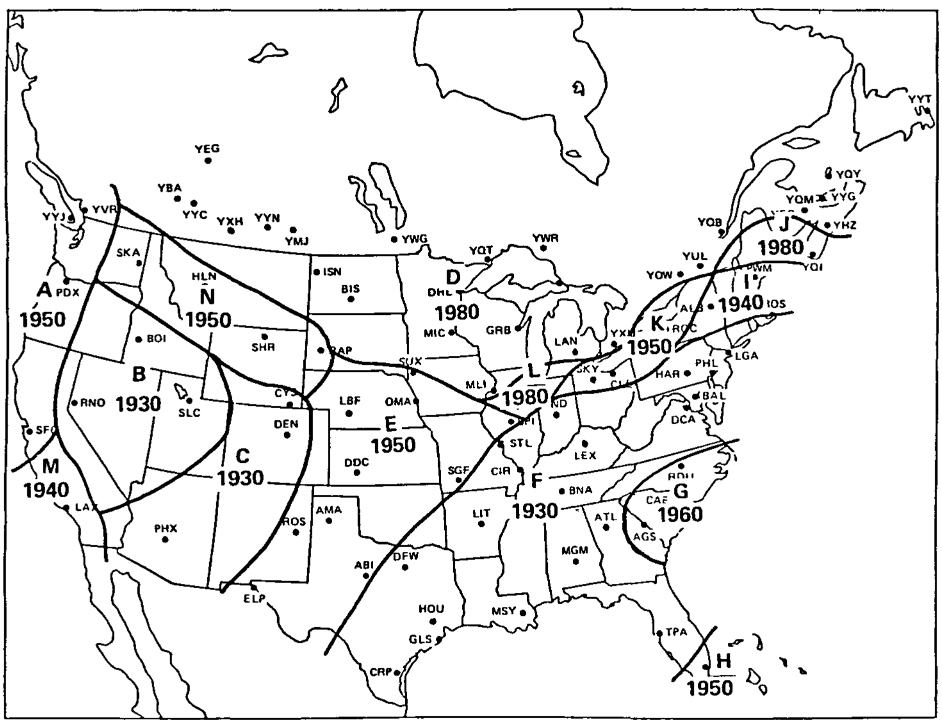

Figure 14. Decades of peak decadal values, 1901-80, in each region

Figure 15 presents the pattern based on the decade achieving the lowest regional values. Most of the lowest values occurred either in 1901-10 (areas with major long-term increases such as D), or in the decade of 1961-70 which included much of the western and southeastern U.S. The central and southern Great Plains achieved their minimums in the 1931-40 drought period, with a minimum achieved in the 1951-60 period in the extreme western U.S.

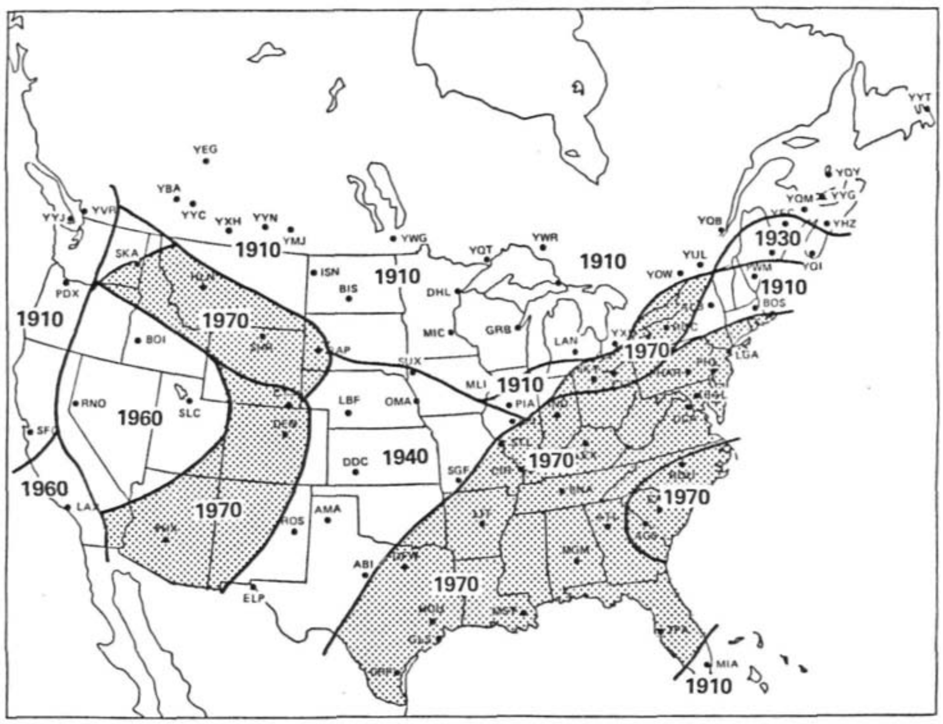

Figure 15. Decades of lowest decadal values, 1901-80, in each region

The general 80-year trend interpretation of the standard deviation values, as shown in Table 5, were used to develop figure 16. This reveals three broad types of areas. Downward trends, or decreasing year-to-year variability, occurred in much of the western half of the U.S. and in the large northern sections. The transition climatic zones including Regions A, N, L, K, and I exhibited no marked up or downward trends in their standard deviations, being classed as flat trends. The third major area identified had upward trends in standard deviations, or increasing variability with time. This area included the southern and southeastern portions of the United States including the tropical area.

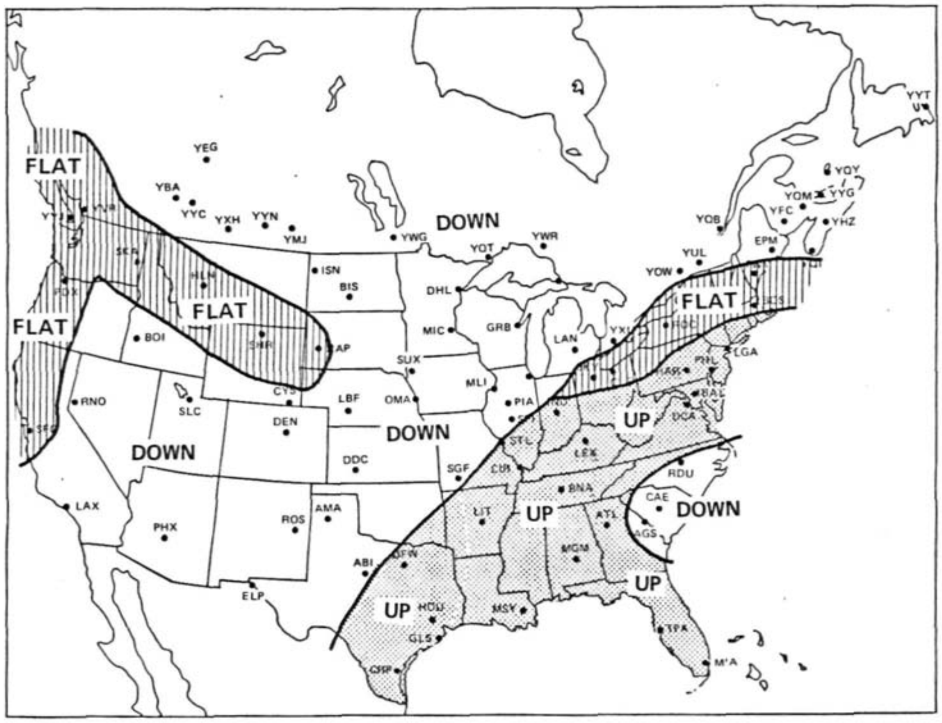

Figure 16. Regional patterns defined by temporal trends in the variability (standard deviations) in annual regional thunder-day values

Spectral Analysis

A non-integer spectral analysis (Schickedanz and Bowen, 1977) was used to derive periodicities for each of the 14 regions using the yearly values of thunder days. The periodicities which were significant at 1%, 5%, and 10% levels were identified for each region. An example of these future regions is shown in figure 17. The width of each periodicity indicates its degree of persistence over time. The narrower it is, the better the periodicity is defined. More than one significant periodicities were usually found in each region. The most dominant periodicity in each region was usually significant at 1%, except those in regions H and L, where they were significant at 5%. A summary map of the dominant periodicities over these regions (figure 18) shows that there are three identifiable features.

A dominant feature over the entire study area was the existence of a long wave periodicity, here defined as longer than 15 years. It covered the southeastern two thirds of the U.S. except Florida (see figure 17b). The upper Rocky Mountains (Area N, figure 10) had a primary periodicity of 35.1 years, while the southern California area had a primary periodicity of more than 40 years, which might be a long-term trend instead.

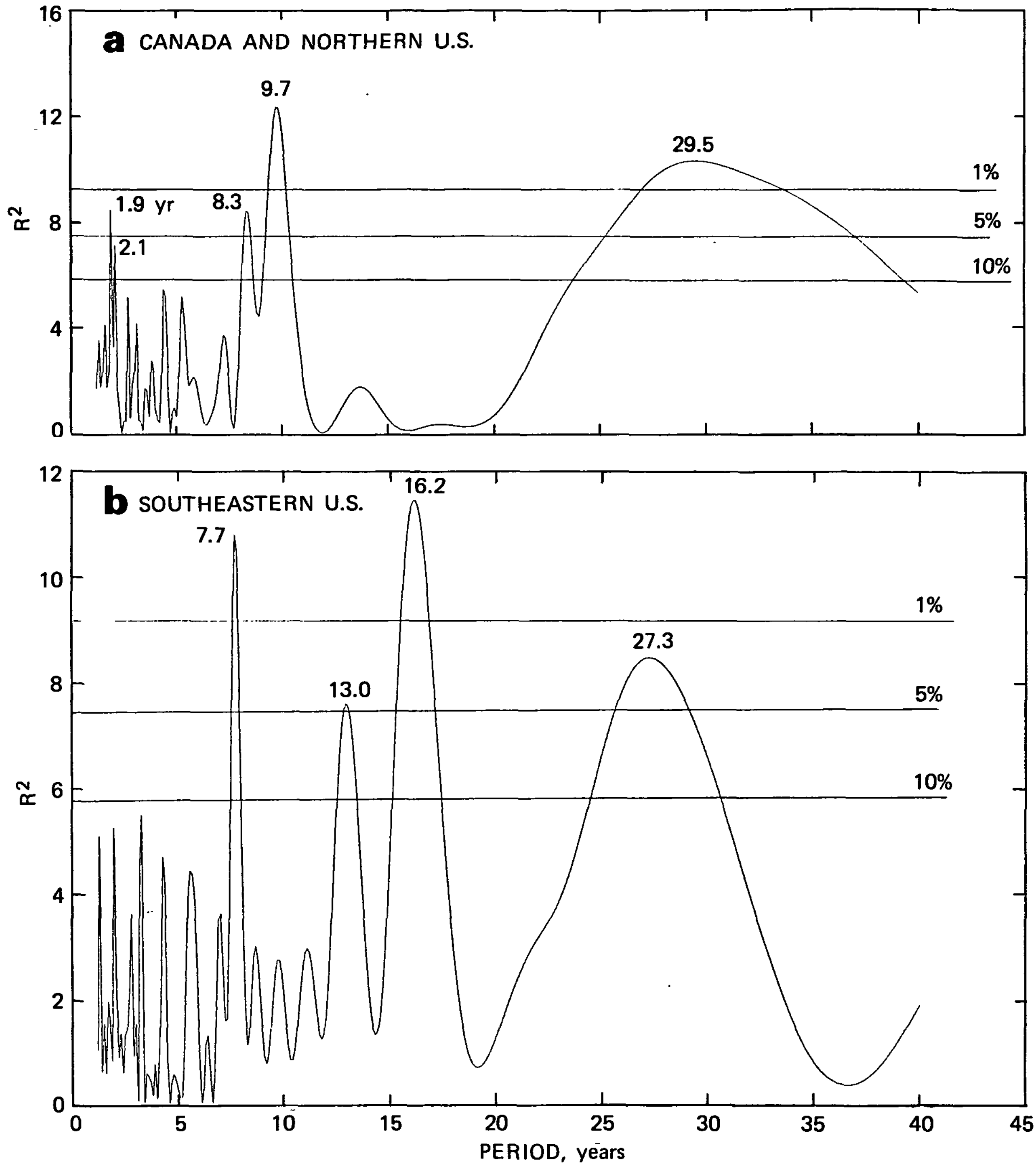

Figure 17. Periodicities in two areas and significance levels

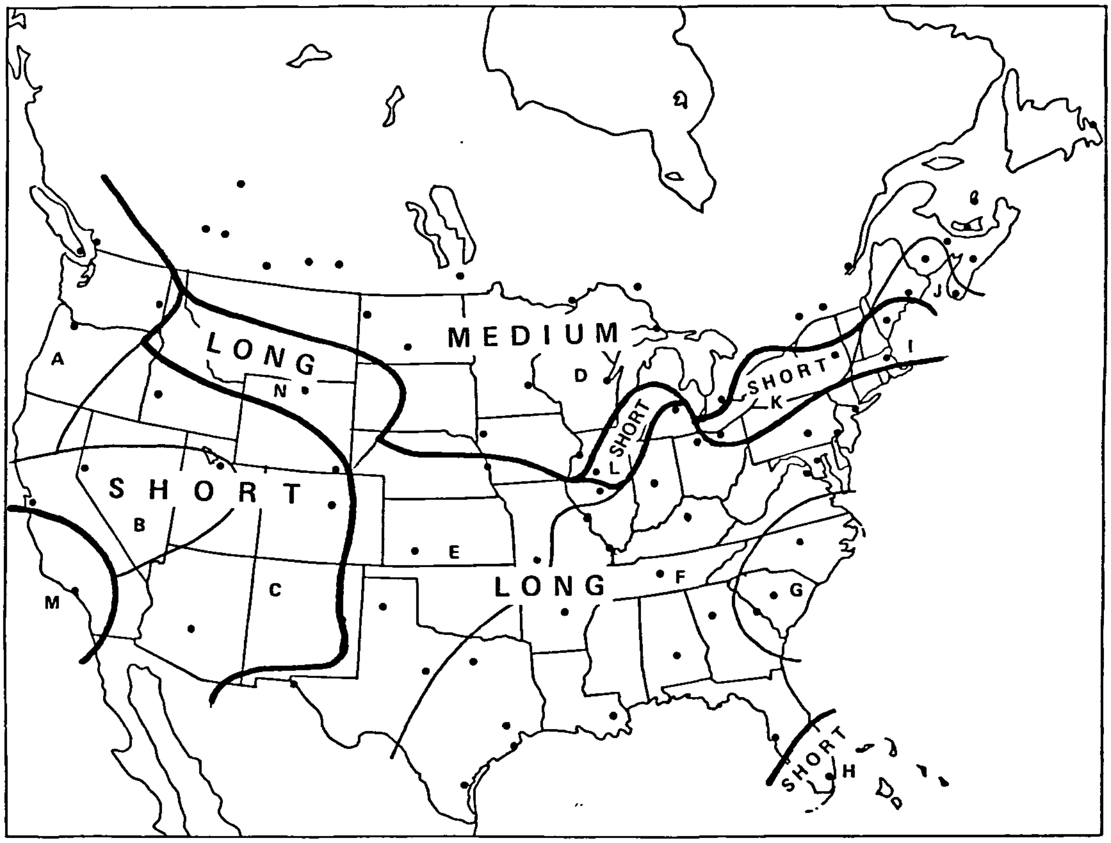

Figure 18. Map of dominant periodicities

A second distinct feature is an area of medium periodicity which covers most of the Canadian stations and north central U.S. (figure 17a) which is area D on figure 10. The wavelength in this area is between 7 and 15 years.

The third feature is the short wave area, with wavelengths less than 7 years. This covered most of the western U.S. (except southern California), Florida, and a narrow band extending from northern Illinois eastward into New England. This last band lies between the long wave and medium wave areas, and apparently is the transition zone of overlapping periodicities between the two areas. Similarly, the area in the upper Rocky Mountains designated as long wave areas may reflect a transition zone between the short wave area of western U.S. and the medium wave area of Canada.

Conclusions

Regional differences in the temporal characteristics of thunder days have been established. They were based both on the thunder day frequencies and on their standard deviations during 1901-80. A generalized interpretation of the regions is presented in the pattern shown in figure 19. The northern half of the continent and a sector through the central United States (largely the Great Plains) form an area that has a general increase in thunder days during the 80-year period with a comparable general decrease in standard deviations; that is, a trend to more thunder days with lesser yearly variation around the mean. A transition zone stretching from the central Midwest eastward to New England, which is typically classed as a transition climate zone, had moderate up and down trends in thunder days with little or no change in the standard deviations over the 80-year period.

The third major area incorporated most of the western third of the United States. Here a temporal decrease in the number of thunder days exists with a corresponding decrease in standard deviations. The fourth area, which included the southeastern third of the United States, also had a decrease in frequency of thunder days with time, but with temporal increases in standard deviations.

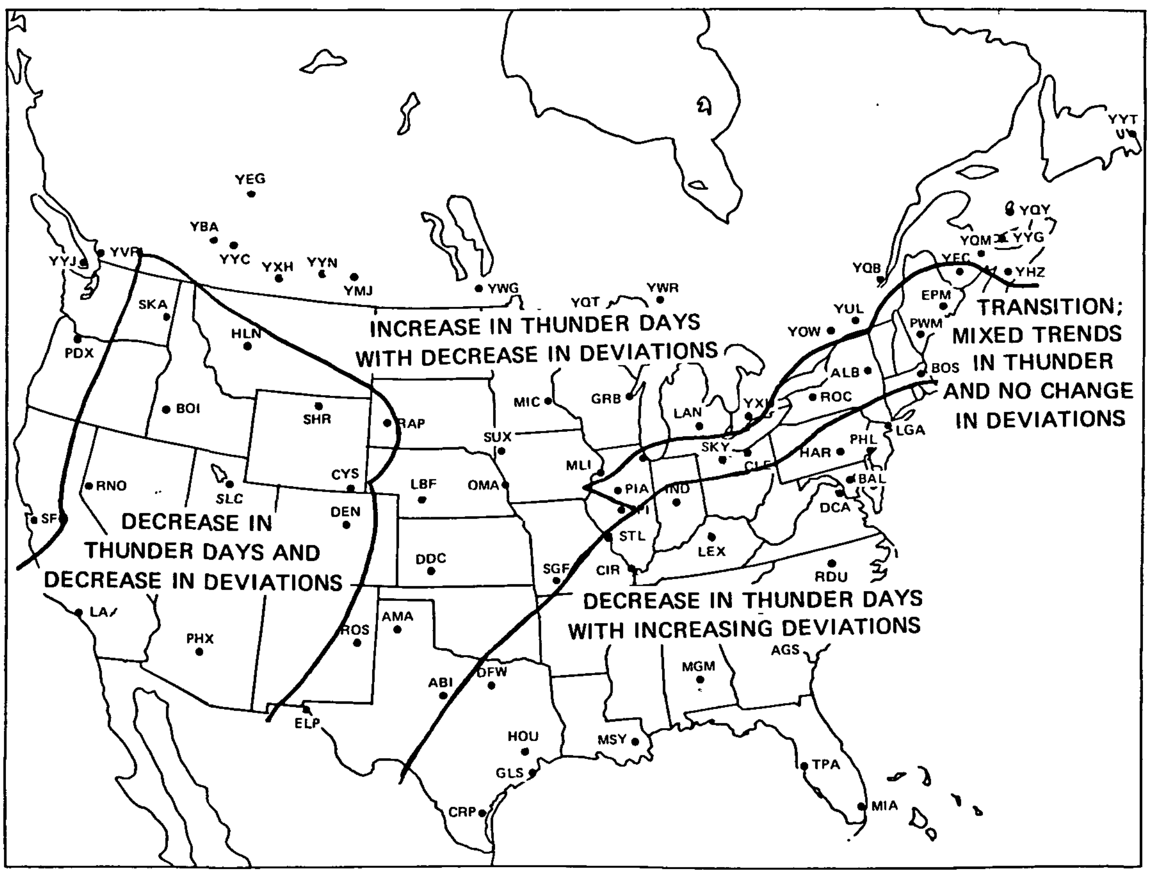

Figure 19. Summary map of basic trends in thunder-day frequencies and their variability

OBJECTIVE ANALYSES OF TEMPORAL DISTRIBUTIONS

Introduction

Another portion of the study focused on statistical analyses of the seasonal and annual frequencies of thunderstorm days at both individual stations and regional groups of stations. The data of the individual stations were subjected to factor analyses to define regions. The station and regional values were also tested, using time series methods, to investigate the underlying trends as well as to search for periodicities. Linear curves were fitted to the data at each station. These curves represented the general trend of the basic data, and in some analyses were subsequently removed from the basic data to 'detrend' it. Non-integer spectral analyses (Schickedanz and Bowen, 1977; Neill and Hsu, 1981) were then used to extract statistically significant periodicities from the detrended data for each station. Periodicities, such as 10 or 11 years found by Stringfellow (1977) in Great Britain for 1930-73, were anticipated. Next, spatial coherence, if any, over a climatic zone or geographical region was investigated by use of factor analysis.

In another approach, the station and regional data were divided into various time increments including 5-, 10-, 20-, and 40-year periods, such as 1901-05, 1906-10, etc. For the 5-and 10-year periods, tests for up or downward trends (Lee, 1980) of thunderstorm day frequencies in 1901-80 were performed.

Factor Analysis of Thunder-Day Data

Annual. Several factor analyses using the annual thunder-day data from the quality 76 North American stations were done. An orthogonal rotation, Varimax, of the factor axes was used. The maximum numbers of factors used in the analysis were restricted to 9, 10, and 11. The major spatial patterns remained the same in all three analyses, only the less-important (i.e., smaller variance explained) factors changed by either merging with other patterns or simply being dissolved. Figure 20 shows the results of the analysis of 9 factors.

The nine spatial patterns identified in the figure included most of the stations used, except Phoenix, El Paso, and three northwestern Canadian stations. The nine factors explained 54% of the variation. The areas encompassed by dashed lines were a "transition zone" between two patterns. Every station was marked with associated pattern numbers; a negative number meant that the station was negatively correlated with the pattern, hence had an inverse temporal evolution. Los Angeles had a peculiar variation, which can be classed as either pattern 6 or pattern 9. Miami did not belong to any pattern; its thunder days varied inversely with pattern 3 (eastern U.S.). Overall, patterns 8 and 9 had lots of "noise," which is the characteristic of the less-important factors. It is not possible to get rid of such noise by using fewer factors.

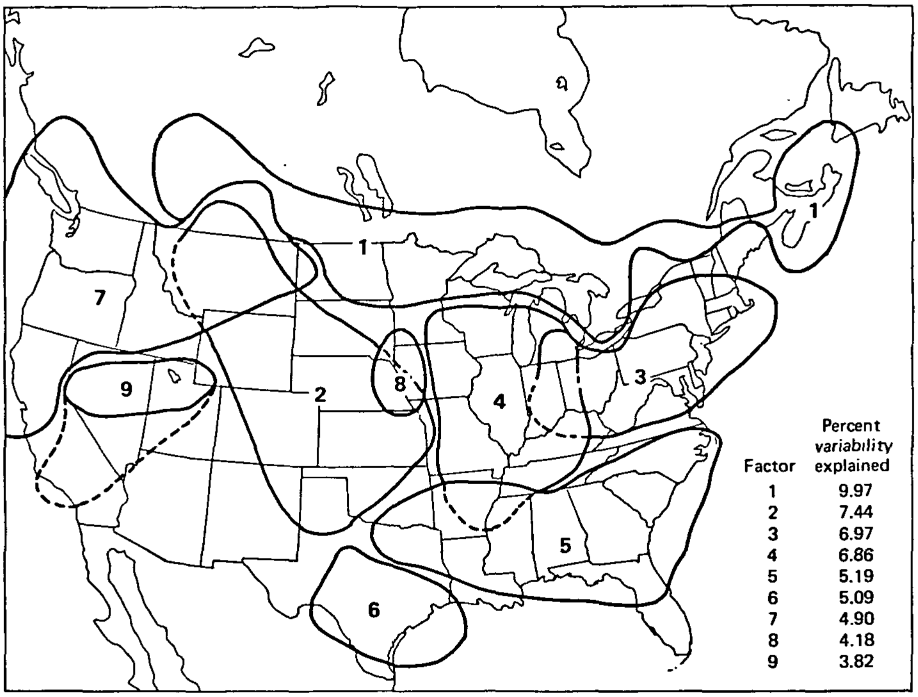

Figure 20. Nine areas defined by factor analysis of annual thunder-day values

The time series plots of each pattern (factor) showed that:

1) Pattern 1 (Canada, upper Midwest) had a clearly increasing trend;

2) Pattern 2 (west Great Plains) had a peak in 1950 and a low in 1970;

3) Pattern 3 (east U.S.) had a low in 1960-70 and a high in 1946;

4) Pattern 4 (Midwest) was stationary except for the abrupt peak in 1975 and low in 1976;

5) Pattern 5 (southeast U.S.) displayed a peak in 1914, 1952, and during 1971-75, and lows in several years;

6) Pattern 6 (southern Texas) revealed 5 segments of frequency — a low segment in 1912-19, a high in 1912-50, a low in 1951-73, then a high in 1974-79, low in 1980 — with a generally decreasing trend;

7) Pattern 7 (northwest U.S.) showed a considerable year-to-year variation, and a slight increasing trend in 1940-80;

8) Pattern 8 revealed a bell-shape with 9 peaks in 1940-50; however, this pattern had too much noise to attribute it to a meaningful area; and

9) Pattern 9 was stationary.

Seasonal. Seasonal values were derived for each station and each year by averaging all values. Months used in computing seasonal values were 1) March, April and May for spring; 2) June, July and August for summer; and 3) September, October, and November for fall. All stations were used in the analyses (figure 6). The years 1901-11 were excluded from the seasonal factor analysis because of some missing observations which were judged infeasible to estimate. The time period of study used was 1912-80.

The number of factors was limited to no more than nine in each of the three seasonal factor analyses (FA). The Varimax method was used in the analysis to rotate the factor axes to obtain more identifiable spatial patterns.

Spring. Percent of variance explained by each factor in spring (figure 21a) was between 4% and 7%; totally, the 9 factors explained 53% of the variance. The patterns identified for each factor are as follows.

1) Western Great Lakes region, extending northeast into Quebec (YQB). The time series of the associated factor score coefficients show that this region is relatively stationary. Only a barely noticeable upward trend exists; however, there seems to be a decrease of thunder days during the last 15-year period.

2) Central U.S. region. This also shows a stationary time variation. There is a slight dip during late 1920.

3) Eastern Great Lakes region, extending eastward to Appalachian Mountains. .. The time series shows a minimum during 1940-50, and from then on there is an upward trend.

4) Great Plains-eastern Rocky region. The time series remains stationary during 1912-70, then it rises upward in the last 10 years.

5) Mid-Atlantic region. An interesting temporal variation is displayed by this factor. There is a 20-year periodicity for the peaks and lows. A noticeable low of thunder days occurred during 1950-55.

6) Upper Mountains region, extending westward into California. A relative low of thunder days existed during 1950-70.

7) Gulf Coast region. There is a general downward trend throughout the entire 69-year period.

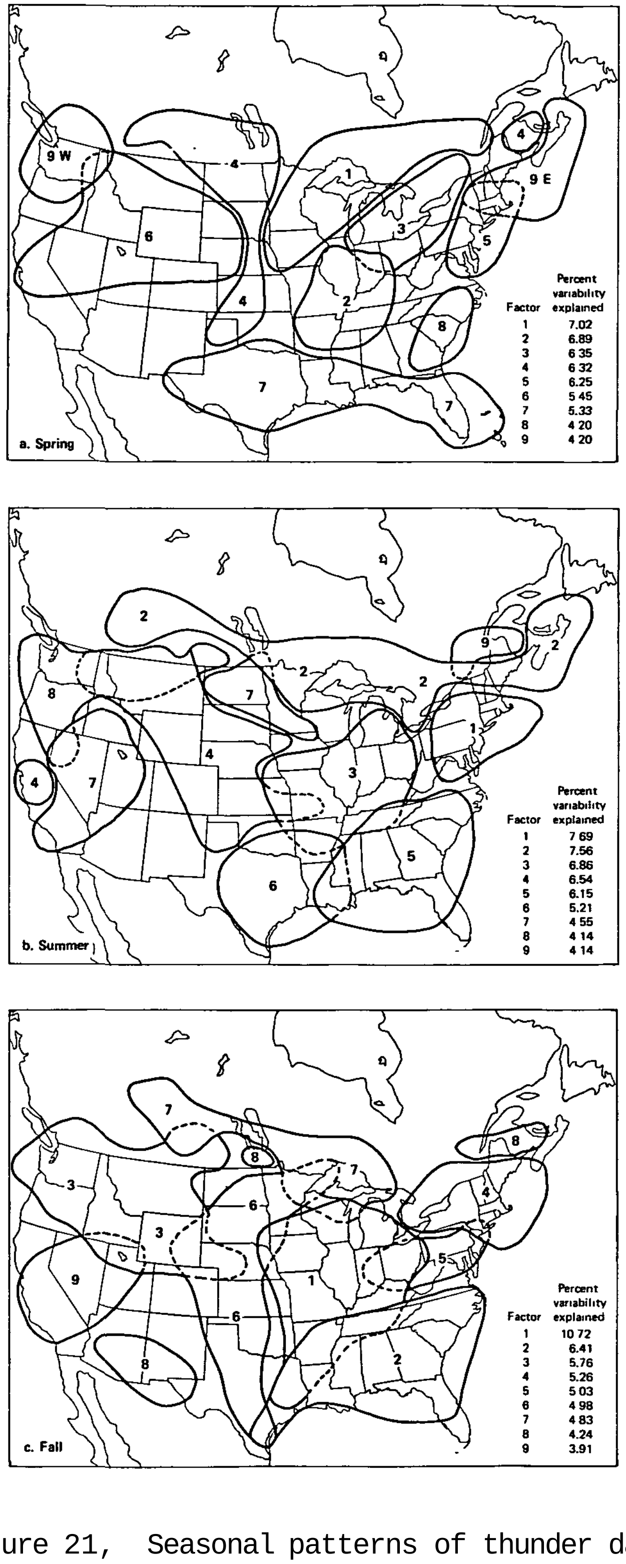

Figure 21, Seasonal patterns of thunder days based on factor analysis and 9 areas

8) Lower Atlantic Coast region. There is an upward trend throughout the entire period.

9) New England (9E) and North Pacific Coast (9W) regions. The corresponding time series shows two abrupt peaks in 1932 and 1939, and a low in 1934.

Summer. Percent explained by each factor is between 4% and 8%; totally, the 9 factors explained 53% of the variance. The patterns (figure 21b) identified for each factor are described below.

1) Mid-Atlantic Coast region, extending northeast into Quebec (YQB). The time series of the associated factor score coefficients show that there is a downward trend during the entire period, though a minor upward trend exists in the last 15 years.

2) Canada-North Great Lakes region. This shows an upward trend throughout the entire period. There is a noticeable dip during the late 1950's.

3) Central U.S. region. The time series is stationary. The variability in the earlier years is larger than that in the later years.

4) Rocky Mountains region. The time series shows a U-shape curve with a minor peak during the 1940-50 period.

5) Southeast U.S. region. This region shows a barely noticeable downward trend with a peak in 1914.

6) Texas region, extending eastward into Mississippi and Arkansas. This time series is stationary with a low in 1980.

7) Upper Plains region. This is not a well-defined region. Stations in North Dakota and Minnesota had a reverse but similar variation of thunder-day frequencies. The time series is stationary with occasional peaks (or dips for reversed region).

8) Northwest U.S. region, extending eastward into Montana and Canada. The times series is bell-shaped.

9) East Canada region. This is an obscure region with only 2 stations associated with it. The time series shows a distinct low in 1940-50.

Fall. Percent of variance explained by each factor is between 4% and 7%. The first factor was able to explain 10.7% of the variance. Totally, the 9 factors explained 51% of the variance. The nine patterns (figure 21c) identified for each factor are described below.

1) Central U.S. region, including the Midwest and extending into the Gulf Coast. The times series of the associated factor score coefficients shows a weak downward trend.

2) Southeast U.S. region. The time series display a cyclic pattern with 3 cycles.

3) Western Mountains region, including the northern Pacific States. The distinct feature of the time series is the peaks in late 1930 and late 1950.

4) New England region. The time series displays considerable variations, with a peak in 1980.

5) Mid-Atlantic region. The variation of the time series is large in the 1912-50 period, and smaller in the 1950-80 period.

6) Great Plains region. This is a stationary region with considerable temporal variations.

7) Central Canada region. There is an upward trend throughout the entire 69-year period.

8) Eastern Canada region. The time series displays a cyclic pattern.

9) Southwest U.S. region. The time series shows one abrupt peak in 1972.

Seasonal Assessment

Most of the recorded thunder days over North America occur in the summer months (see figure 22). The average number of thunder days in a month is 2.53 days, while the average number of monthly thunder days is 6.23 days in the summer, 2.46 days in the spring, 1.17 days in the fall, and less than 1 day in the winter.

The frequency of thunder days is less than 1 day in January, gradually rises to 7 days in July, then decreases to less than 1 day in December. The curve of monthly thunder day frequency, averaged over all the North America stations, is slightly skewed.

The means and standard deviations of seasonal thunder-day frequencies (figure 23) show major features. In the spring, there is an area of high thunder activity centered in Arkansas and southern Missouri. The frequency of thunder days gradually decreases towards the north and west. The standard deviation for the spring also displays a similar pattern.

In the summer, a maximum of thunder activity occurs in central Florida. The frequency decreases gradually towards the north and west. A

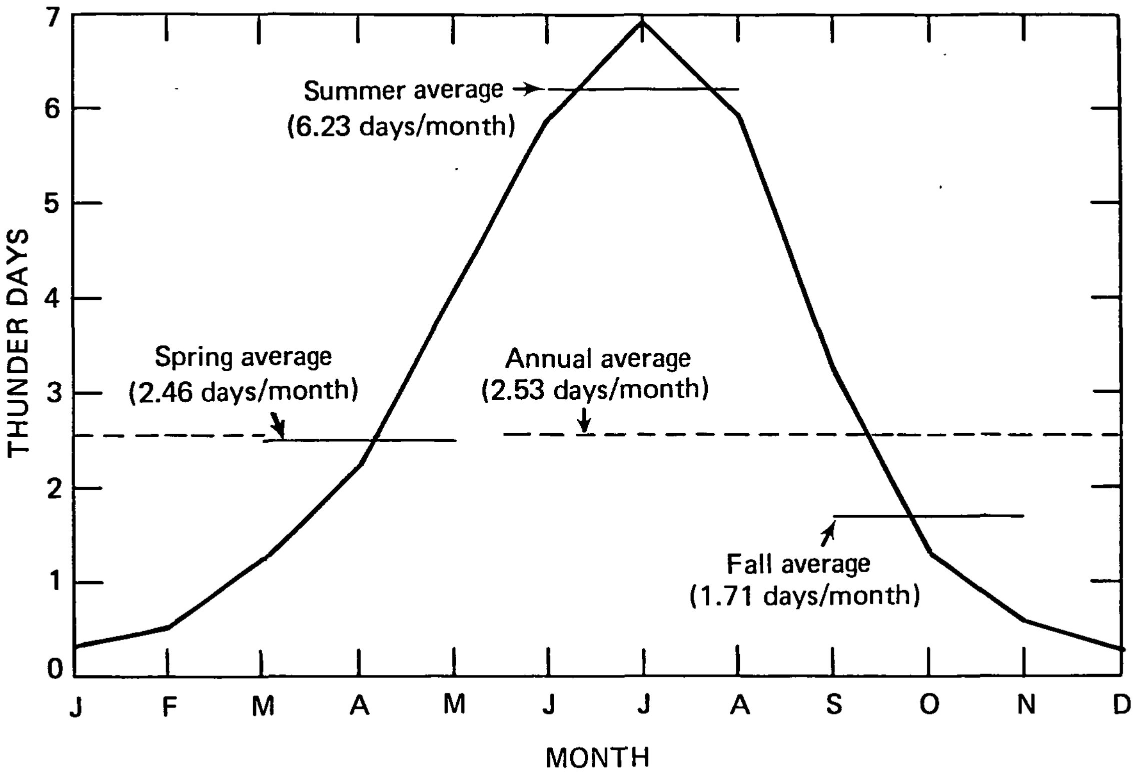

Figure 22. Monthly thunder-day averages for North America

secondary maximum occurs in the central Rocky Mountains. A rather low frequency of thunder days exists along the California coast when the value is less than 1 day for the entire season. The pattern of the standard deviations for the summer is sporadic with no distinct regional features.

In the fall, the maximum number of thunder days occurs in Florida, with a secondary high from the Gulf Coast into the Central U.S. Again, the Pacific Coast has the least thunder days. The pattern of standard deviations in fall was essentially identical to that of the means.

The regions developed in the factor analysis of the three seasons are shown in figure 21a-c. Although there some variations between maps, one important result is revealed. That is, eight regions were found in the same geographical areas on all three seasonal maps. These include the regions delineated in the Midwest, the East Coast, extreme northeastern U.S.-Canada, southeastern U.S., the Great Plains, the northern U.S.-Canada, the northwest U.S., and the U.S. intermontane area. These regions were all identified in a subjective analysis described earlier (figure 10).

The number shown on each seasonal map for each region reflects its factor rank. For instance, area 1 explains the greatest amount of variance, area 2 the next greatest amount, etc. If one assembles from the

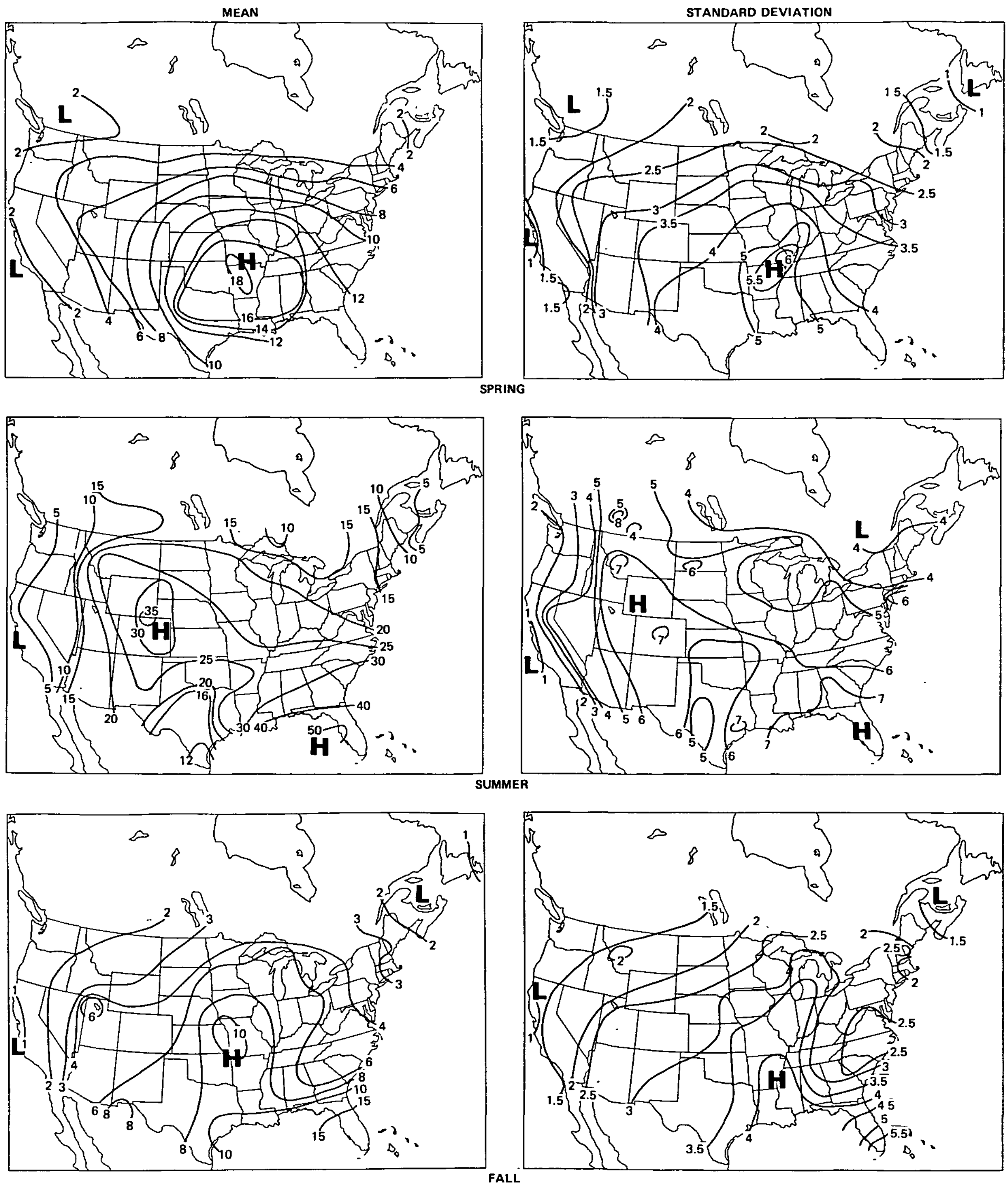

Figure 23. Average seasonal patterns of thunder days and their standard deviations

percentage values on figure 21 the ranks of the factors identified by general areas (that is, the factor value of the midwestern regions in spring, summer, and fall), one can examine the sum of these ranks to gain a sense of the relative strength or importance of the regional characteristics. This calculation was done for the eight areas.

The regional factors identified in the Midwest had a rank of 2 in spring, 3 in surtmer, and 1 in fall, for a combined score of 6. This is the highest score achieved by any geographical area. The regions in the northern U.S.-Canada had factors that achieved the next highest score with its factor ranking 1 in spring (see figure 21a), the second ranked factor in summer, and the seventh rank in fall, for a total of 10 points. Using this type of grading analysis, one finds that the regions in the East Coast area ranked third; the southeast U.S. fourth; the Great Plains fifth; the extreme northeast U.S. sixth; the northwest seventh; and intermontane region eighth.

Another analysis performed using the regions defined by factor analysis involved a comparison of the temporal distribution according to the eight areas. Figure 24 shows these seasonal curves for the Midwest and the southeast U.S. One can make a general season-to-season consistency evaluation by comparing these curves. For example, the Midwest region curve in spring shows a generally stationary distribution over time, as does the summer distribution; however, in the fall, there is a weak downward trend.

Based on this type of general assessment, the seasonal distributions were compared for all eight areas. As can be noted in figure 24, the spring and summer distributions for both the Midwest and southeastern U.S. are similar, but their fall distributions are notably different from their spring and summer trends. The upper U.S.-Canadian region seasonal distributions were similar, but in the East Coast, the distributions in each season are different. Comparisons for the other five areas showed a general disagreement between seasons; that is, spring disagreed with summer, and the fall distribution disagreed with summer and spring distributions.

These between-season differences lead to two important conclusions. First, if there were data biases due to observational differences or siting, there would be season-to-season consistency in trends (all up, all down, etc.). Since there was not in 7 of the 8 areas, it helps establish that the trends are real and not artifacts of observations. Second, the differences in seasonal trends in most areas help reveal that the weather conditions producing thunderstorms differ sufficiently between seasons to behave in very different ways over time. The similarity of the trends in all three seasons found in the upper U.S.-Canada area is likely a result of the fact that there is uniformity of synoptic weather conditions in the short warm season of convective storm activity. That is, most of the spring storms relate to May events, which are generally produced by the same type of weather conditions producing the summer storms.

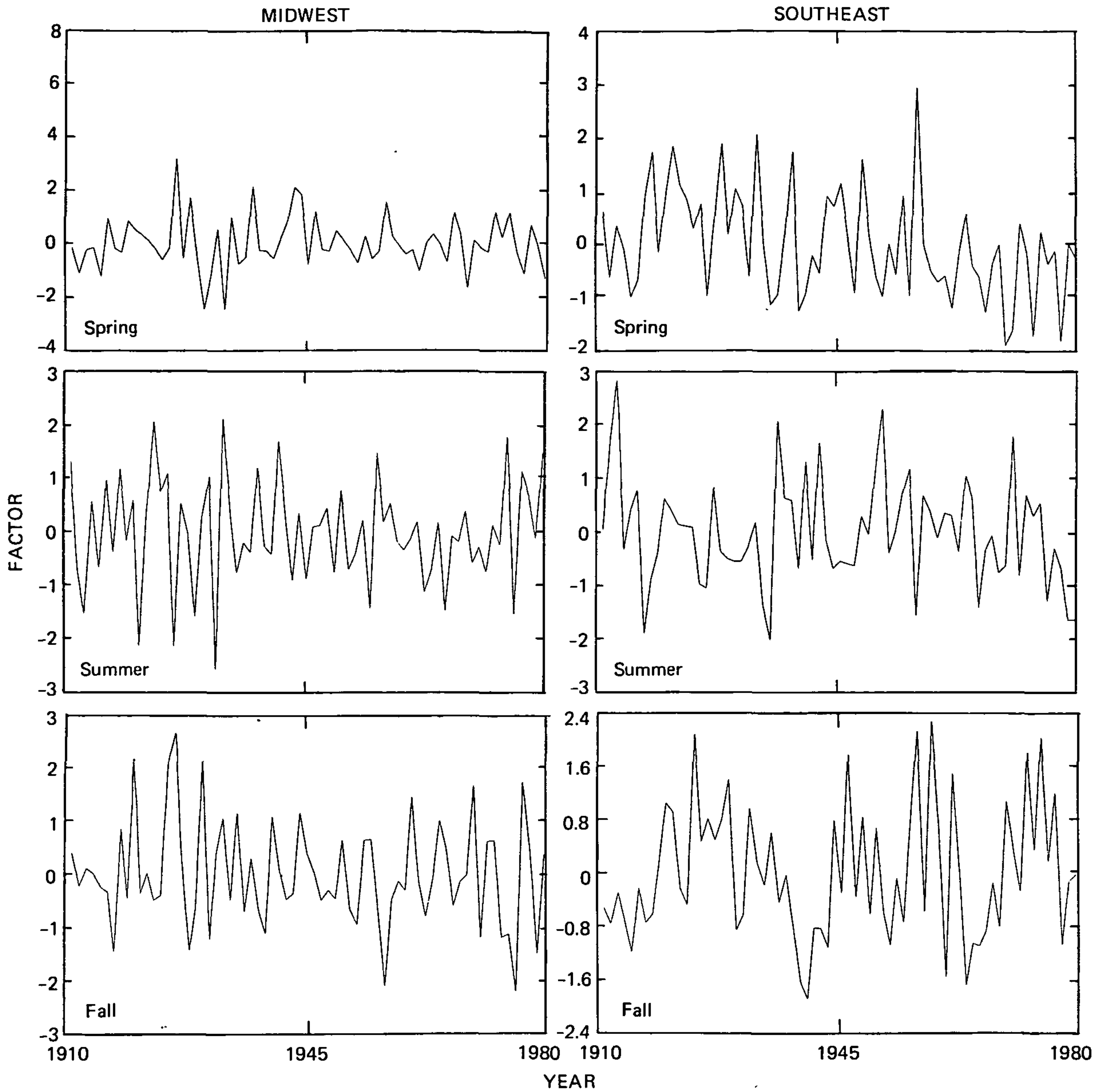

Figure 24. Temporal distribution of thunder-day values (factors) for three seasons

Testing for Uptrends in 1901-1980

The data of each station were subjected to testing for the presence of an uptrend. The statistic used was $\sum_{i=k}^{80} f(i)$

with /(i) the thunder-day value in ith year, and k the starting year. These were tested on varying periods: a) 1901-05 as a base vs 1906-80, b) 1901-10 vs 1911-80, etc.

For each test, the P values of the 76 stations were plotted on a map, and isolines were drawn for the 0.05 and 0.1 values, indicating the probability of a significant uptrend in the data. Figure 25 presents eight of these trend maps based on the test of the trends in 1906-80, 1921-80 (last 60 years), and other combinations. Figure 25a shows the existence of a highly significant uptrend area encompassing most of Canada and the upper Great Plains. Smaller uptrend areas exist in the Midwest, southeast, southwest, and in southern California.

Figure 25c for 1921-80, still reveals the significant Canadian uptrend, with other significant uptrend areas in the West Coast and Great Plains. The other small areas apparent in 1906-80 pattern disappeared as significant uptrends in 1921-80. Figure 25e for uptrends in 1941-80 has a pattern very similar to 1921-80. The test for uptrends in the last 20 years (1961-80) reveals the persistence of the significant uptrend area in Canada, although the one in the Great Plains greatly diminished in the last 20 years.

These results reveal that the persistent general uptrend area in Canada was continually present and quite statistically significant throughout the 1901-80 period. The U.S. Great Plains had significant uptrends in the 1921-80 and 1941-80 periods, but not in more recent years.

CLIMATOLOGICAL INTERPRETATION

Regional Climatic Conditions Related to Thunderstorms

A climatic explanation of the temporal distributions of thunder days is important to provide understanding and credibility for the regional patterns derived from this study. In the simplest forms, the major factors affecting thunderstorm activity in North America fall into three regional classes. The first of these is the marine climate of the west coast of North America; the second is the orographically controlled climate of the intermontane area of the western United States; and the third is the air mass controlled area east of the Cordillera. A brief treatment of the thunderstorm-producing conditions in these three broad areas is appropriate as a preface to more detailed explanations of the specific climatic factors apt to be causing thunderstorms in each region.

The west coast of North America from southern California to Alaska receives most of its precipitation and thunderstorms during the winter season. Winter synoptic scale storms produce most of the thunderstorm activity. Figure 26 presents the predominate winter air masses in North America.

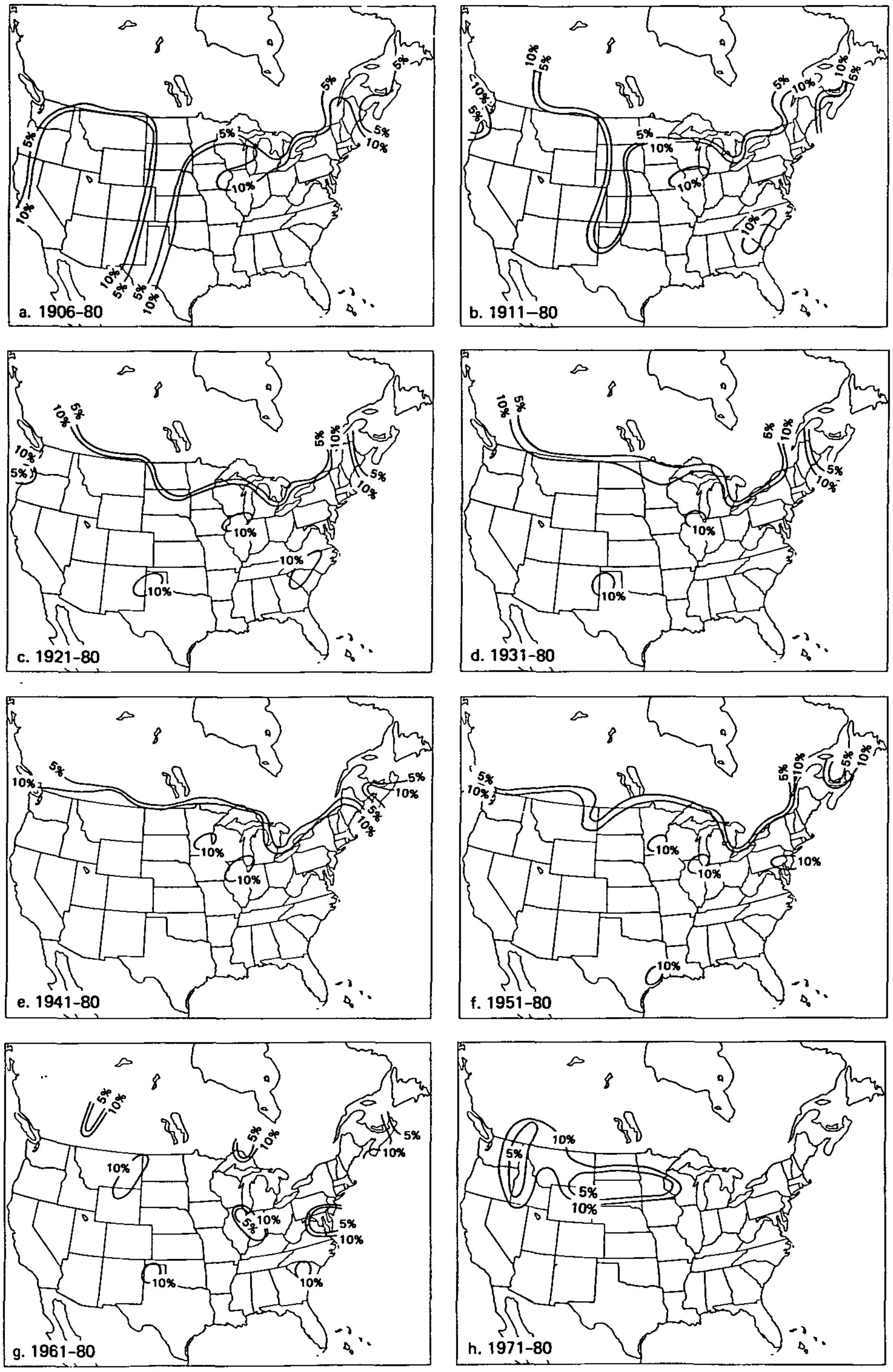

Figure 25. Patterns of statistically significant upward trends (5% and 10% levels) for periods within 1901-80

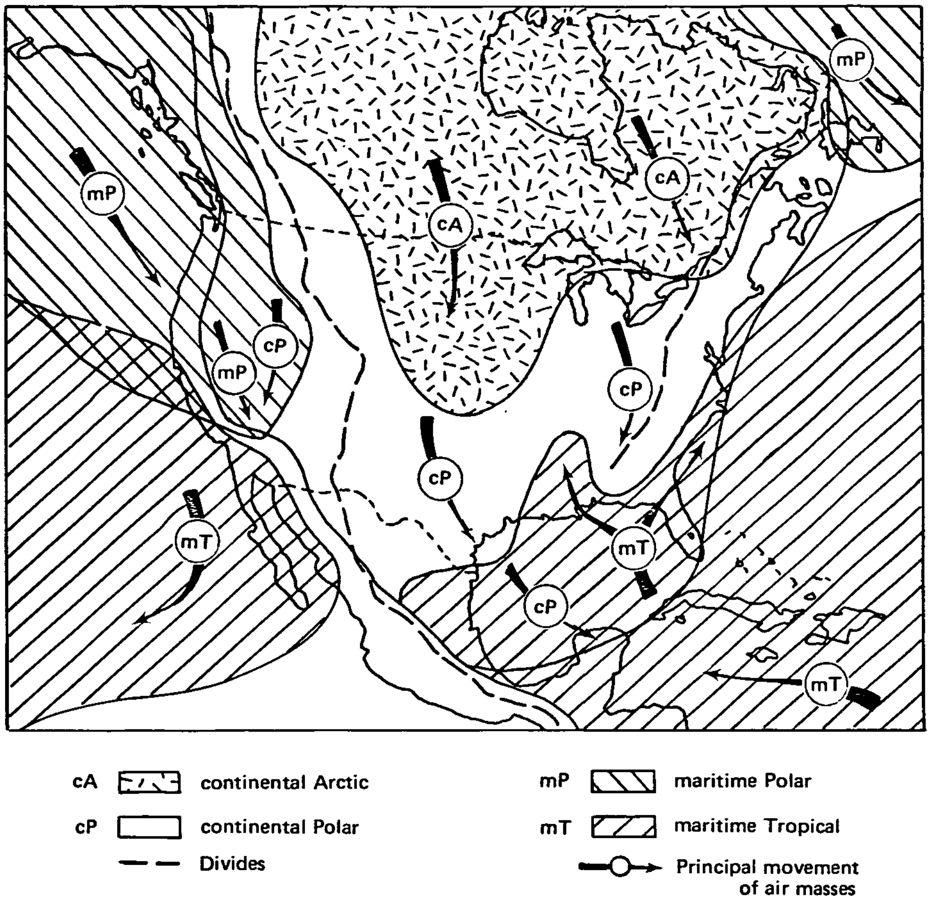

Figure 26. Principal winter air masses (from Bryson and Hare, 1974)

The intermontane area is defined by the double mountain chain structure of the Cordillera which is a very significant factor affecting the climate of North America. The coast ranges (Sierra Nevada-Sierra Madre Occidental Chain) form the western edge of the Cordilleran Plateau, and the Rockies-Sierra Madre Oriental Chain form the eastern boundary. These mountains and the upland regions between the two ranges have distinct regional factors affecting thunderstorm development. Basically, this is an area of orographic lifting, heating, and summer thunderstorm activity. Portions of the internal plateau and eastern mountains are influenced by northward intrusion of moist tropical air from the south during mid-summer. The airflow into the region varies seasonally, and in summer (figure 27) continental tropical air moves northward into the southern half of the intermontane region.

The eastern two-thirds of the United States experiences thunderstorms that are largely the result of interactions between air masses moving from the north and south, although other localized/regional factors create additional thunderstorm activity. Figure 28 portrays the sources of major

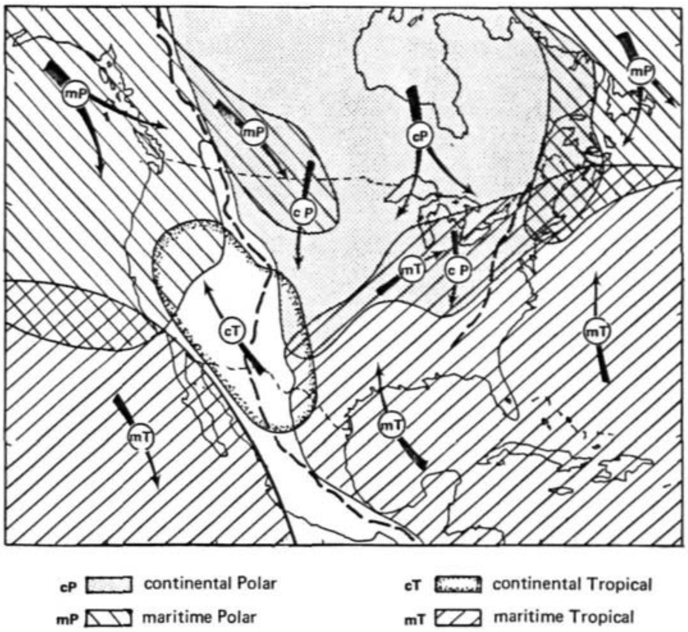

Figure 27. Principal summer air masses (from Bryson and Hare, 1974)

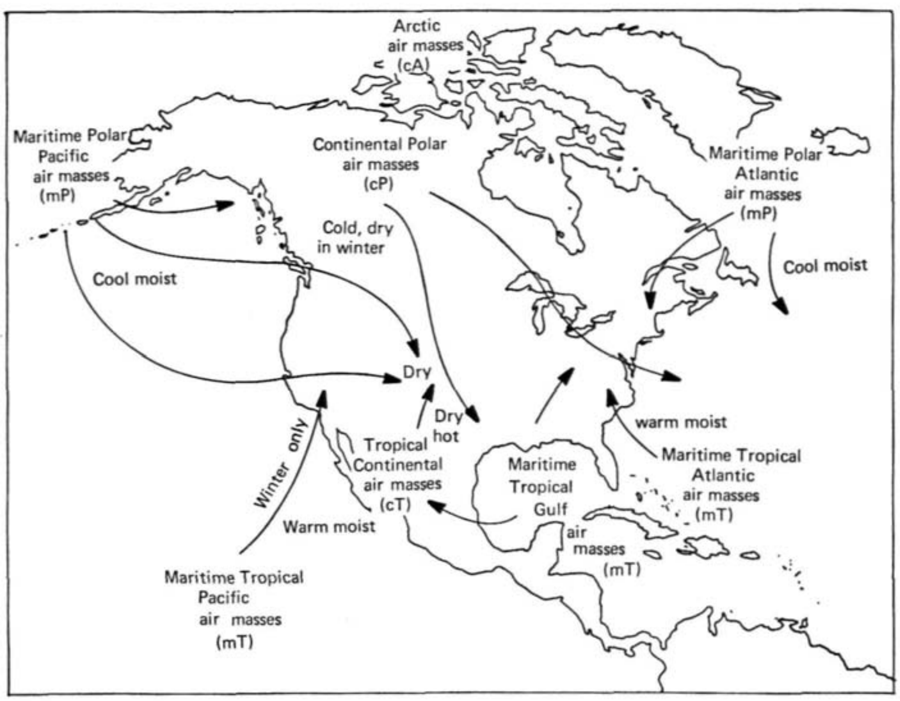

Figure 28. Source areas of major air masses
(from Griffiths and Driscoll, 1982)

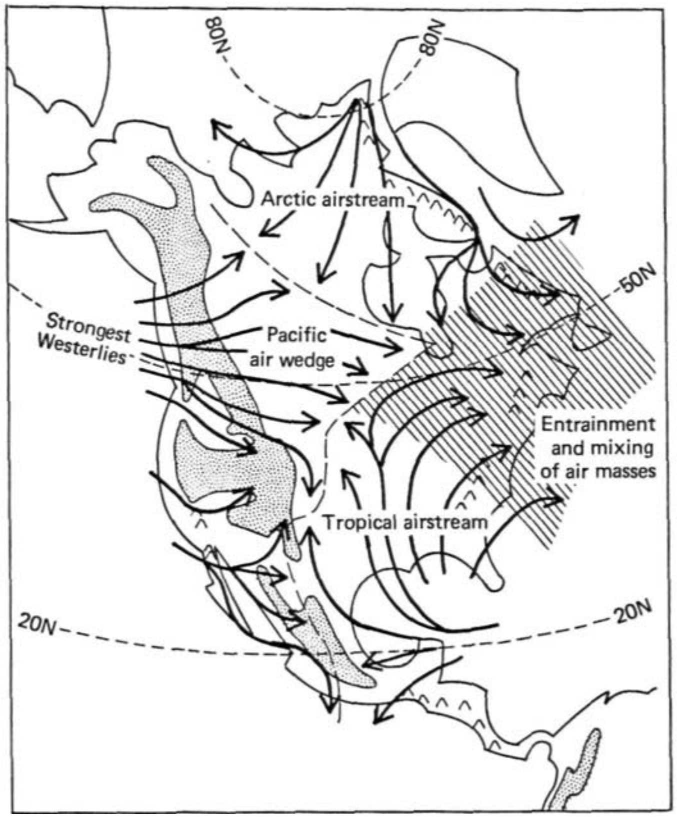

Figure 29. July resultant surface wind pattern
(from Bryson and Hare, 1974)

air masses and major trajectories for North America. Maritime tropical air masses, either from the Gulf or from the Atlantic, move northward into the eastern U.S., along with tropical continental air masses (cT) into the Great Plains. These are met by the continental polar air masses (cP) moving from the north. Depending on air mass conditions, their interactions result in most of the thunderstorm activity in the eastern U.S. The interaction between the air masses shifts seasonally, and this interaction helps define the boundaries of many of the thunderstorm regions in the eastern half of North America.

The interaction of the air masses in midsummer, based on July resultant surface winds, is displayed in figure 29. The streamlines of the tropical airstreams are shown interacting in mid-July with the Pacific and Arctic airstreams at about 50°N latitude, with a broad area of entrainment and mixing in a triangle from the northern Dakotas to northeastern Canada and to the southeastern United States.

Further understanding of the thunderstorm-producing conditions in the eastern North America is gained by considering figure 30. This shows the frequency of cyclones in July for 1950-77, and their genesis areas and

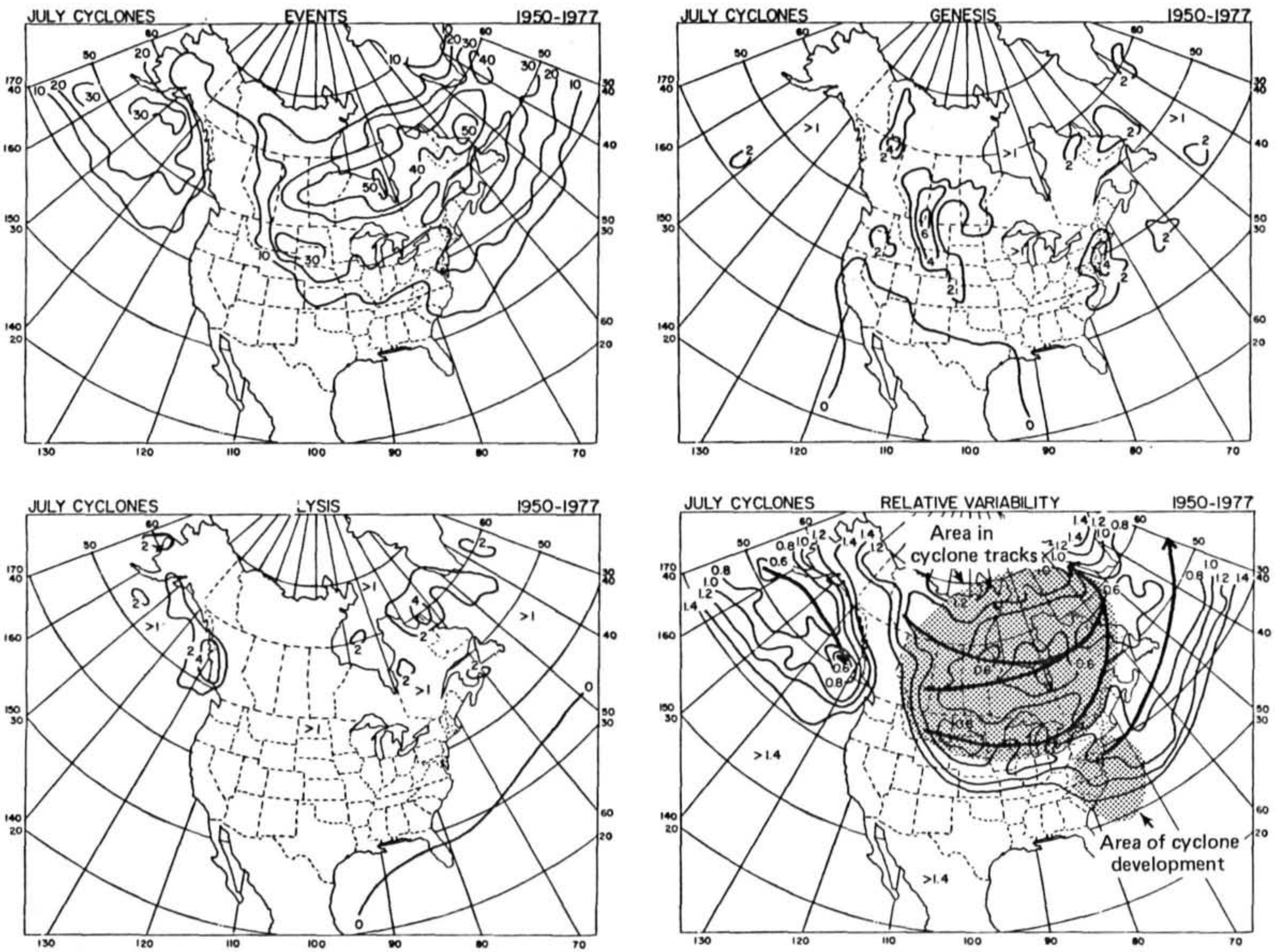

Figure 30. Map of July cyclone frequencies, 1950-77 (from Zishka and Smith, 1980)

tracks. One notes the high frequency of cyclonic tracks across the northern U.S. into northeastern Canada with cyclogenesis areas in 1) the Northern Great Plains-Rockies, and 2) the eastern-southeastern coastal zones of the United States.

Another type of summer thunderstorm that develops in the eastern two-thirds of North America is labeled as the insolational type, often isolated air mass storm. The surface wet bulb temperature for June-September is a useful indicator of the potential development of these air mass thunderstorms since the wet bulb temperature is a key to thermodynamic mechanisms needed to trigger thunderstorm activity. A wet bulb temperature of 75°F is often a critical level. Inspection of figure 31 shows the pattern of surface wet bulb temperatures in summer which are exceeded less than 5% of the time. The key 75°F isotherm includes the central U.S. and East Coast areas.

A third factor relating to thunderstorm incidence in eastern North America relates to atmospheric conditions that produce nocturnal thunderstorms. Studies of nocturnal thunderstorm activity (Dept. of Commerce, 1947) have shown an area of maximum occurrences between midnight and 0600 LST in the central part of the United States. This appears to be related

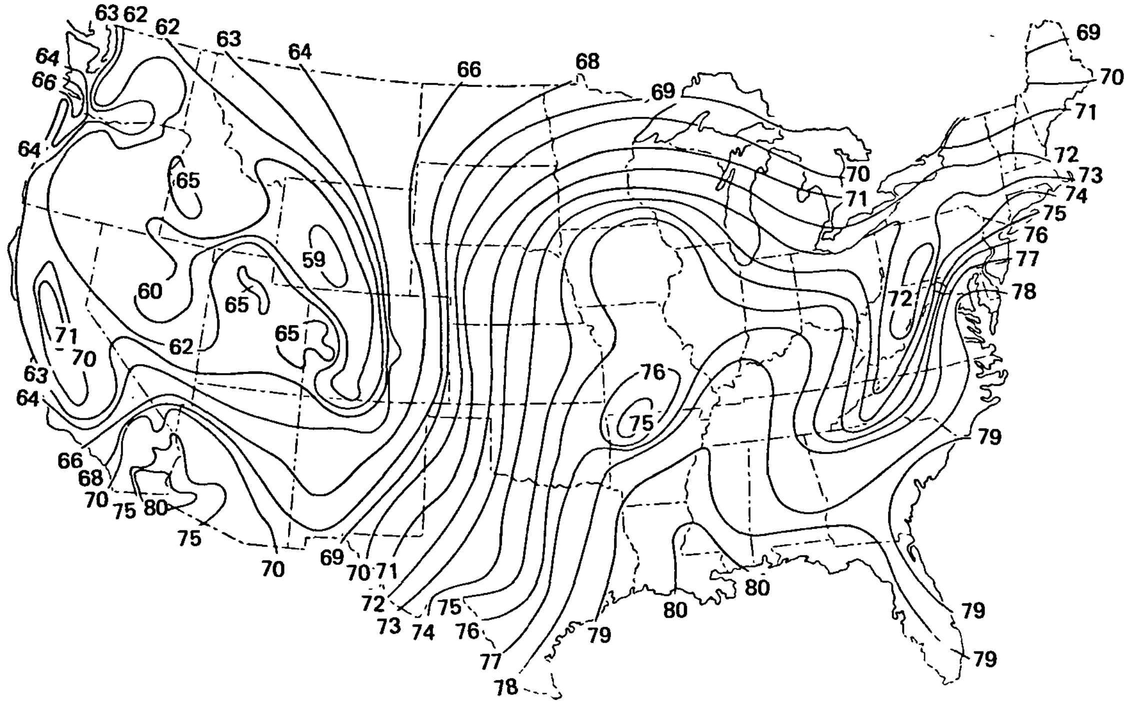

Figure 31. Surface wet bulb temperature (°F) pattern (from Dept. of Commerce, 1947)

to advective temperature warming. Figure 32 presents the distribution of advective temperature effects in the lower layer showing a distinct warming (negative values) in the central United States.

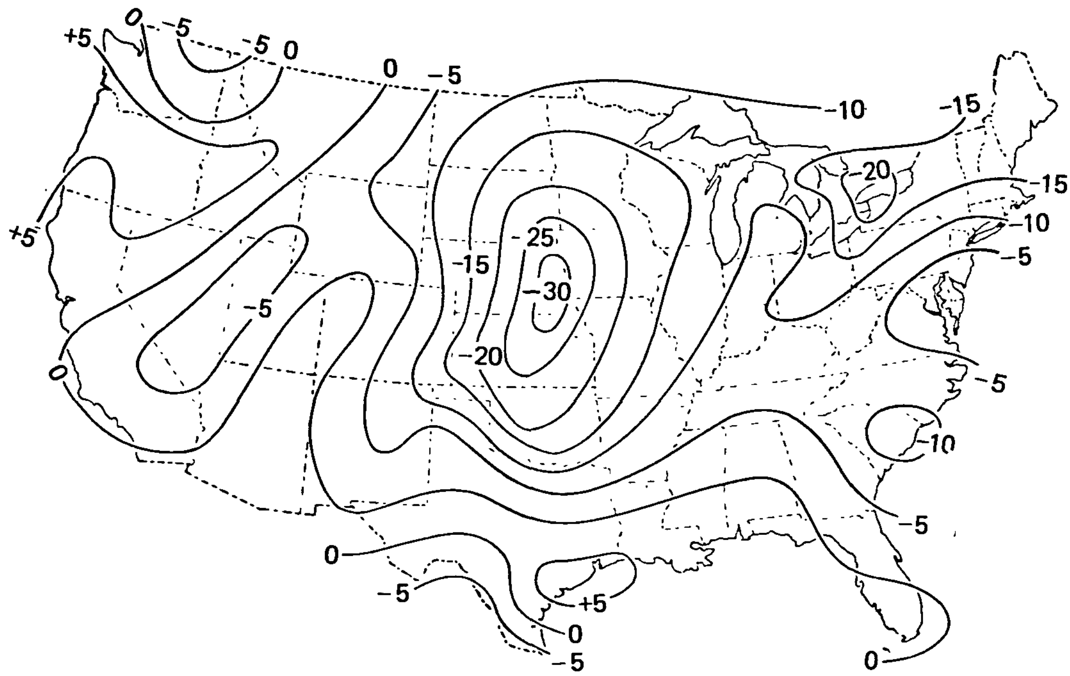

Figure 32. Distribution of advective temperature effect in the lower layer (Negative values indicate warming, positive values cooling)

Specific Thunderstorm Regions

Regions A and M. These two regions have their maximum in thunderstorm activity in the winter season, and as shown in figure 26, thunderstorms occur occasionally with the synoptic-scale storm system that affect the western coast in winter. The air mass influence on the area from northern California northward to Alaska differs from that for southern California. The northern coastal area comes under the influence of maritime polar air, whereas the southern is under maritime tropical air in the winter, as shown in figure 26. Bryson and Hare (1974) identify these as West Coast climates with the northern one being wet and the southern one typically dry. Thunderstorms, according to Court and Griffiths (1982), are more frequent in winter than in summer along the Pacific coast from southern California to southeastern Alaska. In California the percentage of annual thunderstorm days occurring in the winter half-year includes 46% at Fresno (central valley), 56% at Los Angeles, and 64% at San Diego and San Francisco.

Kendrew (1953) identified climatic regions of the United States based on precipitation types. Region A (figure 10) identified well with Kendrew's "Pacific type" which has a strong winter maximum and least rainfall in July-August. The dry summers are a result of the extension on the north Pacific and the anticyclones at that time. The winter rain is cyclonic but also orographic in much of the region, helping to make it a wetter regime. Kendrew's "California type" which begins south of San Francisco and extends southward is essentially a coastal climate but also embraces the Great Valley of California. The rain maximum is in winter, as in the Pacific type area, but there is a distinctive rainless summer of 2 to 4 months. Again, the differences between the controlling coastal air masses, mP and mT, help bring on these differences. Thus, thunderstorm areas A and M (figure 10) identify well with established and different maritime West Coast climates.

Great Basin, Region B. The Great Basin which comprises much of Utah, Nevada, eastern Oregon and southwestern Idaho is an upland region. Airflow from the west or east is blocked by the western or eastern mountains. In mid-summer, the Great Basin becomes filled with unstable tropical air from the south, and this coupled with localized heating and orographic effects produces most of the region's thunderstorms. The "summer monsoon" is also an influence defined in the precipitation regions by Kendrew (1953). He identifies this as the precipitation area labeled the "Snake River."

Rocky Mountains, Regions C and N. These two regions largely embrace the Rocky Mountains and include parts of the southern deserts and the intermontane region of the Columbia Plateau. Region C extends northward from Arizona-New Mexico into Colorado and southern Wyoming. Both regions have a summer season maximum of thunderstorm activity which is largely related to their higher elevations. Localized storms occur due to heating of the upslopes of the mountains.

To some extent, the mid-summer monsoon influences thunderstorm activity in Region C. Inspection of the summer predominating air mass patterns (figure 27) shows that area C is where cT air mass predominates, whereas mountainous Region N is an area of greater mP and cP air mass. Region N, as shown in figure 30, is also an area of summer cyclogenesis, as opposed to Region C. One of the major tracks of summer cyclones begins in this region and extends eastward across the northern United States. Although both Region C and N are characterized by summer season, mountain-related thunderstorm activity, the southern area has the summer monsoon influence, and the northern area differs by being an area of summer cyclogenesis. Apparently these are sufficient differences to separate them climatically as to long-term thunderstorm distributions.

The North, Region D. As shown in figure 10, this is one of the large regions defined by temporal increases from 1901 to 1980. It comprises the northern U.S. and most of Canada. There are many distinctive climatic aspects that help define this region. Thunderstorm activity in Region D is largely confined to the summer (June-August) season. Comparison of the boundaries of the region with those of the classic climate zones of Koeppen reveals that Region D occupies most of the area defined as Dfb and Dfc climatic zones (Griffiths and Driscoll, 1982). Further, as shown in figure 27, this is the principal summer area of the cP air masses. Bryson and Hare (1974) show that the convergence of arctic and tropical air, on the average, lies from Lake Superior eastward into southern Canada. This zone helps define the southern boundary of Region D.

As Bryson and Hare (1974) have noted, summer marks the maximum northward extent of the tropical regime with the July boundary extending from Texas well into south-central Canada and on eastward to the Atlantic. Zishka and Smith (1980) analyzed the tracks of all cyclones during the Julys of 1950-77, and these were used to construct the patterns shown in figure 30. The pattern based on the frequency of cyclones defined by the frequency of these events well delineates the southern boundary of Region D. This is also well delineated by the major track of cyclones that begins in the Region N and extends eastward. Region D also includes the "St. Lawrence Type" precipitation zone defined by Kendrew (1953). As could be concluded from figure 30, many of the warm season cyclones move through this region and concentrate in northeastern Canada.

Great Plains, Region E. This is an area of high thunderstorm frequencies, on the average. Thunderstorms in this Region are related to the mix of air masses (frontal occurrences) in the spring and fall seasons, and often to mountain-derived mesoscale thunderstorm systems in the summer, plus nocturnal thunderstorm activity (compare figure 10 with figure 32). Court and Griffiths (1882) shows that this is an area of preferred low-level jet activity which is considered responsible for severe thunderstorm activity in this region. It is an area of tropical continental air masses (figure 28) and maritime tropical air masses. Presumably it is distinctive from the Regions C and F because of the lack of direct orographic influences and the monsoon effect present in Region C, and with greater frontal effects than in Region C. It may be distinguished from Region F to the east by the nocturnal thunderstorm activity that is sizable in E, but not in F.

Thunderstorm Maximum of the Southeast, Region F. This broad region comprising most of the southern, southeastern, and eastern U.S. is the area of the greatest thunderstorm activity, on the average, in North America (figure 6). As shown in figure 27, it is an area that is dominated in summer by maritime tropical air. Kendrew (1953) labeled this the "Gulf Type" precipitation area which is distinguished by its late summer rain maximum, but with rain abundant in all seasons. This late summer maximum results because this is the primary area of the United States affected by tropical cyclones typical of the late summer and early fall. Region F is where 5% or more of the annual precipitation is due to tropical cyclones (Court, 1974). The western and northern boundaries of Region F are generally defined by the predominating cyclonic tracks in the spring and fall seasons. These lie along the Ohio River Valley. As noted in figure 31, it is also largely the area defined by surface wet bulb temperatures (exceeded 5% of the time or less) of 76°F, a key to localized instability thunderstorms. It is also the Cfa climate zone defined by the Koeppen climatic classification system.

Thunderstorms occur all year-round in Region F. Frequent cyclonic passages help produce thunderstorm activity in the winter, spring and fall seasons. Tropical depression storms are a factor in the summer, and isolated air mass thunderstorms occur frequently throughout the region in summer. These combine to make the region distinctive. The reduction in thunderstorm activity in this area in the last 40 years (figure 11) could relate to less frequent cyclonic disturbances and/or to fewer tropical storms.

South Atlantic Coast, Region G. This area in southeastern United States probably exists partially as a result of the circulation of warm moist tropical (Atlantic) air masses into the area, as shown in figure 28. It is also an area with considerable rainfall from tropical storms (Court, 1974). Bryson and Hare (1974) note that this is an area of "southern anticyclonic air" in the fall season. Figure 33 helps demonstrate this feature in the September surface streamlines. Another feature making the region unique is reflected in figure 30. This area is where July cycle—genesis occurs for cyclones that then move northeastward over the Atlantic.

Tropical Area, Region H. Miami and areas to the south have truly tropical climates and are defined totally by tropical storm conditions including tropical cyclones. Moist tropical airstreams predominate in all seasons (Bryson and Hare, 1974). It is a region distinct from Region F and all others of North America.

Central Transition-Areas, Regions I, J, K, and L. These four east-west oriented regions extending from the Great Plains to the Atlantic Coast are narrow in north-south extent, and separate large regions D and F. These are considered as "transition areas," separating the thunderstorm-producing conditions of D (largely summer-only storms) and F (all season thunderstorm activity). Reference to the discussions of the thunderstorm-producing weather conditions for Regions D and F helps reveal their great difference. Regions I, J, K, and L sit astride two major cyclonic tracks. Zishka and Smith (1980) show that principal cyclone track in the spring is along the Ohio River Valley generally forming the southern boundary of these four transition regions.

Figure 27 helps reveal that these transition areas are in a zone of mixed mT and cP air in the sunmer. Fluctuations, north-to-south between years or decades, of the positions of the major cyclonic tracks probably help define the northern and southern edges of these transition regions, particularly since the major track across North America lies where these transition regions exist.

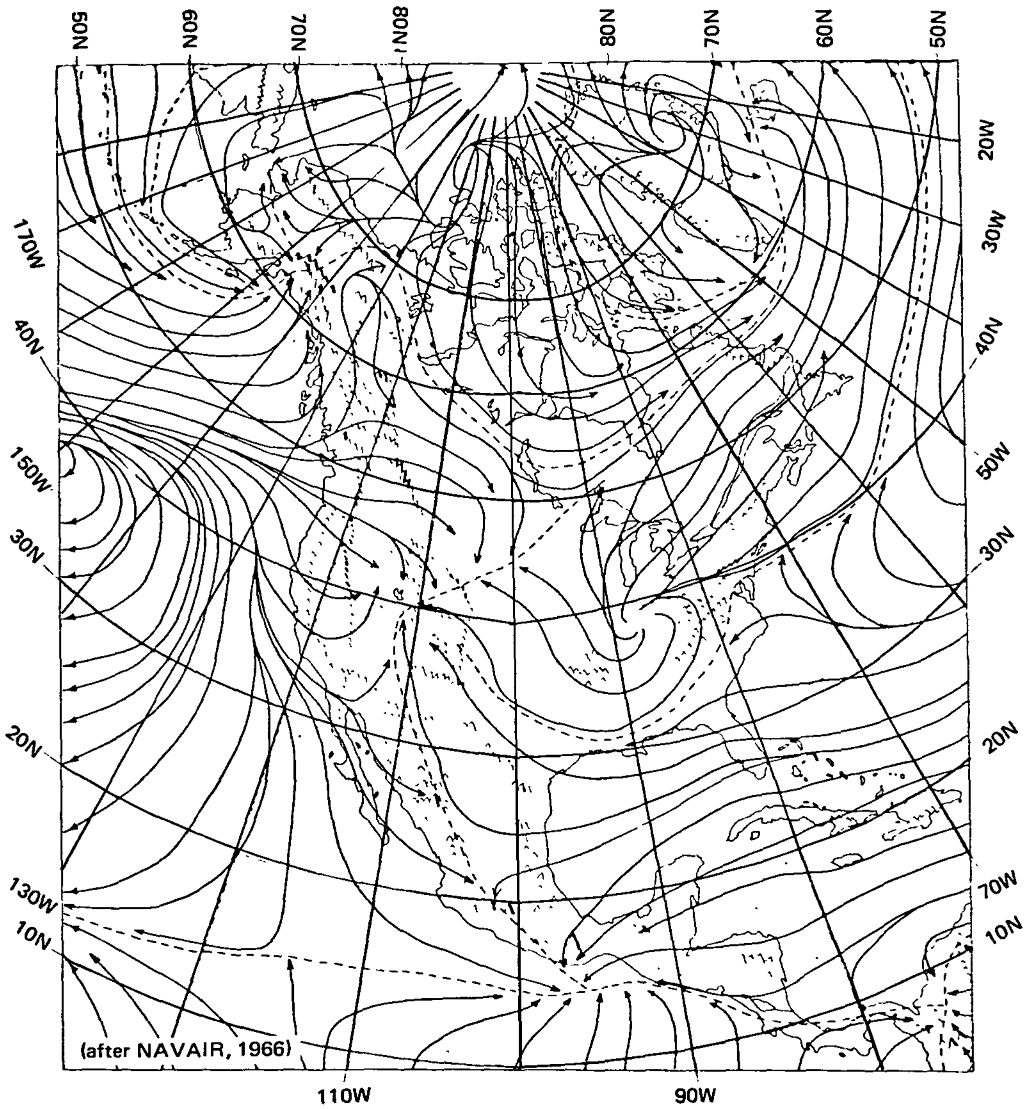

Figure 33. Resultant surface streamlines for September (from Griffiths and Driscoll, 1982)

Bryson and Hare (1974) show that the mean zone of convergence of Arctic and tropical air in the spring (March-May) occurs at 35-40°N which is the southern boundary of these transition zones. Kendrew (1953), in assessing the precipitation zones of North America, points to the fact that in the western sectors, this is a transition zone between the Gulf type and Plains type climates. This presumably helps define the differences of Region L across northern Illinois from Region E. He further points to localized lake effects on thunderstorm activity, a factor which likely causes the differences between Regions L and K. Regions I and J presumably come under maritime influences of the Atlantic which separate them from lake-related Region K.

Summary. Reasonable climatic justification exists for the 14 regions that were defined by their distinctly different temporal distributions of their thunder-day frequencies from 1901 to 1980. The winter storm control exists in the West Coast climates (Regions A and M), the intermontane effects in Region B, and the high-mountain related thunderstorm climate (Regions C and N on figure 10). The southern Great Plains climate reflecting mountain-initiated storm systems and nocturnal thunderstorms related to advective warming, as well as frontal activity in the spring and fall, establishes Region E.

The summer-only thunderstorm activity of the northern portions of North America with frequent cyclonic passages delineates Region D. The area of greatest year-round thunderstorm activity, involving tropical disturbances, frontal activity, and isolated air mass thunderstorms, defines Region F. Region F is separated from Region G due to the influences of East Coast cyclogenesis and fall circulation in the lee of the Appalachians. Region F is also different from truly tropical thunderstorm activity in southern Florida (Region H). Separating large Regions D and F, where thunderstorms are due to distinctly different synoptic weather conditions, are four relatively small transition thunderstorm climate zones (Regions I, J, K, and L). These are separated along their east-west extent by differences between the Great Plains synoptic features, the influence of the Great Lakes, and maritime influences of the Atlantic. Major climatic differences in precipitation-producing conditions and circulation patterns relate well to the 14 thunderstorm regions.

Temporal Variations in Synoptic Weather Conditions

The patterns defined by varying temporal behaviors in thunderstorms appear to be well explained by differences in climatic features, as described in the previous section. However, questions about the temporal fluctuations during the 1901-80 period of these key synoptic weather features is needed to further explain the temporal distributions found in each of the 14 regions. Unfortunately, a search of the literature has not yet provided an 80-year record of the behavior of the thunderstorm-producing conditions on a space scale that is needed to interpret the fluctuations noted in all the regions.

However, studies of the historical frequencies of cyclones and pressure were performed for broader areas. Hosier and Gamage (1956) studied the cyclone frequencies in the United States for the 1905-54 period. Recently, Zishka and Smith (1980) studied the cyclone frequencies over North America and environs for 1950-77. These two studies provide results illustrating historical fluctuations in cyclones for the continent.

The Hosier study showed a general increase in cyclonic activity over the United States from 1905 to 1954, but with a major singular decrease in cyclonic activity in the early 1940s. The results of zishka and Smith (1980) on July cyclones in the North American area are shown in figure 34. This shows a general decrease of 24% from 1950 through 1977, but the trend is significant at only the 90% confidence level. Zishka and Smith do not present patterns of regional differences with time, but they do state that the 1950 to 1977 decrease in July cyclonic activity, based on a comparison of the east and west sectors of North America, is due primarily to the reduction in cyclonic activity east of the Rocky Mountains. This would support the major downward decrease in thunderstorm activity found in Region F (figure 10).

Zishka and Smith presented patterns of July cyclones for 1950-54 and for 1970-74. These suggest temporal decreases in frequencies across most

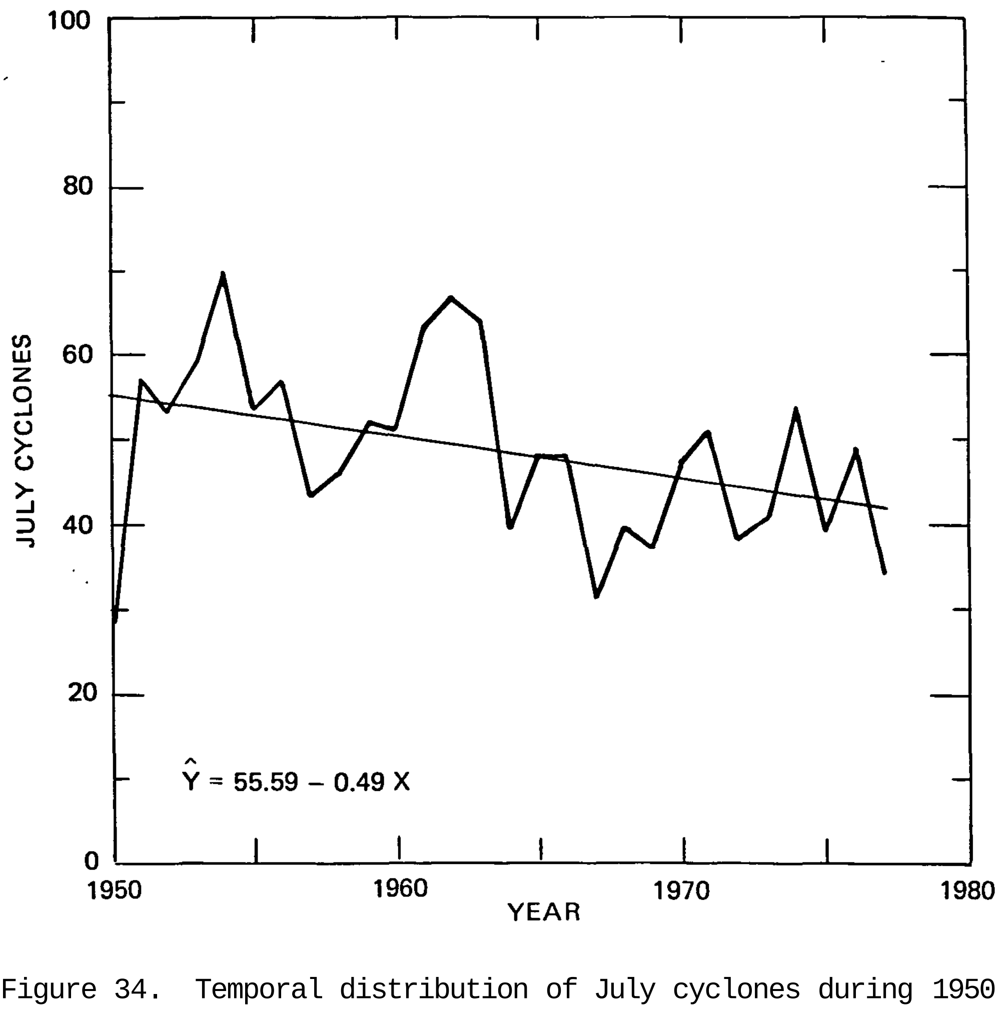

Figure 34. Temporal distribution of July cyclones during 1950-77 (from Zishka and Smith, 1980)

of the eastern U.S., but with little change in cyclonic frequency in Canada, where thunderstorm Region D exists. In general, these limited regional results for July cyclones tend to support what is reflected in the recent, post 1950, temporal behavior of thunderstorms in Regions D and F which cover most of eastern North America.

Zishka and Smith (1980) adapted the Hosler-Gamage cyclonic data for 1950-54 to their 1950-77 data to reconstruct a "normalized" yearly fluctuation of cyclone events over the United States for the 1905-77 period. The result is shown in figure 35. The mean annual frequency of North America thunderstorms, based on all North American stations from

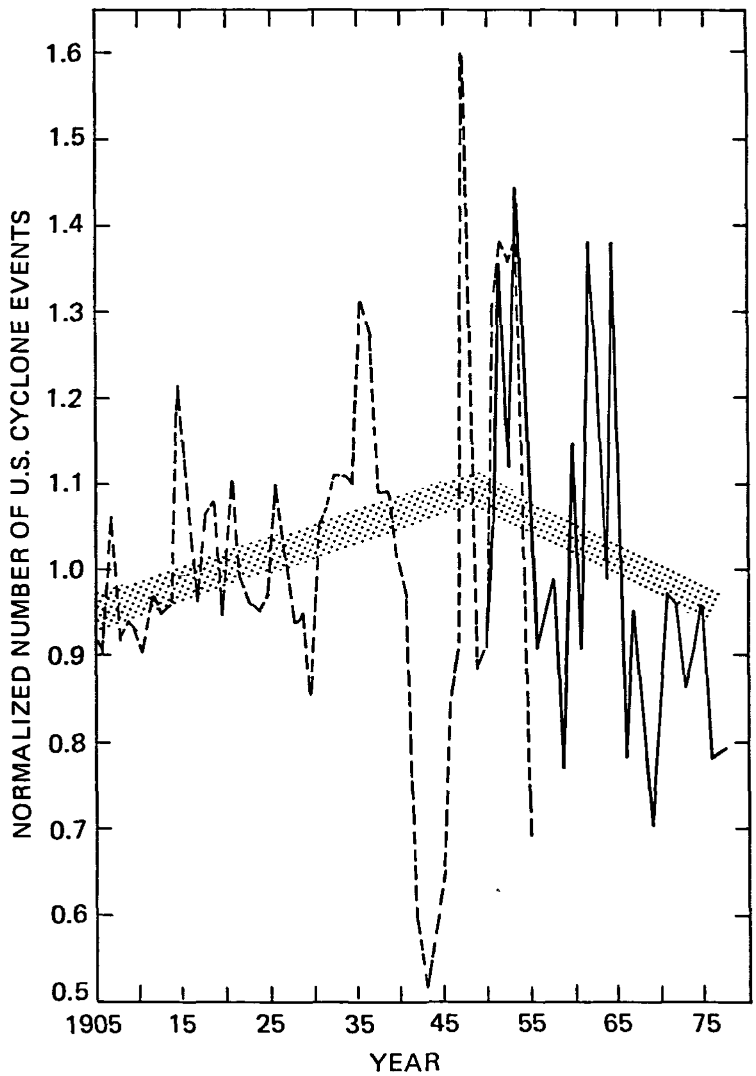

Figure 35. Annual fluctuations of cyclone frequencies in North America (from Zishka and Smith, 1980)

1900 through 1980, is shown in figure 36. Reasonable agreement is found in the basic trends of figures 35 and 36; that is, an uptrend exists in both cyclone frequencies and thunderstorms from 1905 through 1945-50, followed by a general decrease in thunderstorm and cyclonic activity through 1977. There are points in disagreement. The abrupt decrease in cyclonic activity in the early 1940s is not shown in the thunderstorm activity which actually reached its 80-year peak at this time. The recent anomalous high in thunderstorm activity during 1971-77 is not with a comparable major peak in cyclonic activity; however, there is a peak in cyclonic activity during these years. In general, one would conclude that the temporal distribution of cyclones for North America agrees with the temporal distribution of thunder-day frequencies across North America (figure 36). Such thunder-day increases during the first half of the 20th Century and subsequent decreases since 1950, are related to some systematic changes in the general circulation and the correlated meteorological fields.

Hayden's (1981) analysis of secular variations of extratropical cyclones in the eastern half of U.S. and the western Atlantic, for the 1885-1978 period, provide further relevant information for the thunder trend regions. For example, Hayden found that since about 1925, cyclone frequencies have declined over an area embracing Region F (southeast U.S.), which agrees well with the general decrease in thunder days in Region F. Further, a sharp increase in cyclones began after 1970 which further supports the recent upward shift in thunder days in Region F (figure lie).

Hayden's statistical analysis also identified a secular increase from 1900 to 1960 in cyclogenesis in the area embracing Region G, with a maximum achieved in 1951-60. As shown in Table 5 and figure llc, this agrees well with temporal distribution of thunder days in Region G. A sharp decrease in cyclone frequencies has occurred after 1960, which further agrees with the thunder-day distribution (figure llc).

Another result of Hayden is relevant to the thunder regions. He identified a region of general increase in cyclone frequency (relative to the Gulf Coast) in the Great Plains and across the Ohio Valley and northward. This helps supports the findings of thunder increases in Region D (northern U.S.) and Region E (Great Plains). Spatial patterns of time trends of eigenvectors revealed sharp east-west differences in cyclones across the upper Midwest, the central Midwest, and the east (PA and NY). These may help explain the east-west differences that defined the boundaries of transition Regions I, J, K, and L.

Brinkmann's (1983) statistical analysis of the precipitation climate across the Great Lakes shows a sharp difference in behavior between the western and eastern portions, helping to substantiate the Region L and K separation. In general, Hayden's results strongly suggest that the thunder regions (defined by their trends) in the eastern U.S. were largely the result of broad circulation shifts, as reflected in cyclone frequencies.

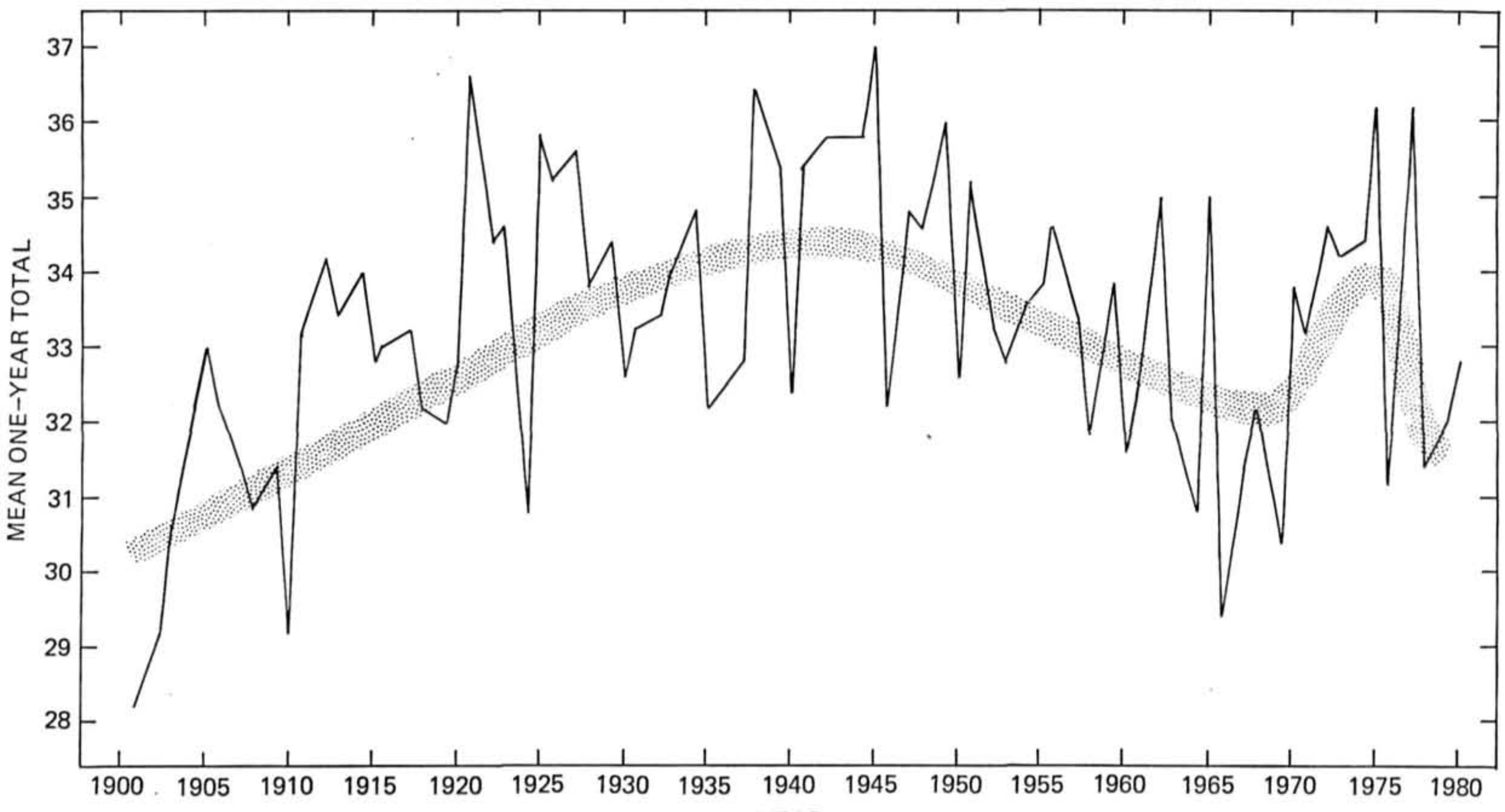

Figure 36. Annual values of thunder days in North America

Brinkmann (1981) identified periods of major changes in the northern hemisphere circulation as occurring in 1925, 1940, 1950, and 1965 (during 1899-1976 period). Using eigenvector analysis, level pressure patterns in eastern North America were studied to examine for secular changes. The pressure values showed relatively high pressure existed during 1899-1924 (low pressure in summer was less intense). This agrees with the fact that 1900-20 was a period of relatively low thunder day frequencies (figure 36). Brinkmann's evaluation for the 1925-39 period showed anomalous low pressures and longer summers, also agreeing with the fact that this was the period of greatest frequency of thunder days during 1901-80. Pressure conditions over eastern North America were considered average in 1940-64, with pressure conditions in 1965-76 relatively high like those in 1899-1924. This agrees with the lower incidences of thunder days in the last 15 years.

Summary. The results of these comparisons of the thunder trends of the varying regions against available information on historical variations in cyclones and sea level pressure, provide two important conclusions. First, there is strong agreement between regional and continental thunder trends and the various trends indicative of circulation conditions. This helps establish the reality of the thunder regions. Secondly, it helps establish that the temporal variations in thunder were largely caused by temporal variations in synoptic weather conditions that produce thunderstorms.

GLOBAL RESULTS

Average Annual Patterns

Yearly totals of thunder days were averaged for the 221 stations whose data we were able to acquire. (A list of 90 North America stations appears in Table 2, and 131 non-North America stations in Table 3.) The average annual thunder days are shown in figures 37, 38, and 39. Although

Figure 37. Annual average pattern of thunder days in Europe and Africa

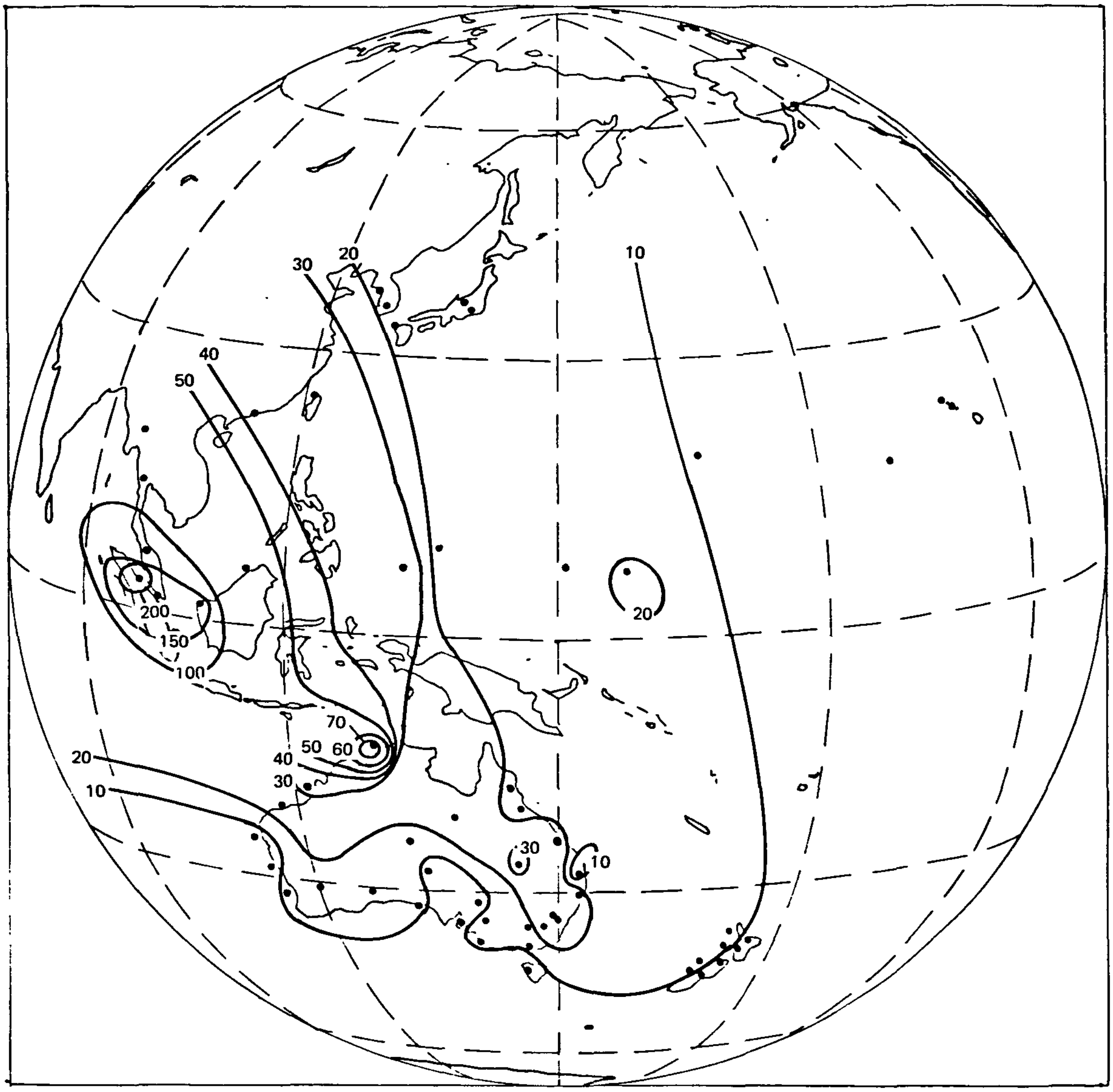

Figure 38. Annual average pattern of thunder days in Asia and Australia

a considerable effort was exerted to obtain thunder-day records for the 1901-80 period, the length of the station record actually acquired varied from country to country. For instance, a majority of North America stations had 80 years of thunder-day records, while those in Zambia had only 15 or so years of records. If there were 40 years of records available for a station, the 40-year total of the thunder days was divided by 40 to obtain the average annual value for that station.

The density of the stations also varied from region to region, as shown in figures 37-39. The density in some regions is adequate for

Figure 39. Annual average pattern of thunder days
in North and South America

spatial analysis, but others are not as desirable. Several regions had a more uniformly gridded network of stations, namely North America, Australia, and southern Africa.

There is an area in Indonesia where more than 100 thunder days were recorded per year (figure 38), with the highest average being over 200 days. This area is located in a tropical zone, very close to the Equator. The area probably has the highest annual frequency of thunder days observed in the world, as was also found in the study of Kotaki et al. (1981) who used the count of lightning discharges observed by the ISS-b satellite to obtain global maps of thunderstorm activity. However, the area with highest thunder-day frequency identified in an earlier WMO (1956) study occurred over tropical South America, where unfortunately no data were available to us. Besides, it is not clear in the WMO study whether the maps presented long-term averages or just annual values. Another area having more than 100 thunder days per year is located in Zambia, also in the tropical zone (figure 37).

In general, the annual thunder-day frequency in the equatorial tropical regions (the area between 30°N and 30°S latitude) is higher than 50 days. The thunder-day frequency in the temperate zones (between 30° and 60° latitude) is less than 50 days per year. This is a generalized and subjective judgment based on the data we accumulated. A more accurate statement on the global distribution of thunder day frequencies would require more data for those "blank" areas without data. Comparison of figures 37-39 with the corresponding WMO (1956) map shows that the two sets of patterns are quite similar, especially those in North America and for the western Pacific and Australia area where station densities were higher.

The annual thunder-day frequency in North America is higher than those in western Europe or in the southern South American continent, regions with comparable latitude. However, station densities in Europe and South America are not as high as desired.

Trends in Frequencies and Variability

Two investigations were pursued for the thunder-day data outside of North America. They were based on a) the general trends at stations with records longer than 50 years, and b) a factor analysis (temporal and spatial variations) for western Europe where most stations had data longer than 70 years.

General Trend of Thunder Days. A qualitative assessment of the temporal characteristics of the thunder-day values of each station was pursued to delineate regions of similarity, if any. The annual values of thunder days for stations with records longer than 50 years were used. The temporal distributions of these stations were examined to discern stations with similar patterns of trend. No rigorous grouping of stations to form regions of uniform trend pattern was done as for the North America continent (figure 11). Stations selected for this analysis did not have identical record lengths, which ranged from as short as 50 years to as long as 80 years. The temporal distributions of thunder days were examined for 1) overall trend, either an up (U) or down (D), and for 2) the shape of the time series, which could be convex or concave, to identify the years with maximum or minimum frequencies. The results are shown in figures 40-42.

An upward trend was found for western Europe and Turkey. The shape of thunder-day time series for most of the western European stations was

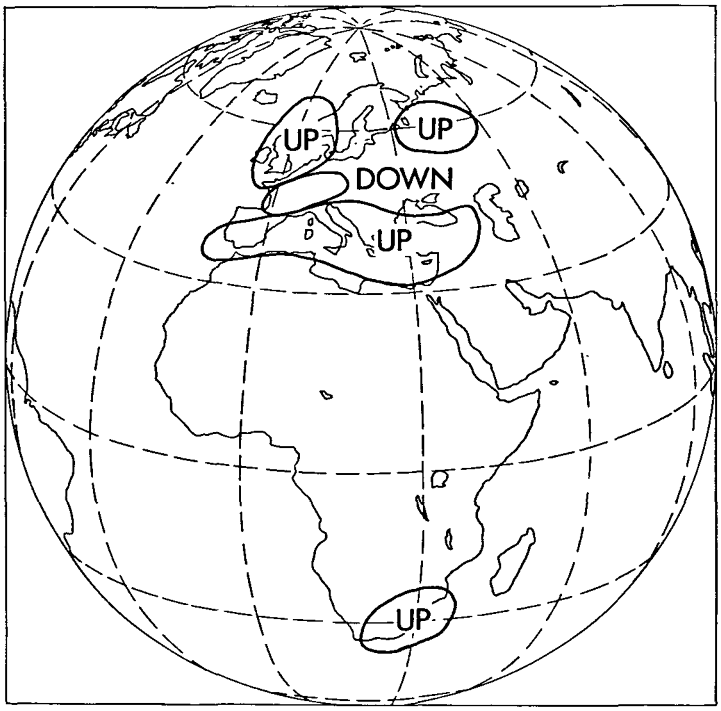

Figure 40. Long term trends (up or down) in thunder days in Europe and Africa

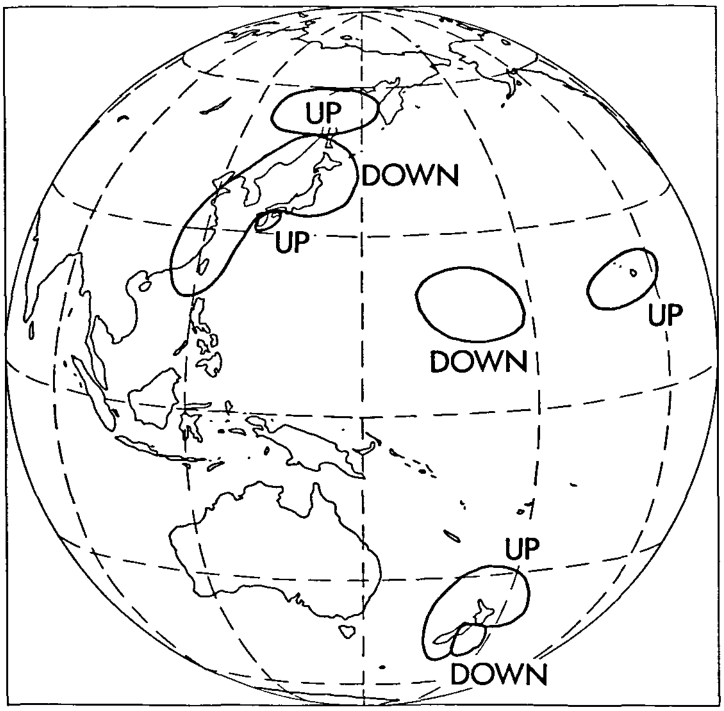

Figure 41. Long term trends (up or down) in thunder days in Asia and Australia

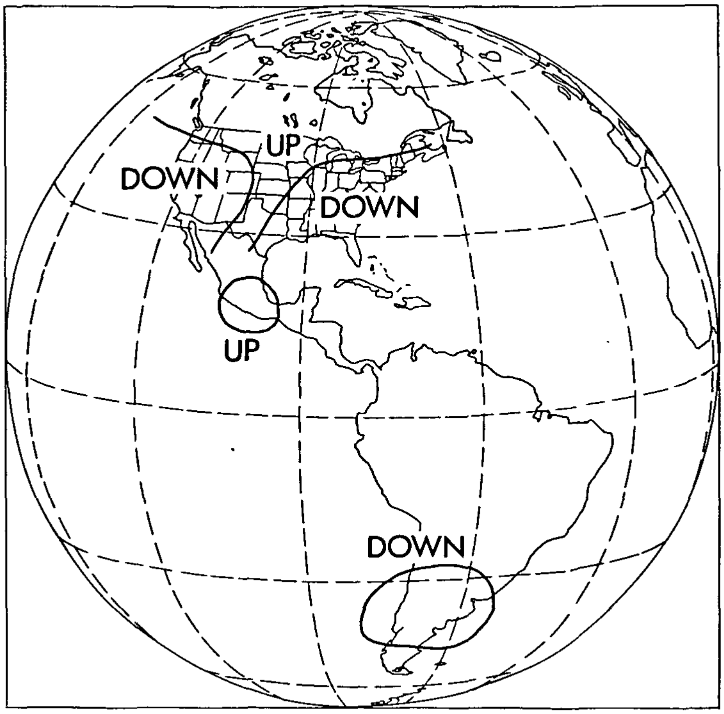

Figure 42. Long term trends (up or down) in thunder days in North and South America

convex with a minimum occurring in 1930-40. The overall upward trend over western Europe was rather profound. On the other hand, the shape of thunder-day time series foremost in the Turkish stations was concave with a maximum occurring in 1960-70. A noticeable downward trend of the Turkish stations occurred after 1970.

An analysis of the European data, based on all available station data and the trends in thunder-day frequencies, suggests three areas. To the north, including the British stations and Hamburg, one finds uptrends. In France, Switzerland, and Austria, which form an east-west zone, one finds downtrends. Farther south in an area generally along the Mediteranean Sea (Portugal, Yugoslavia, Greece and Turkey), the common trend is upward with time.

A general downward trend was found in the Far East and in Hawaii. The time series of the thunder-day frequencies in this region show a mixture of up and down trends for the period before 1950. However, a distinct downward trend was found in most stations after 1950.

Similarly, a downward trend was found for the three stations in South America which had long records. The two Argentine stations had a curve of concave shape with maximum frequencies occurring in 1930-40. The sole Chilean station showed a distinct downward trend for the entire period.

The sole Mexican station with a long record showed a convex time series and an overall upward trend.

Three of the New Zealand stations showed an upward trend and a convex temporal curve. The other two showed a downward trend.

Available data suggest that in the Northern Hemisphere and in areas north of 45°N uptrends exist for 1901-80. This includes Canada, northern Europe and the Soviet Union, and northern Japan.

Factor Analysis of European Data. Most western European stations had records of longer than 50 years, so the data were examined for temporal and spatial variations using factor analysis. Three factor analyses using the annual thunder-day data from the 14 western European stations were done. In each factor analysis, an orthogonal rotation (Varimax) was applied to facilitate the identification of spatial patterns. The maximum numbers of factors used in the analysis were restricted to 4, 5, and 6. The major spatial patterns remained the same in all three analyses. Figure 43 shows the results of the analysis based on four factors.

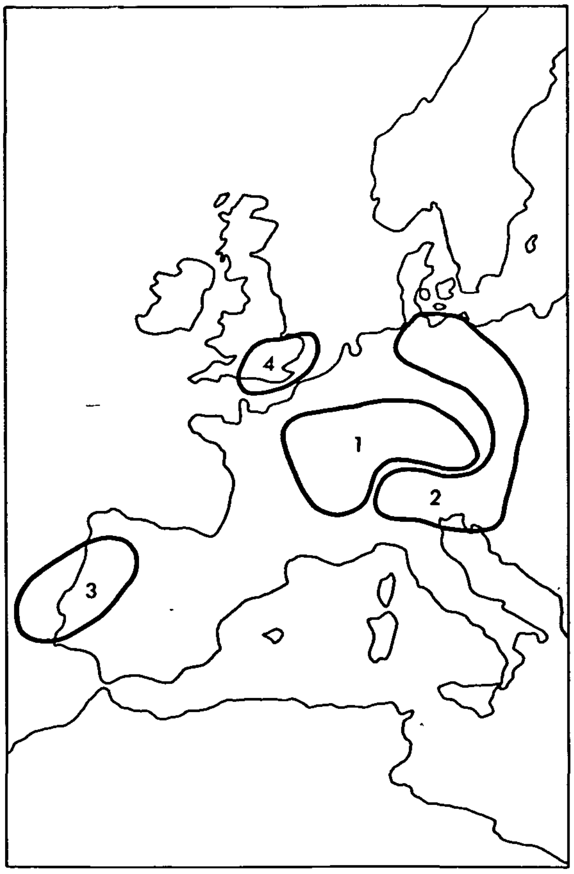

Figure 43. Areas in Europe based on factor analysis of thunder-day data

The spatial patterns identified in the figure included all the 14 stations used. The four factors explained 31%, 28%, 21%, and 20% of the variance. The spatial patterns identified are: 1) west European continental region; 2) east European continental region; 3) Portugal region, and 4) British region. The time series of the corresponding factor score coefficients showed that:

1) Pattern 1 was stationary with a high in 1925-35,and the variation became smaller after 1955;

2) Pattern 2 had a distinct increasing trend, especially after 1945, with a maximum in the last year of the data used;

3) Pattern 3 had a minor increasing trend until 1960, then it became stationary;

4) Pattern 4 had a minor increasing trend from 1915 until 1960 when a decreasing trend began.

Overall, there was an increasing trend of thunder days in western Europe during 1915-1955. After 1960, the eastern part of the area showed a distinctly increasing trend, while the western part showed either a minor decreasing trend or no trend.

SUMMARY

This one-year project has a central goal of studying the temporal variations in long-term (80-year) thunder-day records using quality records from weather stations scattered around the globe. It was deemed desirable to obtain records for all or most of the 1901-80 period so as to appropriately discern slow long-term trends and fluctuations, if they existed.

The thunder day is based on a definition for recording thunderstorm occurrences at first-order weather stations that began in 1897. If one or more peals of thunder are heard anytime during the 24-hour period from midnight to midnight, the day is recorded as having been a day with thunder.

Data were collected in a variety of means including purchases from the weather services of many nations, contacting acquaintances in the climatological field, and utilizing data already available from prior studies of thunderstorms. We collected data for 90 first-order stations in North America including 22 in Canada, 2 in Mexico, 1 in Puerto Rico,and 65 in the United States. All stations were those which had operated on a 24-hour basis for the period of record, 1901-80. We also collected data from 131 stations scattered around the globe. We found it extremely difficult to obtain foreign data that covered most or all of the 1901-80 period. Many foreign stations had records of only 30 to 50 years in length. All data received, much in tabular form, were entered with monthly totals of thunder days on computer tapes. These data are now available on 9 track, 10-inch tape in EBCDIC format, and can be obtained at the costs for reproducing the tape and mailing by contacting the Illinois State Water Survey.

After the data that could be a reasonably obtained were assembled, a series of evaluation tests were made of the thunder values. Studies of potential temporal fluctuations of 5 to 15% over periods of 10 to 40 years require high quality data. Potential problems in the thunder-day data included those of audibility due to the fact that the observers were housed in different areas or buildings, or were located in regions where the noise level had varied. For example, weather stations in busy downtown business districts might miss an occasional peal of thunder due to noise, or weather stations at major airports with heavy jet traffic in the last 30 years might miss thunder because of aircraft noise.

We applied three tests to the North American data. First the historical values of many of the larger stations (Chicago, New York, Washington, DC, etc.) were compared with values from nearby stations in smaller communities where potential noise problems, particularly in the last 30 years due to aircraft, would not exist. If a larger station showed a shift in its relationship with the nearby small stations over time, this would be interpreted as an indication of a questionable record.

Another test involved inspection of the frequencies of thunder days before and after known shifts in station locations. Most U.S. stations were relocated from an in-city site (from 1901 to mid 1930's) to an airport site in the 1930's or 1940's. These and other station relocations were studied. If statistically significant changes in thunder-day frequencies occurred around the time of a shift, the records were rejected.

The third test involved a station vs area comparison of the 10-year averages during 1901-80. Values at one station were compared with the mean of several stations around it. If major persisting discontinuities developed at the station under evaluation, it was rejected.

North America data had been obtained for 90 stations, and these tests led to the conclusion that 4 stations (Atlanta, Kansas City, Portland, ME, and Toronto) had records that were incorrect during the period, and hence were rejected. We could not apply similar tests to all the global stations because of the lack of station histories. The results of the tests showed that the data quality problems came at or near times of station relocations. We did not find questionable values at stations during the 1950-80 period when the potential airport noise problem could have existed particularly at stations at major airports. The conclusion is that these recent potential noise problems did not exist. Once the quality data stations were established, the various temporal and spatial analyses of the data proceeded.

Much of the research focused on the North American data which were the most spatially dense and highest quality long-term records available. The continental data (all stations in U.S. and Canada) were combined to examine North American trends on a seasonal and annual basis. This revealed one of the most important findings of the study; that is, the annual values for North America revealed a general increase from 1901-45 of about 15%, followed by a general decrease of 10% from 1945 to 1980. Studies of the variability of thunder days across North America from 1901 to 1980 showed a general decrease with time, particularly after 1940. Inspection of the seasonal (spring and summer) thunder-day values for North America revealed both were similar to the annual distribution. The major finding, which might be considered surprising, is that for areas as large as the North American continent, the frequencies of thunderstorms have long trends. This has interesting implications for global atmospheric electrical considerations.

One hypothesis set forward for examination of the North American data was that varying temporal distributions existed in different parts of the continent. This was investigated in a variety of ways. First, the continent was divided into four sectors based on 100° W longitude and 40° N latitude. The northwest and northeast sectors both had temporal distributions during 1901-80 that were similar; they both featured a general increase in frequency from 1901 to 1980 with it being more marked in the northeast sector. The southwest sector also exhibited a general increase from 1901-1945; however, this was followed by a rapid decrease in frequency during 1946-55, followed by relatively low frequencies until 1980. The southeast sector showed a generally flat trend until about 1930 followed by a general decrease through 1980, although a short major peak occurred in 1971-75. This sector study substantiated that there were major regional differences in temporal frequencies of thunder days across North America. These regional differences were then investigated in several ways.

The 5-year values (1901-80) of the individual stations were examined, compared, and classified into regions of similarity. If two or more adjacent stations had similar distributions they were used to develop a region. Based on this analysis, 14 regions were defined in the U.S. and Canadian area (Mexican data were so limited that they could not be used). There were two major regions: 1) northern U.S. and all of Canada where some 30 stations all exhibited a general increase from 1901 to 1980; and 2) the southeastern third of the United States, the area of greatest average thunder-day frequency. It exhibited a major decrease in thunder day frequencies after 1925. Four of the 14 regions formed a transition zone between the two large aforementioned areas in the northern area of increase and the southeastern area of decrease.

A general classification of the trends, both in the frequency of thunder days and in their variability during 1901-80, revealed three major regions in North America (figure 19). The northern section, including the northern U.S. and Canada plus the Great Plains, is a large region where thunder-day frequencies during 1901-80 generally increased while their variability decreased with time. The area to the west of the Great Plains and south of Canada also exhibited a downtrend of thunder-day frequencies but with a decrease in variability with time. The third region included the broad area of the southeastern U.S. which showed a decrease in thunder frequencies, but increased variability with time.

The data from these 14 regions was also examined for the existence of periodicities. Those significant at the 1% level further revealed the presence of interesting periods. Most of the U.S. area exhibited significant periodicities at a long return interval, defined as greater than 15 years. The western third of the United States also exhibited the presence of a short periodicity, defined as something less than 7 years. In the northern U.S. and Canada there was a statistically significant period in the medium length range, classed as somewhere between 7 and 15 years in length. Importantly, there are several significant periodicities reflected in the thunder-day data for North America.

Regional variations in the temporal trends in North America were further studied using statistical tests. Factor analyses of the annual thunder-day data were done using anywhere between 9 and 11 factors. Nine factors (regions) explained 54% of the variation. The most statistically significant region was the upper Midwest and Canadian area which showed a very marked uptrend.

Factor analyses were also applied to the seasonal (spring, summer and fall) data. This revealed the presence, in all seasons, of factors (regions) appearing in the same areas of North America. Regions appeared in the Midwest, East Coast, northeast U.S.-eastern Canada, southeastern U.S., Great Plains, northern U.S.-Canada, the Rocky Mountains, and the northwestern U.S. in all three seasons. Ranks based on the seasonal factor analysis indicated that the factors, or regions, explaining the greatest amount of variation were the Midwest, northern U.S.-Canada, the East Coast, and the southeastern United States. Trend distributions in the seasons, based on the factor analysis, did not show strong relationships between the seasons; that is, areas with uptrends in spring did not necessarily have uptrends in summer and fall. This helps substantiate that we were not using data that had inadvertent audibility mistakes which would have likely resulted in similar trends in all seasons. It also indicated to a certain degree that the conditions that were fluctuating and causing thunderstorms were not fluctuating in the same way in spring as in summer, or were different in fall. Since most thunderstorms in most areas in North America are concentrated in summer, the summer temporal distributions tend to dominate the annual.

Statistical tests for the presence of uptrends in the data were conducted. These revealed that statistically significant trends, at the 1 to 5% level, existed throughout the 80-year period in the northern U.S. and Canada. They were also present during most of the 80 years in the U.S. Great Plains.

The one-year research period did not allow intensive investigations of the possible causes of the trends and fluctuations found in the frequency of thunder days and their variability with time. Basically, the factors leading to temporal changes could be physical (atmospheric) factors that fluctuate over time, or man-made (pollution) influences on thunderstorms.

The potential for man-made influences on thunderstorms is supported by a secular change in the atmosphere conductivity found in the North Atlantic over the past 40 years (Cobb and Wells, 1970). Furthermore, Huff and Changnon (1973) established that the combined influences of large metropolitan areas in the United States led to localized increases in thunder activity. Broader scale influences on thunderstorm activity at the regional, continental or hemispheric scales are conceivably related to large scale effects due to pollutants which as aerosols and condensation nuclei affect 1) conductivity of the atmosphere (conductivity decreases with an increase in the number of CN), and 2) the thunderstorm electrification processes. Changes in atmospheric conductivity over the mid North Pacific Ocean have been found related to polluted air masses (Morita and Ishikawa, 1977). Markson's (1977) series of measurements of the ionospheric potential from several locales around the world show a distinct downward trend for the 1950 to 1974 period of record. If the ionispheric potential is changing globally, it would suggest that thunderstorms are either becoming less frequent and/or less intense (fewer strokes).

Earlier research involving thunder-day data established areas of major decreases in North America for 1951-1970 (Changnon, 1973).

Research dealing with aircraft-generated contrails which can act as cirrus clouds has revealed evidence of increased cloudiness in the United States. Changnon (1981) in studies of contrails in the central United States, revealed an increase in cloudiness and a decrease in sunshine since the 1930's at times and places where thunderstorm frequencies apparently decreased (Changnon, 1977). A midwestern area of cloud cover increase, particularly notable since the late 1950's, appears to be partly related to aircraft induced contrails. Such changes in cloudiness and their causes may be relevant and related to the decrease in thunderstorms because high cloudiness should, on the average, inhibit convective activity and thunderstorm development.

The other basic explanation for varying trends in thunder-day frequencies includes natural atmospheric fluctuations. Kamyshanova (1974) analyzed historical (1900-68) thunder-day data at two Soviet stations (Leningrad and Moscow). He found an increase in thunder-day frequencies during the 1930-68 period, which agrees with the results from the northern U.S.-Canadian stations located at similar high latitudes (greater than 50° North). Kamyshanova also concluded that the period of altered frequencies found in the Soviet data was related to periods with large scale differences in circulation types and hence prevailing air masses. If changes in thunderstorm frequency are totally or largely related to large scale circulation changes associated with hemispheric warming (Brinkmann, 1976), one would expect areas of maximum thunderstorm frequency to be displaced with time resulting in spatial patterns of negative and positive anomalies. Such was the case found for North America.

Comparison of the locations of the 14 North American regions, defined on the basis of different trends, reveals that all can be related to pre-identified major climatic zones. The regions are identified as being related to 1) differences in a major air mass sources particularly those in summer, or 2) as areas of cyclongenesis, or 3) as locations of major tracks of cyclones. However, the area of major decrease, the southeastern portion of the United States, is an area of major industrial development and pollution in the United States. This may or may not be related to potential influences due to air pollution and/or contrails.

The comparison of the North American thunder-day frequencies from 1901 to 1980 with cyclonic frequencies showed comparable trends. The agreement is sufficiently strong to support a general conclusion that the major temporal variations in thunder days including the uptrend from 1901 to 1945, and the downtrend since then, were largely due to major shifts in atmospheric circulation reflected in the continental scale frequencies of cyclonic storms. Unfortunately, regional scale data on the frequency of cyclones were not readily available to further determine the factors causing the sizably different trends in different regions of North America. At this state of these studies, it appears that the physical factors are the overwhelming reasons for the temporal and spatial fluctuations found in thunder days, but more investigation is warranted.

The limited investigations of the thunder-day trends at stations in other parts of the world identified certain regions of major up and down trends. Inspection does not suggest these are related to certain high or low latitude locales. No interpretations of the trend patterns found are yet available. Inspection of the western European data by factor analysis reveals the presence of four distinct regions with distinctly different trends. Again, further investigation is warranted.

This one-year project has provided some unique data sets and interesting findings about major temporal shifts in thunder days around North America and also in the world. Results suggest that the fluctuations are due to large scale circulation fluctuations. However, the data and findings call for more research relating to causes of the fluctuations. For example, historical regional data on cyclone frequencies in North America would be useful in identifying the regional varying trends found, at least in the major regions of Canada, the southeastern United States, and the Great Plains. Time did not permit a thorough study of the global data beyond that in North America, and in certain areas where data are sufficiently dense more study of the fluctuations is warranted. Further, since the thunder day is just a simple index relating to atmospheric electrical behavior, comparisons of thunder days with actual thunderstorm durations and other measures of atmospheric electricity are called for. If strong relationships exist, then the historical fluctuations in thunder days will take on more meaning for assessing possible temporal fluctuations in lightning discharge activity.

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