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Cyclone Climatology of the Great Lakes

by
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CYCLONE CLIMATOLOGY OF THE GREAT LAKES

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Title: Cyclone Climatology of the Great Lakes.

Abstract: A historical cyclone dataset was constructed for the period 1900 to 1990 from those cyclones passing over the Great Lakes with a central pressure ≤992 mb. This dataset was used to address the following five research topics: a) the trends and fluctuations in the characteristics of cyclones, b) the balance between cyclone frequency and intensity, c) the sensitivity of cyclone characteristics to climate variables, particularly temperature and precipitation regimes, d) the preferred tracks of cyclones passing over the region and changes over time, and e) the influence of the Great Lakes on passing cyclones.

This study documents a statistically significant increase in the frequency of strong cyclones over the Great Lakes during the 20th century in both November and December. There are indications that a balance exists between cyclone frequency and intensity. The two major source regions for Great Lakes cyclones are Colorado and Alberta, Canada. An analysis of changes in cyclone characteristics, temperature, and precipitation yields a positive relationship between cyclone frequency and precipitation. This research also provides climatological evidence (as opposed to case studies or models) of the important influence of the Great Lakes on passing cyclones. Cyclones accelerate into the region, slow and deepen over the lakes, and then return to their prior speed and rate of deepening after they exit the region.

Reference: Angel, J.R., Cyclone Climatology of the Great Lakes, Illinois State Water Survey, Champaign IL, Miscellaneous Publication 172.

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1. INTRODUCTION

Cyclones over the Great Lakes are an important feature in the physical and socio-economic environment of the region. Cyclones are centers of low pressure that can span from 1000 to 3000 km in diameter. In North America, cyclones generally move from west to east and are widely recognized as providing the day-to-day variability in weather. While often associated with inclement weather, cyclones are an important mechanism for the poleward transport of momentum, heat, and moisture and are driven by regions of strong temperature gradients known as baroclinic zones. The stronger of these cyclones have traditionally brought great risk to shipping. For example, the "Great Storm of 1913" sank a dozen ships and killed more than 250 men (Barcus, 1960). Cyclone frequency and intensity have a significant impact on lake stratification (McCormick, 1990). Winter cyclones, with associated high wind speeds, can alter the amount of ice cover over the Great Lakes (Assel, 1991). Also, cyclones, along with elevated lake levels, can cause extensive shore erosion and damage to lakeshore property (Changnon, 1987). In fact, it was the terrible loss of life in the Great Lake severe cyclones of 1868 and 1869 that prompted U.S. Congress to form a national weather service at the urging of University of Wisconsin-Milwaukee Professor Increase Lapham (Hughes, 1970).

The Great Lakes also have an impact on passing cyclones. During winter, when the air is generally colder than the lake waters, the energy that a passing cyclone gains from the Great Lakes can deepen the cyclone's pressure (Petterssen and Calabrese, 1959). Thus, any changes in the frequency and intensity of cyclones over the Great Lakes would likely have an impact on the weather and climate of regions downwind and perhaps far beyond the Great Lakes region.

Previous Studies of Cyclones on the Great Lakes

Despite the importance of Great Lakes cyclones, only three studies have directly documented their features. Garriott (1903) described 238 cyclones that occurred over the Great Lakes during a 25-year period from 1876-1900. Each cyclone was described in four maps depicting surface pressure and temperatures that cover from 32 to 48 hours of the cyclone's history. This study was motivated by the need to identify conditions associated with the approach of these cyclones for forecasting purposes. Four source regions were identified - the southwest U.S., the middle-west U.S., the northwest U.S., and the Gulf of Mexico. Cyclones over the Great Lakes were most frequent in November, while summer cyclones were infrequent.

Lewis (1987) provided the second study of cyclones along the Great Lakes. He defined storms as disturbances producing winds greater than 88 km/hr. This study examined 100 storms from the period 1957-1985 and included a surface analysis, storm track, and important meteorological parameters for each storm. Of these 100 storms, 92 were cyclones while the remaining storms occurred in summer and were associated with thunderstorms and/or squall lines. Lewis identified eight source regions for Great Lakes storms: a) Alberta low (typical late fall/early winter), b) Colorado low (lee side of Rocky Mountains), c) Texas low (approach from south southwest), d) Gulf low (approach from the Gulf of Mexico along the Appalachian Mountains), e) Hatteras low (east coast cyclones that extend into the Great Lakes region), f) Lakes low (locally formed cyclones), g) Northwest low (approach from the northwest), and h) Pacific low (low from the Pacific that remains intact over the Rocky Mountains). Fifty-seven percent of the cyclones were associated with the Colorado and Texas source regions and 76 out of the 92 cyclones occurred between November and March. The strong temperature contrast between the cold air and the ice-free water during winter intensified these cyclones. While no trend was evident in the annual total for the 29-year study period, a strong peak existed in 1972. While both authors provided extensive case studies, very little climatological analyses were presented beyond discussion of source regions and a seasonal/monthly categorization of the occurrences of cyclones over the Great Lakes.

Harman et al. (1980) provided a more extensive study of cyclones for the months of October through February for the period 1955 to 1976 and focused on Lakes Superior, Michigan, and Huron. This study found December and January to be the most active months for cyclones, while November cyclones had the lowest average pressure. The two major source regions for cyclones passing over the western Great Lakes were identified as the northern Great Plains (Montana and Saskatchewan) and southern Great Plains (Colorado, Arizona, New Mexico). The cyclones of southern origin were stronger in all months than those of northern origin. The greater strength of southern track cyclones was attributed to the associated large troughs or long-wave features of the upper air flow and to the greater availability of low-level moisture. While this study described the features of cyclones affecting the western Great Lakes and the associated 500 mb flow, it did not cover all the Great Lakes and did not address changes in the cyclone characteristics over time.

On a larger scale, several studies have been made regarding the mean tracks and cyclone frequency in North America (Klein, 1958; Reitan, 1974; Zishka and Smith, 1980; Whittaker and Horn, 1984; and Changnon et al. 1995). These studies typically examined 30-40 years of surface maps and counted cyclones as they crossed a coarse grid (usually 5°latitude by 5° longitude). The counts were isoplethed to compute mean cyclone tracks. Table 1.1 gives an overview of these studies. The motivation for these studies was primarily for climatology or forecasting, and not the analysis of climate change. They generally documented large-scale features of cyclones, namely their preferred tracks. For example, in winter the Great Lakes was noted as the region of convergence for the Alberta and Colorado cyclone tracks, explaining why there is a winter maximum in cyclones over the Great Lakes. These studies documented a decline in cyclone frequency over North America between 1950 and the mid-1970s with an increase since the mid-1980s. However, due to the large-scale nature of these studies, it is not possible to draw conclusions about changes in cyclone characteristics over time for a particular region such as the Great Lakes.

Agee (1991) examined trends in cyclone and anticyclone frequency over the Northern Hemisphere and compared them with wanning and cooling periods for this century. Two surface analyses were used in this study: Zishka and Smith (1980) for the period 1950-77, and Hosier

Table 1.1. Summary of large-scale studies of cyclone activity in the Northern Hemisphere.

	Grid Size	Period of Record	Spatial Coverage
Brennan and Smith (1978)	2°x2°	1950-1974	Midwestern U.S.
Changnon et al. (1995)	5°x5°	1950-1993	North America
Colucci (1976)	1°x1°	1964-1973	Eastern U.S.
Hosier and Gamage (1956)	5°x5°	1905-1954	U.S. only
Klein (1957)	5°x5°	1899-1939	Northern Hemisphere
Reitan(1974)	740km x 740km (~8°x 8°)	1951-1970	North America
Whittaker and Horn (1984)	5°x5°	1958-1977	Northern Hemisphere
Zishka and Smith (1980)	2°x2°	1950-1977	North America

and Gamage (1956) for the period 1905-54. The Zishka and Smith data show a steady decline in cyclone frequency of 30% since the 1950s. This decline is also noted by Whittaker and Horn (1981) for the period 1958-77.

Agee noted that, according to the NASA temperature data set for the Northern Hemisphere (Hansen and Lebedeff, 1988), a wanning trend occurred from 1900 to 1940, a cooling trend from 1940 to 1978, and another warming trend from 1978 to the present. Analysis of the temperature and cyclone datasets show a positive correlation between increased (decreased) cyclone frequency and increased (decreased) hemispheric temperatures. Agee's explanation for the correlation was that "warmer than normal temperatures tend to occur with a flatter pattern of short waves ... that carries more numerous yet weaker disturbances west to east across the continent." The converse could be true for colder than normal conditions with stronger, less numerous disturbances migrating eastward. There is no indication whether a correlation between cyclone activity and temperature at the continental scale also exists for the Great Lakes region.

Environmental and Economic Impacts of Cyclones

Due to increased concern over projections of global warming resulting from increased concentrations of greenhouse gasses in the atmosphere, the U.S. Environmental Protection Agency commissioned studies concerning the Great Lakes based on scenarios of a warmer climate derived from General Circulation Models (GCM). Smith (1991) reviewed these studies and their key findings. Concerning the analysis of long-term changes in ice cover, thermal structure, depth of the thermocline, and fishing in the Great Lakes region, the assumption was made that cyclone frequency would not change during a warmer climate. As noted earlier, the results of Agee (1991) suggest that this may not be a valid assumption.

An examination of the literature suggests that changes in cyclone frequency and intensity over the region would have important impacts on ice cover, thermal structure, and the water quality and aquatic life in the Great Lakes. An increase or decrease in cyclone activity would also affect the shipping industry on the lakes and property damage due to shore erosion and flooding.

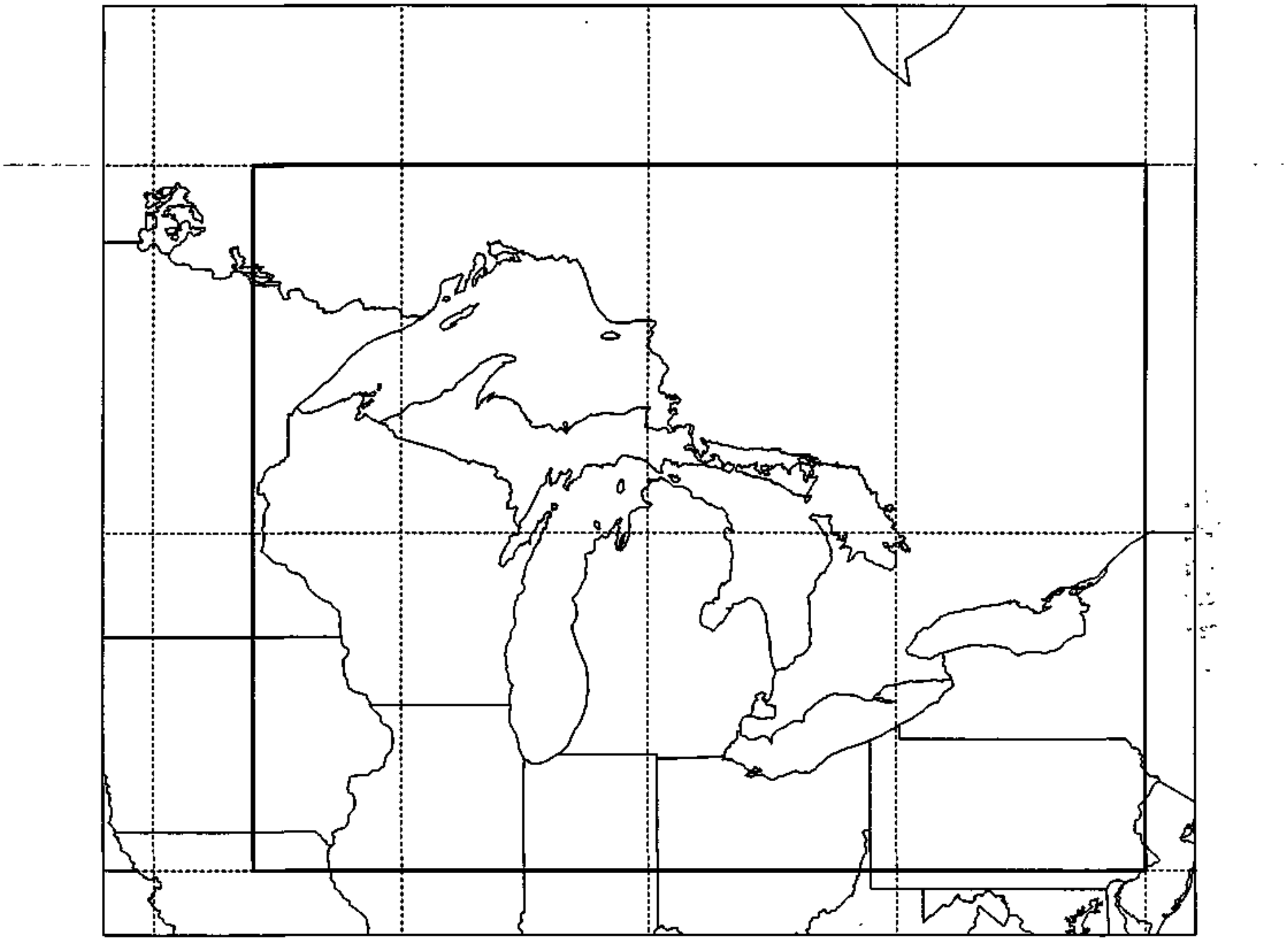
a) Precipitation

Brinkmann (1983) states that most of the precipitation in the Great Lakes region is associated with cyclones and their associated frontal systems. However, a review of the literature reveals no discussion on the exact size of this contribution. Using 10 years of cyclone track data from *Mariners Weather Log* (1981-1990), the dates when cyclones with closed isobars passed through the Great Lakes region, defined in Figure 1.1, were compared with daily amounts of basin-wide precipitation. The daily precipitation was provided by the Great Lakes Environmental Research Laboratory (GLERL) and is spatially averaged from individual stations by a Thiessen weighting technique developed at GLERL by Croley and Hartmann (1985). This comparison indicates that approximately 60% of the annual precipitation in the Great Lakes basin could be accounted for on days when cyclones with closed isobars were present in the region. This is undoubtedly an underestimate of the contribution because it does not fully take into account the accompanying frontal systems.

b) Ice Cover

Usually, the lake ice season for the Great Lakes is considered from late December to early April. Much of the loss of ice cover during this time is due to winds. Winds destroy ice cover in two ways: breaking up and transporting ice to the windward shore, and inducing vertical mixing of warmer water from below the surface to the surface for melting the ice (Assel, 1991). This suggests that an increase in the frequency and intensity of winter cyclones could retard or destroy ice cover while a decrease in winter cyclone activity could allow more extensive ice cover, all else being equal.

Fig. 1.1 Great Lakes region defined for the cyclone analysis.



c) Thermal Structure

The thermal structure of the Great Lakes can be characterized by a stable, stratified vertical profile in summer due to a positive heat flux at the surface (leading to warm, less dense water at the surface and cooler, more dense water below the surface). Wind stress is the major mechanism for mixing and destabilizing the surface layer in summer. In winter, wind stress and a negative heat flux at the surface leads to, and enhances, vertical mixing. McCormick (1990) developed a one-dimensional model of the vertical temperature profile of Lake Michigan and found that the model was most sensitive to changes in wind speed. He also noted that more than 90% percent of the energy for vertical mixing occurs at a daily or higher frequency (i.e., storms on all scales). Therefore, the thermal structure may be particularly sensitive to changes in cyclone occurrences and intensity.

d) Water quality for Aquatic Life

One consequence of the extremely stable vertical thermal structure that can last for long periods in the Great Lakes during summer is the depletion of oxygen and nutrients, particularly in the surface waters. This can have an immediate impact on fish populations. As noted by Schertzer and Sawchuck (1990), winds enhance vertical mixing, thus transporting oxygen and nutrients to near-surface water layers (epilimnion) from deeper layers (hypolimnion) and from the surface. As mentioned earlier, vertical mixing of water in the Great Lakes is very sensitive to wind stress overall and cyclone events in particular.

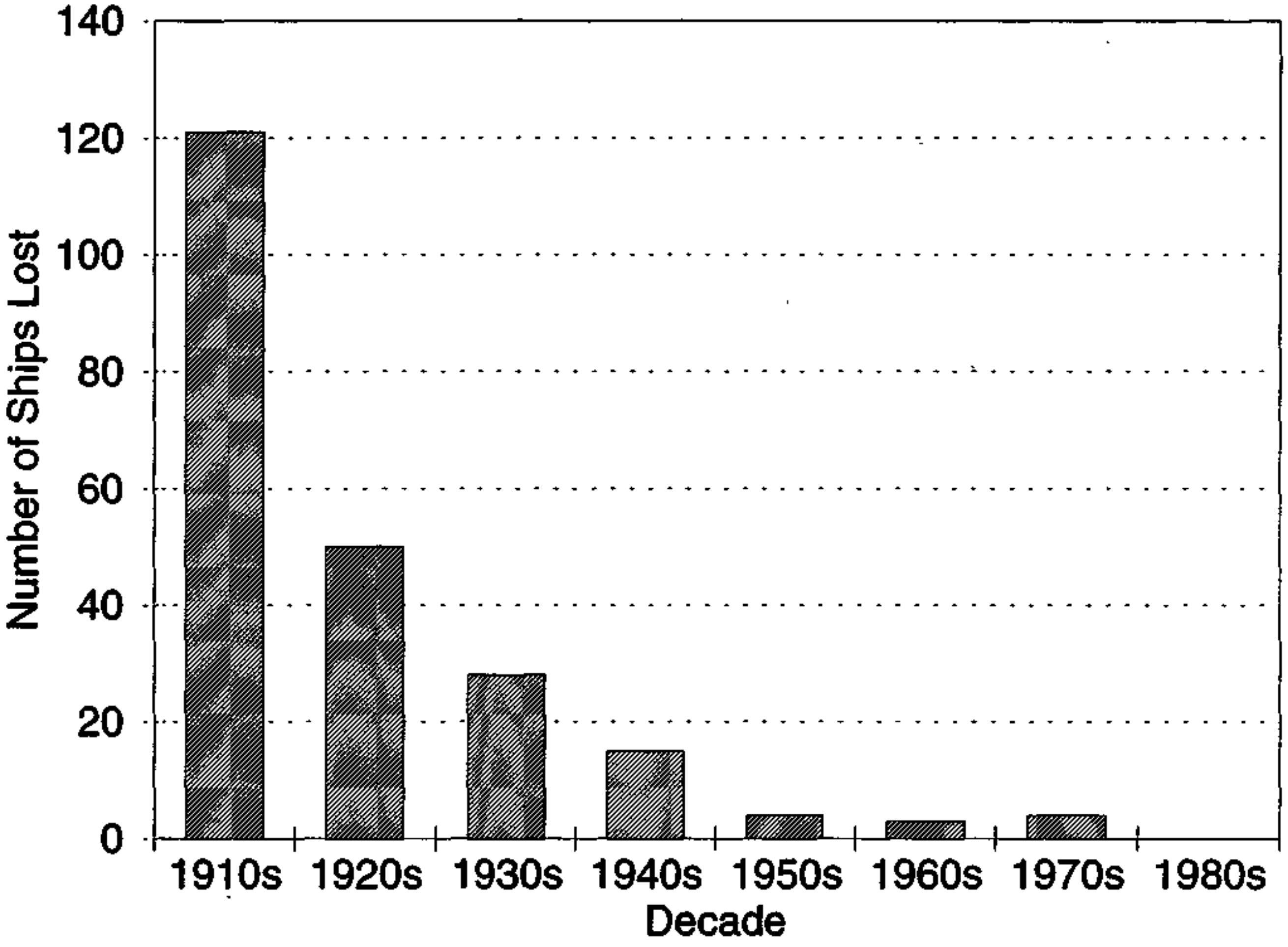
e) Shipping

Historically, Great Lake cyclones have had an enormous impact on shipping (e.g., Barcus, 1960). Since the turn of the century, the Lake Carriers Association included ships lost in storms in their annual report. Figure 1.2 shows the number of ships lost by decade. The rapid decline in the number of ships lost over time reflects the improvements in design, navigation, and weather forecasting. However, stronger cyclones still pose a threat, shown by the sinking of the *Edmund G. Fitzgerald in November,* 1975.

f) Shore Damage

Some cyclones cause millions of dollars of damage to property along the shores of the Great Lakes each year primarily due to shore erosion and flooding. However, no straightforward way is available to assess the sensitivity of shore property damage to changes in cyclone frequency because damage caused by a cyclone of a given intensity also depends on the levels of the water in the lake. The worst scenario would be increased cyclone activity with high lake levels. This was the case in the mid-1980s when Great Lake shores were particularly vulnerable to cyclones due to high lake levels (Changnon, 1987).

Fig. 1.2. Number of ships sunk by Great Lake storms according to the annual reports of the Lake Carriers Association (1990).



Summary

Cyclones are an important feature of the Great Lakes region with significant impacts on precipitation, ice cover, thermal structure, water quality, aquatic life, shipping, and shoreline property. The Great Lakes can also influence passing cyclones by contributing additional sensible and latent heat to the system. Previous studies of cyclones over the Great Lakes do not address the issues of potential future changes in the climate for the Great Lakes region. An historical analysis of Great Lake cyclones is needed to characterize these cyclones and assess how their characteristics might change under scenarios of climate change. A climatological analysis of the influence of the Great Lakes on passing cyclones is also warranted.

2. RESEARCH OBJECTIVES

One objective of this thesis is to identify and classify those strong and more severe cyclones that are capable of producing damages in the Great Lakes region in an objective manner. This thesis will also address several research questions concerning cyclones over the Great Lakes. First, what are the trends and fluctuations in the characteristics of strong cyclones over the Great Lakes? Second, are decreases in occurrences of strong cyclones compensated by increased intensity of strong cyclones over the region? Third, are the frequency and intensity of strong cyclones sensitive to warm/cool episodes as Agee (1991) suggests, as well as wet/dry episodes? Fourth, what are the preferred paths for strong cyclones passing over the Great Lakes and have they changed over time? Fifth, how much do the Great Lakes influence passing cyclones?

The frequency, intensity (measured by central pressure), rate of movement, and direction of movement of strong cyclones in the Great Lakes region will be examined for trends and fluctuations on monthly, seasonal, and annual time scales. These characteristics will be examined for contrasts among the cyclones that pass over the individual Great Lakes.

The relationship between the frequency of cyclones passing over the Great Lakes and their intensity, represented by their central pressure, will be explored. On a regional scale, a quasi-balance between strong cyclone frequency and intensity may exist.

Agee (1991) found a relationship between annual cyclone frequency and annual mean temperatures in the Northern Hemisphere. Is strong cyclone frequency over the Great Lakes sensitive to warm/cool episodes and wet/dry episodes? The long-term records of cyclones will be compared with long-term temperature and precipitation records in the Great Lakes region to develop these relationships. The results may be of use to infer changes in cyclone characteristics from the new NWS long-range forecasts, or, on a longer time scale, changes caused by possible future global warming.

The preferred tracks of strong cyclones passing through the Great Lakes region will be documented by counting strong cyclones as they pass through a grid over North America. Changes in time will be made by comparing the grids from two time periods of equal length.

The effect of the Great Lakes on all passing cyclones will be examined using the part of the historical database from 1965 to 1990 with the higher temporal resolution. Changes in cyclone intensity, measured by the central pressure, and cyclone speed will be documented for all cyclones as they pass through the Great Lakes region during the unstable season when lake water temperatures are warmer than air temperatures and the stable season when lake water temperatures are cooler than air temperatures.

3. CONSTRUCTING A HISTORICAL CYCLONE DATASET FOR THE GREAT LAKES REGION

In this chapter, the available historical datasets are reviewed in terms of their strengths and weaknesses. The dataset for the intended cyclone analysis needs to extend back as far as possible, preferably to the beginning of this century, and remain relatively homogeneous over its time span. The definition of a significant cyclone, in terms of damage caused, is explored using previous studies and available datasets. The cyclone criteria for this study are selected and the construction of the historical database is described.

Review of Available Historical Datasets

Ship-borne observations of atmospheric variables (temperature, winds, pressure) are not well suited for this study for several reasons. While the Comprehensive Ocean Atmosphere Data Set records extend from 1854 to the present, observations over the Great Lakes have only been entered since the 1950s according to Lewis (1987). The number of ships reporting atmospheric variables varies greatly from lake to lake. Reports are infrequent during the months when lake ice closes the navigation routes. Also, a fair-weather bias is present in the reports because ships typically avoid bad weather. As for land-borne records, no upper-air data are regularly available before World War II and the only surface parameters in digital form that extend back to the turn of the century are temperature and precipitation.

The most desirable and accessible data set for examining cyclones are the monthly cyclone track maps presented in the *Monthly Weather Review* from 1894 to 1958 and continued in the *Climatological Data*, *National Summary* and the *Mariners Weather Log* until the present. In these publications, the definition of a cyclonic center is a closed low pressure region persisting at least 24 hours. These maps are the basis for most previous work on cyclone frequencies and tracks (Hosier and Gamage, 1956; Hayden, 1981; Reitan, 1974; Zishka and Smith, 1980; Whittaker and Horn, 1984). With this set of records, examining cyclones from the turn of the century to the present is possible.

As noted earlier, Lewis (1987) found that 92 out of the selected 100 storms over the Great Lakes were associated with large-scale synoptic features. Also, Irish and Platzman (1962) found that extreme wind tides on Lake Erie were strongly associated with cyclones passing over the region, especially in winter. Therefore, the monthly cyclone track maps are considered a suitable data source for the study of cyclones.

Criteria for Defining Strong Cyclones

It is obvious that cyclones pass over the Great Lakes on a regular basis and yet not all of these cyclones pose the threat of economic or environmental damage. Some criterion are needed to help determine which of these cyclones have important impacts. To do this, the major sources of damage assessment in the Great Lakes region are reviewed. Then the various criteria used by previous authors for defining significant cyclones is applied to the extensive cyclone dataset for this study described above. The usefulness of the criteria are assessed by comparing the dates of passing cyclones defined by each criterion with the dates when damages were reported on the Great Lakes.

a) Datasets Available for Assessing Damages

There is only one data source that can be used to assess damages from cyclones on the Great Lakes, NOAA *Storm Data,* which provides reports of damage from cyclones on the U.S. shoreline of the Great Lakes from 1959 to present While annual reports from the Lake Carriers Association report shipping losses, the decreased sensitivity of shipping to severe weather over time (Fig. 1.2) does not make it a viable resource for this study. Unfortunately, no comparable, long-term data sources are available to document damage on the Canadian shoreline of the Great Lakes. Mather et al. (1964,1967) used this data source along with its predecessor, the *Climatological Data National Summary,* to document storm damage along the east coast of the United States. There has heretofore been no detailed climatology of the NOAA *Storm Data* reports for the Great Lakes region.

Most of the NOAA *Storm Data* reports originate from the local National Weather Service (NWS) offices, which, in turn, rely on NWS storm report logs, media accounts, and reports from local officials. A typical storm account includes the storm location, date, time, number of persons killed and injured, estimated category of property damage, nature of the storm, and usually a brief narrative. Most of the reports are for small-scale, severe local storms such as tornadoes, thunderstorms, and hail. However, reports of flooding and shore erosion along the Great Lakes are also noted, as they relate to specific weather events.

For the period between 1959 and 1960, NOAA *Storm Data* reports are examined for shore flooding and erosion along the Great Lakes, as related to large-scale, cyclonic weather events. This study does not include any damages explicitly related to thunderstorms, squall-lines, and other small-scale features or other kinds of damages, such as wind damage or hail. However, it is possible that these kinds of damages may be incorporated into the damage estimates of large-scale storm events. For example, a report may only mention damage due to coastal flooding, but it is possible that some damages may have been from accompanying high winds. Commonly, a cyclone causes damage in more than one state and/or Great Lake. Therefore, when the reports are divided by state or by lake, the number of reports will exceed the 112 cyclone-related episodes reported.

The database does have some limitations. For example, the number and detail provided in the reports may vary from one NWS office to the next. No strong relationship exists between the number of reports in each county and the population of that county, which suggests that the reports are not over-representative of densely populated areas. A second limitation is that the final damage dollar amounts are almost never fully documented in NOAA *Storm Data,* but this is

Table 3.1. Damage categories used in NOAA *Storm Data* reports.

Category	U.S. Dollar Amount
1	Less than $50
2	$50 to $500
3	$500 to $5,000
4	$5,000 to $50,000
5	$50,000 to $500,000
6	$500,000 to $5 Million
7	$5 Million to $50 Million
8	$50 Million to $500 Million
9	$500 Million to $5 Billion

partially compensated by sorting events into classes of loss that allow for a range of dollar amounts (Table 3.1).

The analysis detected 112 episodes of flooding and/or erosion caused by cyclones along the Great Lakes during the period between 1959 and 1990. Figure 3.1 shows the number of reports by year across the entire region. The outstanding features are the very large variation from year to year, and the lack of an upward trend in the number of damage reports that might be expected due to increased development along the shoreline in the last 30 years. As for the number of damage reports, the two most active years are 1973 and 1985. No losses due to cyclones occurred during 1962,1969,1989, and 1990.

A rough estimate of the relative costs of cyclone-induced damage can be made by separately adding the top and bottom dollar amounts in the cost category from each report. For example, if the reported damage is in category 4 (Table 3.1) add $5,000 to the bottom total and add $50,000 to the top total. Next, these amounts are adjusted to 1990 dollars using the U.S.Department of Commerce composite construction cost indices. In the this fashion, the total damages between 1959 and 1990 range from a low of $286.6 million to a high of 2.9 billion.

Fig. 3.2 shows the distribution of damages over time, based on the lower amount of each cost category (the most conservative estimate of damages). The years 1984 and 1985 are clearly outstanding in the amount of damages experienced. A second period with large damages is in the early 1970s (1972-1975). While lake levels are higher than average during both periods, the 1984-1985 period experienced more damage. A comparison of the cyclones generating the

Fig. 3.1. Number of NOAA *Storm Data* damage reports for the U.S. shoreline of the Great Lakes (1959-1990).

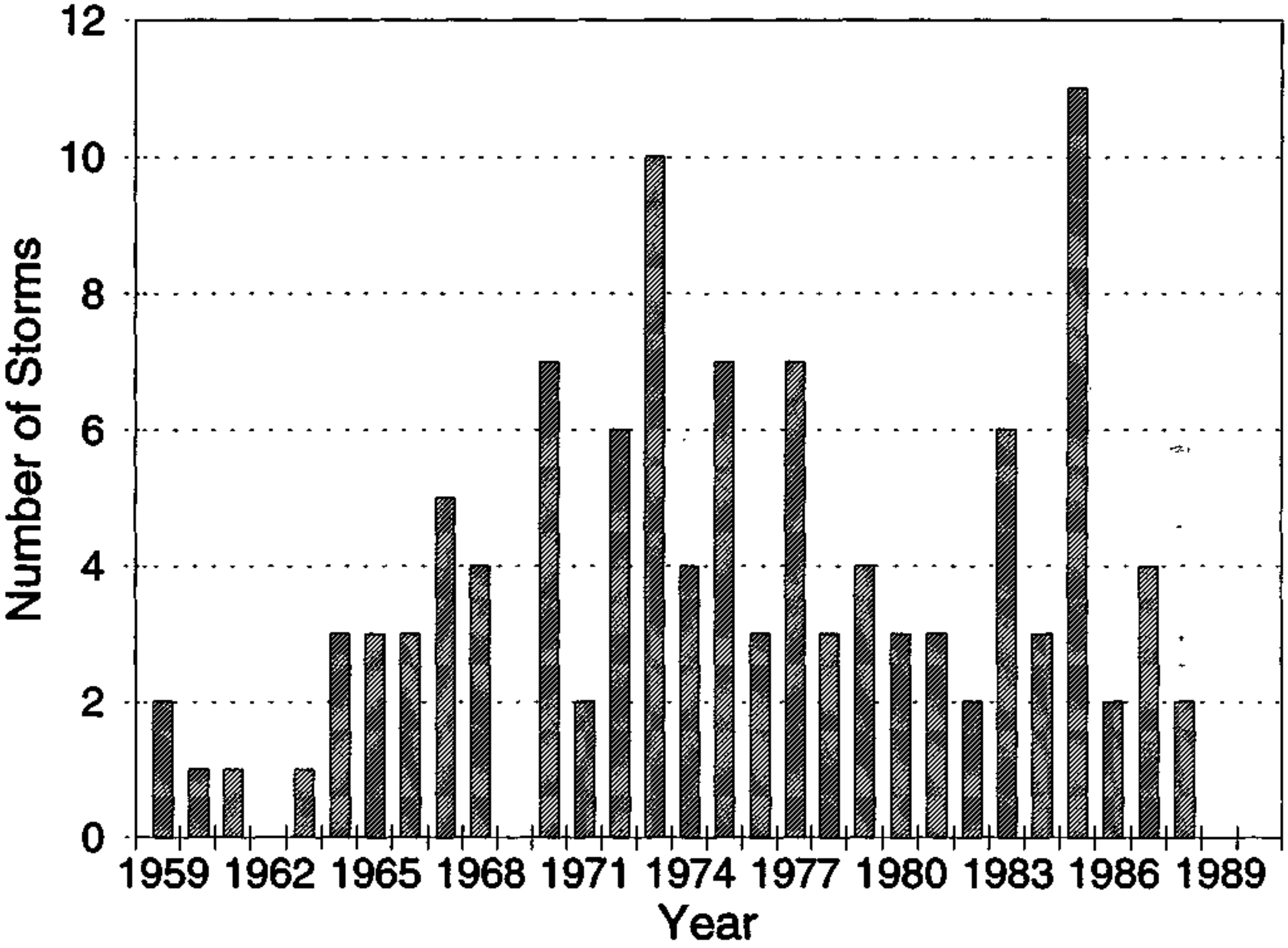
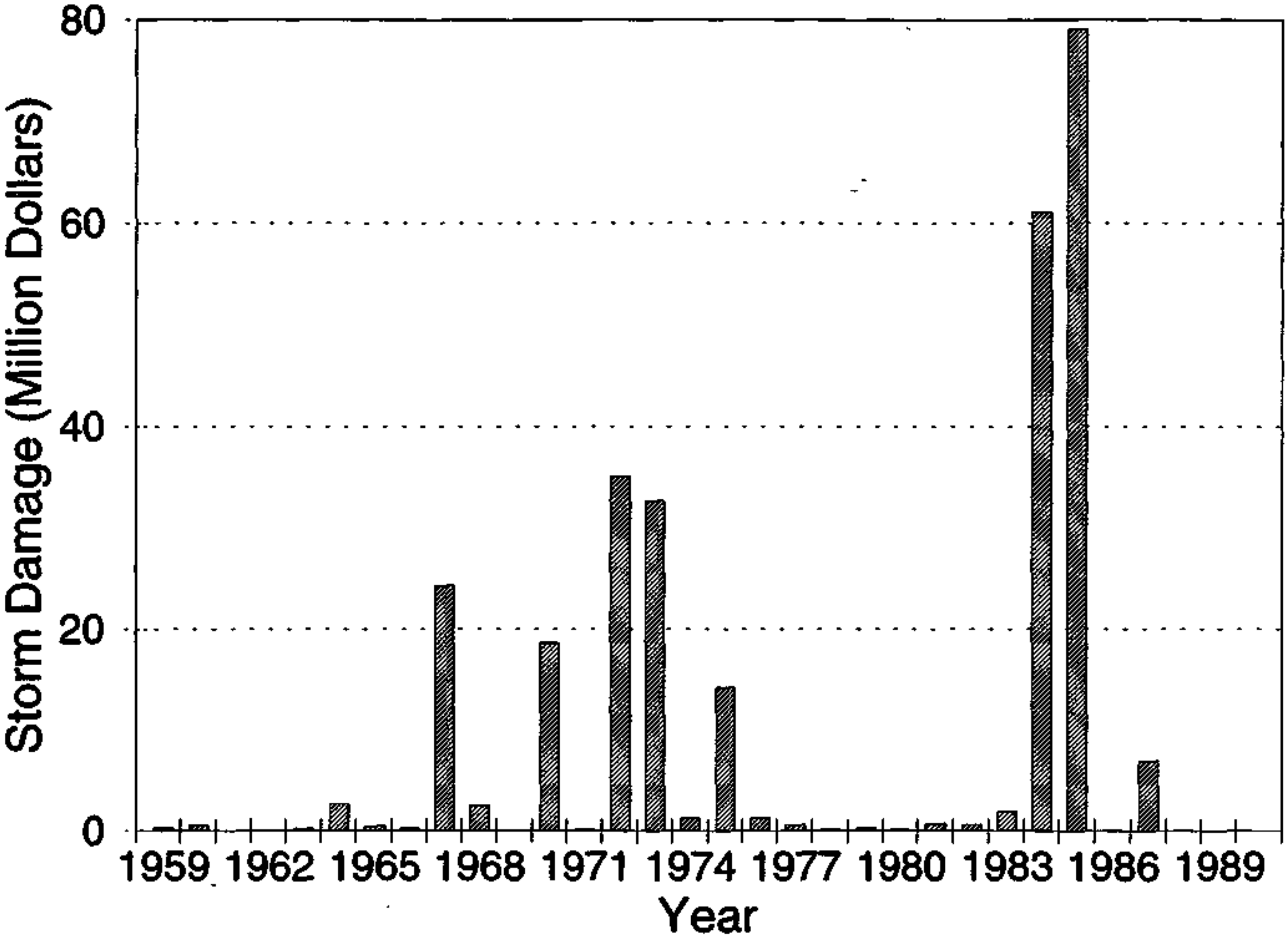


Fig. 3.2. Total U.S dollar amount of damages, adjusted to 1990 U.S. dollars, caused by cyclones along the U.S. shoreline of the Great Lakes (1959-1990), based on NOAA *Storm Data* reports.



damage shows that their average central pressures (one measure of cyclone intensity) are essentially the same. The damage during the early 1970s came from 23 cyclones in four years while the damage from the mid-1980s period came from 13 cyclones in two years (an average of approximately six cyclones per year in both cases). Therefore, the higher damages experienced in the mid-1980s are not explained by differences in the frequency or intensity of the cyclones. Given the record-high average lake levels in the mid-1980s, it appears that a similar number of cyclones produced far more damage than the early 1970s. Kreutzwiser (1988) found similar results in an analysis of damages along the Canadian shore of Lake Erie, which showed damages to be 2.6 times higher in 1985 than in the 1972-1973 period.

The relationship between the number of cyclone-related damage reports and lake levels is examined further by using historical lake levels. Lake levels for the period between 1901 and 1990 were normalized by lake by subtracting the 1901-1990 average for each lake, aggregating the deviations across all lakes for each month of each year, and then dividing the resulting Great Lakes lake level departures into three equal categories (low, average, and high) each with one third of the observations. There are four years with low lake levels, 10 years with average lake levels, and 14 years with high lake levels during the period between 1959 and 1990 (Table 3.2). A comparison of the number of reports per year in each category shows that while two to three damage reports are reported per year during below normal and normal lake levels, the number increases to approximately seven reports per year during years with above average lake levels. Using a two-class system, Carter (1973) found 11 out of 13 damaging cyclones on Lake Erie occurred during above-average lake levels. These 13 cyclones spanned the period 1861 to 1972. Kreutzwiser and Gabriel (1992) divided the Great Lakes levels into a four-class system and found significant damages caused by cyclone activity in both class 3 and 4 (the upper half of all lake levels). All of these studies point to the higher risk of cyclone-induced damages during higher lake levels (remembering that the damages reported in NOAA *Storm Data* are due to specific events and not general flooding caused by high lake levels alone).

Lake levels fluctuate seasonally as well. Based on the 1901-1990 lake level data, summer lake levels are generally 0.2 to 0.4 meters above winter lake levels. An examination of themonthly cyclone track maps, as found in the NOAA publication *Mariners Weather Log*, for

Table 3.2. Damage reports by lake level from NOAA *Storm Data*.

Great Lake Level	Number of Reports	Number of Years with This Lake Level	Number of Reports Per Year
Below Average	11	4	2.8
Average	23	10	2.3
Above Average	102	14	7.3

the period between 1966 and 1990 shows more frequent cyclone passages in winter than in summer (Fig. 3.3). These *seasonal* changes in lake levels are out of phase with the cyclone frequencies and are of smaller size than the historical *interannual* variations in lake levels. Therefore, the generally higher lake levels in summer, compared to winter, have little impact on the damage reported.

The distribution of damage reports by month (Fig. 3.3) shows increased reports in the fall with the maximum number in November. The number of reports declines throughout the winter before increasing to the secondary maximum in April. Meanwhile, cyclone passage is most frequent through the winter. Ice cover may be an important factor in lessening midwinter cyclone damage to shores. Normal ice cover for the Great Lakes generally begins by mid-December and ends by the end of April (Assel et al., 1983; p. 23). Therefore, the reduction in damage reports in winter (December - February) is likely due to protective ice cover alongthe shores, which dampens wave action and helps buffer the shoreline. The secondary increase in April may reflect the loss of the ice cover while the cyclone frequency is still strong. This seasonality was noted by Davis (1976) for coastal erosion on Lake Michigan. The low number of reports in summer corresponds well with the decreased cyclone activity in the Great Lakes region during this time.

Sorting the reports by state (Table 3.3) shows that Michigan has experienced the largest number of damage reports. This is expected, given Michigan's long shore lines and orientation to winds. To evaluate the potential shoreline exposure of each state, the number of reports is expressed as the average shoreline distance per report (Table 3.3, column 4). With this approach, Illinois, New York, and Ohio exhibit the highest density of damage reports while the density in Michigan is much lower. The high density of reports in Illinois can be explained by the high economic value of the shoreline in the city of Chicago and the wealthy suburbs to the north (Changnon, 1987). The high density of reports in New York and Ohio is related to the features of Lake Erie (discussed below).

The distribution of damage reports by each lake also shows some interesting results (Table 3.4). Damage along Lake Erie is mentioned in 51 out of the 112 damage reports (46%) in this study. Lake Michigan is also mentioned in 43% of the damage reports (48 out of 112). Lakes Superior and Huron report far fewer damages, with Lake Ontario and Lake St. Clair reporting the least. As noted earlier, these reports only note damages in the United States and do not reflect the total damages along any lake except Lake Michigan, which is totally within U.S. boundaries.

Table 3.3. Number of NOAA *Storm Data* reports by state.

State	Number of Reports	Shoreline	Average Length of Shoreline per Report
Illinois	8	105 km	13 km/report
Indiana	1	73 km	73 km/report
Michigan	46	2349 km	51 km/report
Minnesota	10	282 km	28 km/report
New York	31	581 km	19 km/report
Ohio	15	306 km	20 km/report
Pennsylvania	3	77 km	26 km/report
Wisconsin	22	906 km	41 km/report

Table 3.4. Number of NOAA *Storm Data* reports by lake.

Lake	Number of Reports	U.S. Shoreline	Average Length of Shoreline Per Report
Superior	19	1468 km	77 km/report
Michigan	48	2193 km	46 km/report
Huron	15	991 km	61 km/report
St. Clair	8	76 km	10 km/report
Erie	51	551 km	11 km/report
Ontario	9	467 km	52 km/report

Figure 3.4 shows the geographic distribution of damage reports. Damages are most frequently reported on the eastern and western shores of the Great Lakes. Pore et al. (1975) also noted this pattern, which is explained by the position of the passing cyclone relative to the lake. If the cyclone passes to the north of a particular lake, strong southwesterly winds are observed that cause water to pile up on the eastern shores, resulting in increased risk to flood damage. If the cyclone passes to the south of a lake, strong northeasterly winds are observed and cause water

Fig. 3.3. Monthly number of NOAA *Storm Data* damage reports for the U.S. shoreline of the Great Lakes and cyclone frequencies from *Mariners Weather Log,* both expressed as the percent of their total amounts.

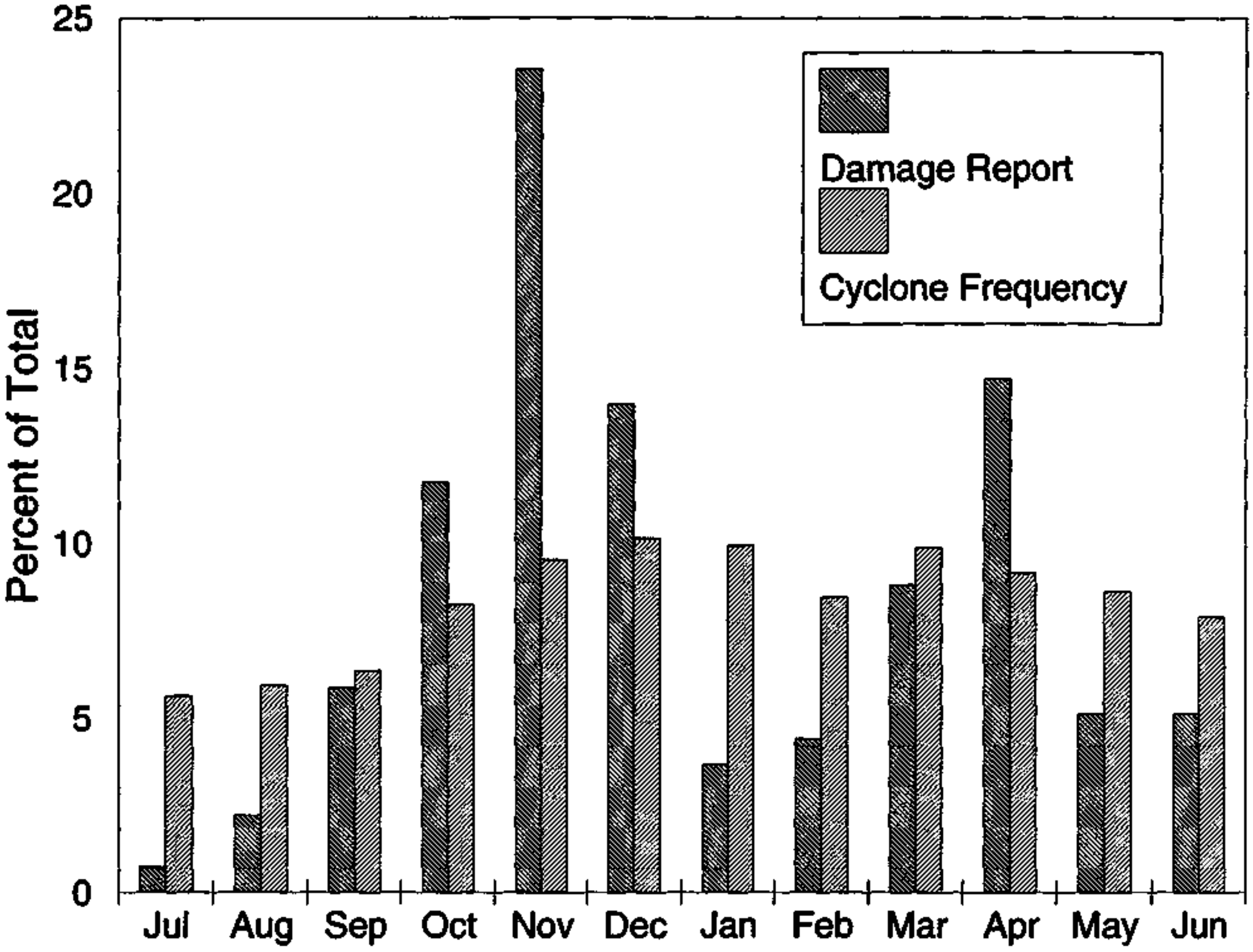
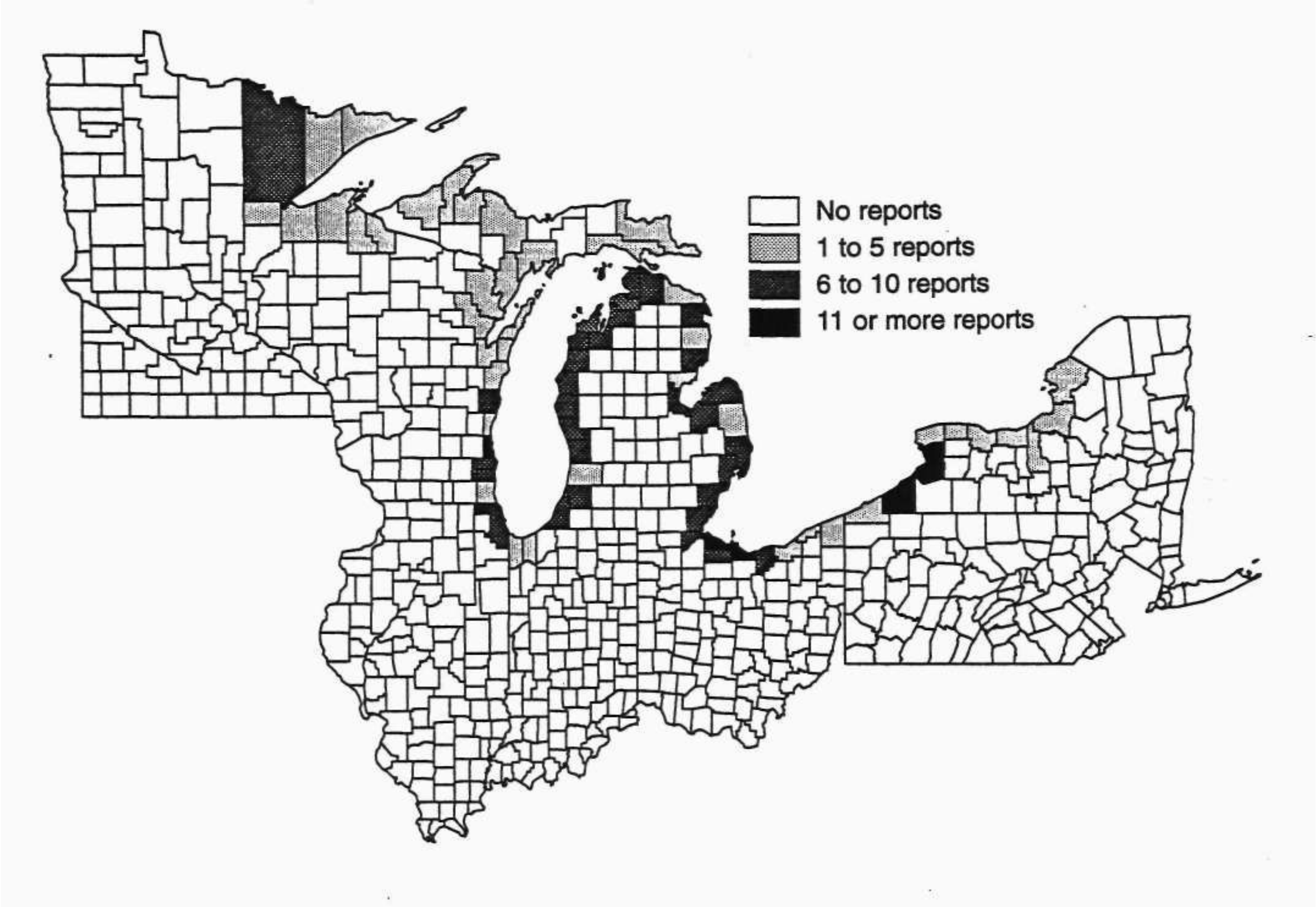


Fig. 3.4. Number of NOAA *Storm Data* reports by county for the U.S. shoreline of the Great Lakes.



to pile up on the western shores. The damages on the eastern and western shorelines are most noticeable on Lake Erie due to its shallowness and orientation along the prevailing cyclone tracks (Mortimer, 1987). It is impossible to assign dollar amounts to individual counties because only total damage per event is reported. However, counties with more damage reports usually suffered larger losses (e.g., Erie County, New York).

The following discussion will focus on two sets of physical data used to determine potential thresholds for significant cyclones as well as review previous studies for potential thresholds. These datasets will be compared with NOAA *Storm Data* to determine their usefulness in indentifying events that could potentially cause damage.

i) *Mariners Weather Log* Cyclone Tracks

Digitized cyclone tracks from May 1965 to 1990, as found in the *Mariners Weather Log,* were defined as containing at least one 4 mb closed contour and persisting at least 24 hours. Only cyclone tracks that pass over the 84 °W meridian between 38°N and 52°N latitude are examined here. The monthly variability (Fig. 3.3, striped bars) shows that December and January report the highest frequency while July and August report the lowest. In this part of the study, all cyclones are examined regardless of intensity, and includes events during the warm season. For comparision purposes with Lewis (1987) and NOAA *Storm Data*, the 100 cyclones with their lowest central pressure at 84° longitude (interpolated as needed) between 38° and 52° latitude were selected. The annual totals of these cyclones (Fig. 3.5) show no general trends although there is increased interannual variance during the period from 1968 to 1978.

ii) Wave Information Study

The U.S. Corps of Engineers produced the Wave Information Study (WIS) for a 32-year period (1956-1987). This dataset was generated from models to augment the lack of wave information needed in coastal design work. They used measured wind data from nearby shore stations. Adjustments were made to the wind speeds for air-water temperature differences based on Schwab and Morton (1984). The air-water temperature differences were measured from available ship data and applied monthly. The over-lake wind speeds were then interpolated to a grid (16 km on a side) overlaying the Great Lakes using a weighted inverse distance interpolation routine. These wind values were also calibrated using linear regression with the limited amount of wind data from NOAA buoy data. Next a spectral wave model (DWAVE), described by Resio and Perrie (1989), was used to generate wave data at each grid point. Due to the large amount of data involved (gigabytes), representative grid points were chosen in each lake. The data are reported in 3 hr intervals. Three studies are made with these data.

The first study is to examine the 100 largest events based on wave height. Figure 3.6 shows no long-term trend in the annual totals, and the period 1965-1972 shows the highest frequency. The monthly distribution shows a maximum in November and a secondary maximum

Fig. 3.5. From *Mariners Weather Log*, the number of cyclones per year based on the 100 cyclones with the lowest central pressure within the Great Lakes region.

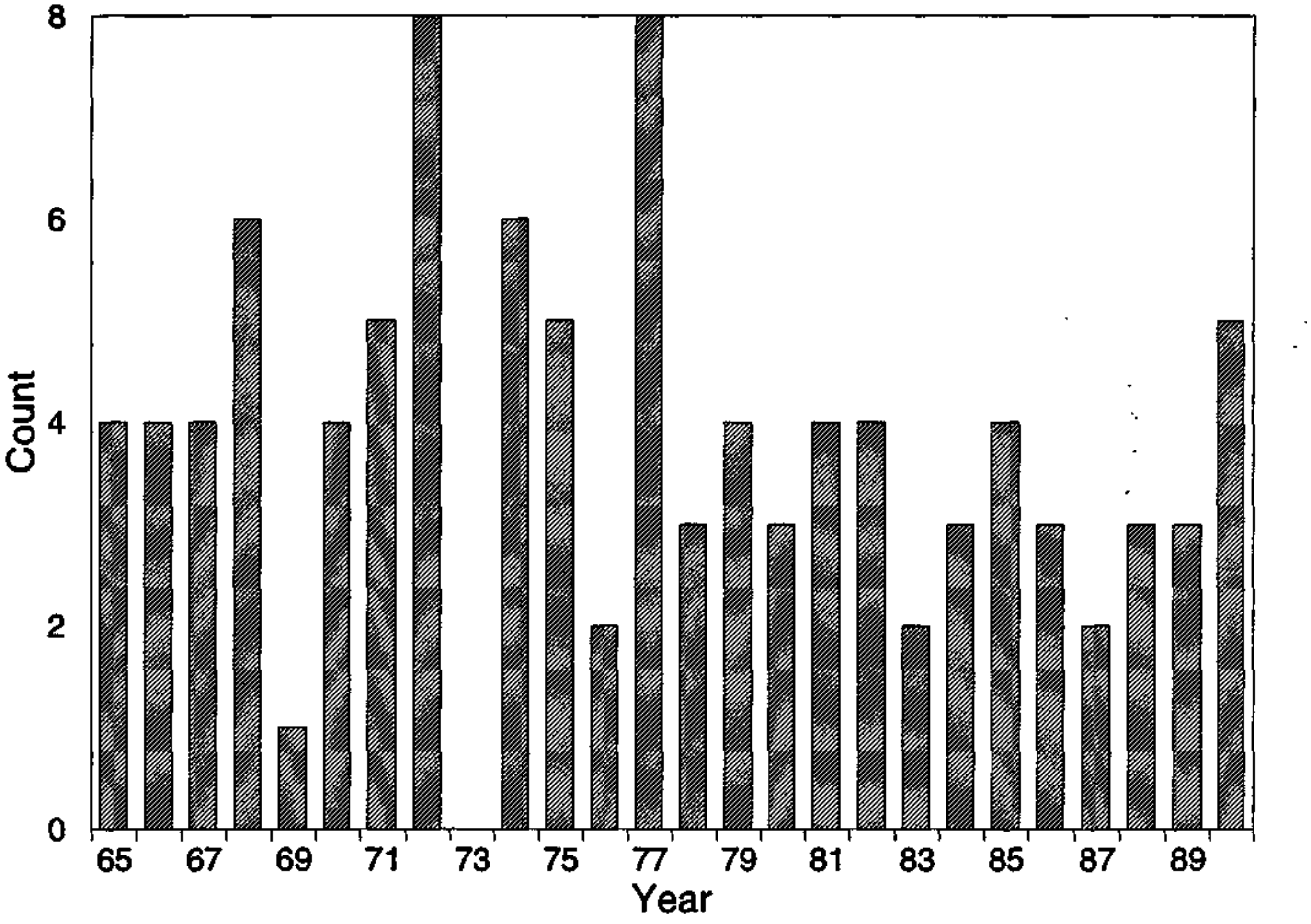
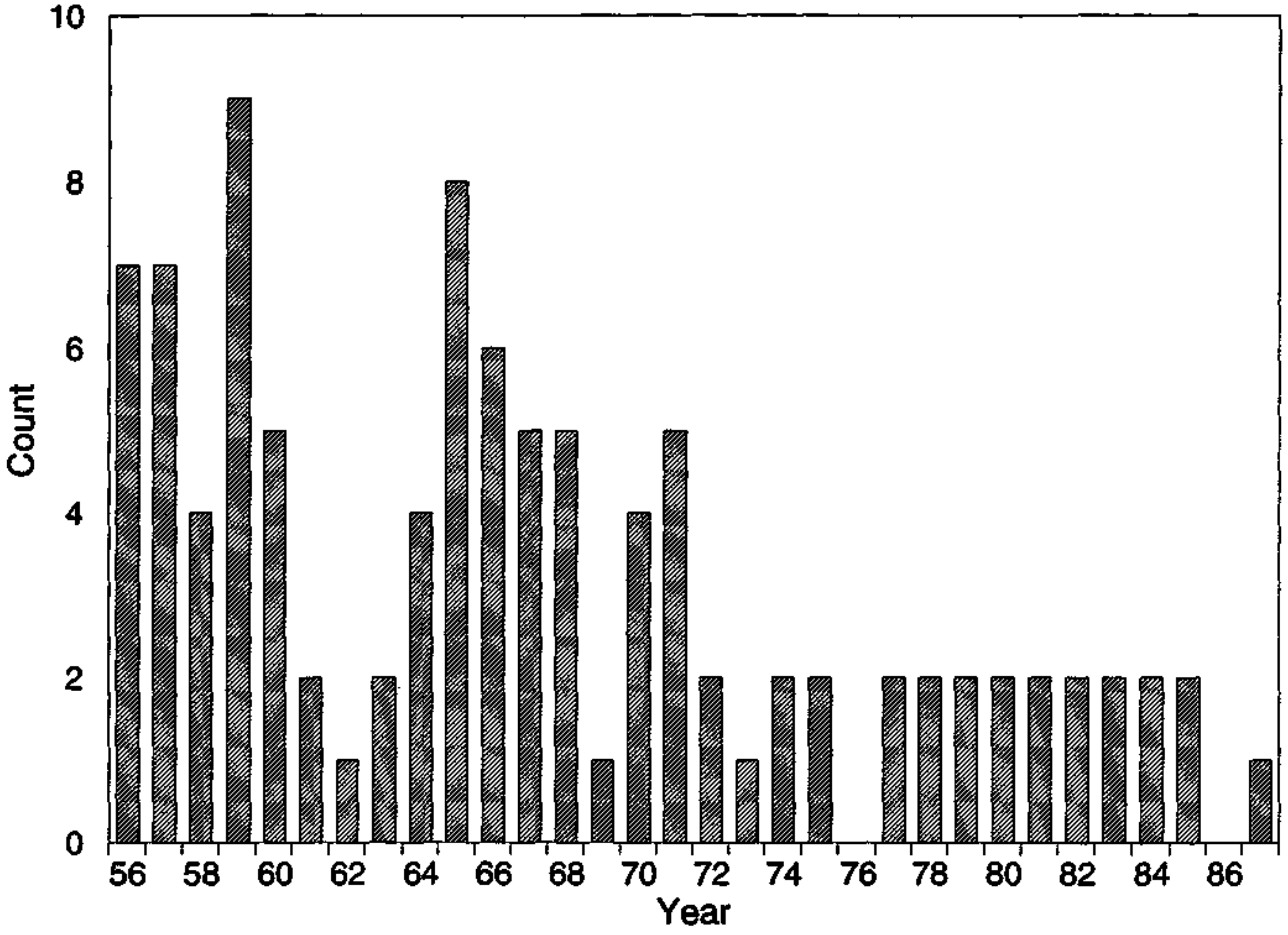


Fig. 3.6. From the Wave Information Study (WIS), the number of events per year based on the 100 events with the highest wave heights on the Great Lakes.



in March (ice cover was incorporated into the model, which may explain the two maxima). The cold season months are much more active than the warm season.

The second study is to examine the 100 largest events based on wind speed. The annual time series (Fig. 3.7) changes dramatically over the period with more of the events (75% of the total) occurring in the first half of the time series. Also, the variability is much greater in the first half of the record. This suggests that there are problems with the shore-based wind data and/or the corrections applied to that data. The monthly distribution shows a maximum in November with most of the events occurring in the colder season (October-April).

b) Previous Studies

Resio and Vincent (1976) suggested a definition of storms as the number of days with average wind speeds ≥ 12.9 m/s (25 knots). This threshold yields a total of 2027 events from the Wave Information Study (WIS) database for the 32-year record, approximately 63 per year. While this is a convenient meteorological definition, it allows for too many events compared with the number of NOAA *Storm Data* reports. Brater et al. (1974) defined a storm as having waves above 1.8 m (6 ft) on the Great Lakes. This threshold yields a total of 1546 such events in the 32-year record of the Wave Information Study (WIS). This is more than the number of NOAA *Storm Data* reports available by a factor of ten. Lamb (1991) presented two power indices in his work on storms in the North Sea. These two indices are applied to the Lewis dataset. The first index is:

$$\text{Power} = \text{Vmax} * \text{Area} * \text{Duration} \qquad (1)$$

where Area is the area containing winds of ≥ 25.7 m/s, Vmax is the highest wind speed and duration is the time when the storm maintains winds ≥ 25.7 m/s. The second index is:

$$\text{Power} = \text{Vmax}^3 * \text{Area} * \text{Duration} \qquad (2)$$

While these indices provide a way of ranking the severity of the storms, a comparison with NOAA *Storm Data* was disappointing. Only four out of the top 10 cyclones report damage for the first index. Two out of the top 10 cyclones report damage with the second index.

i) Chen Study

Chen (1988) looked at storm surges from 1962 to 1987 for selected water level gauges on the Great Lakes. Most of these were associated with large-scale events and consequently occurred during the November-March season. Unfortunately, storm surges are not the only source of damage so it is an incomplete dataset.

Fig. 3.7. From the Wave Information Study (WIS), the number of events per year based on the 100 events with the highest wind speeds on the Great Lakes.

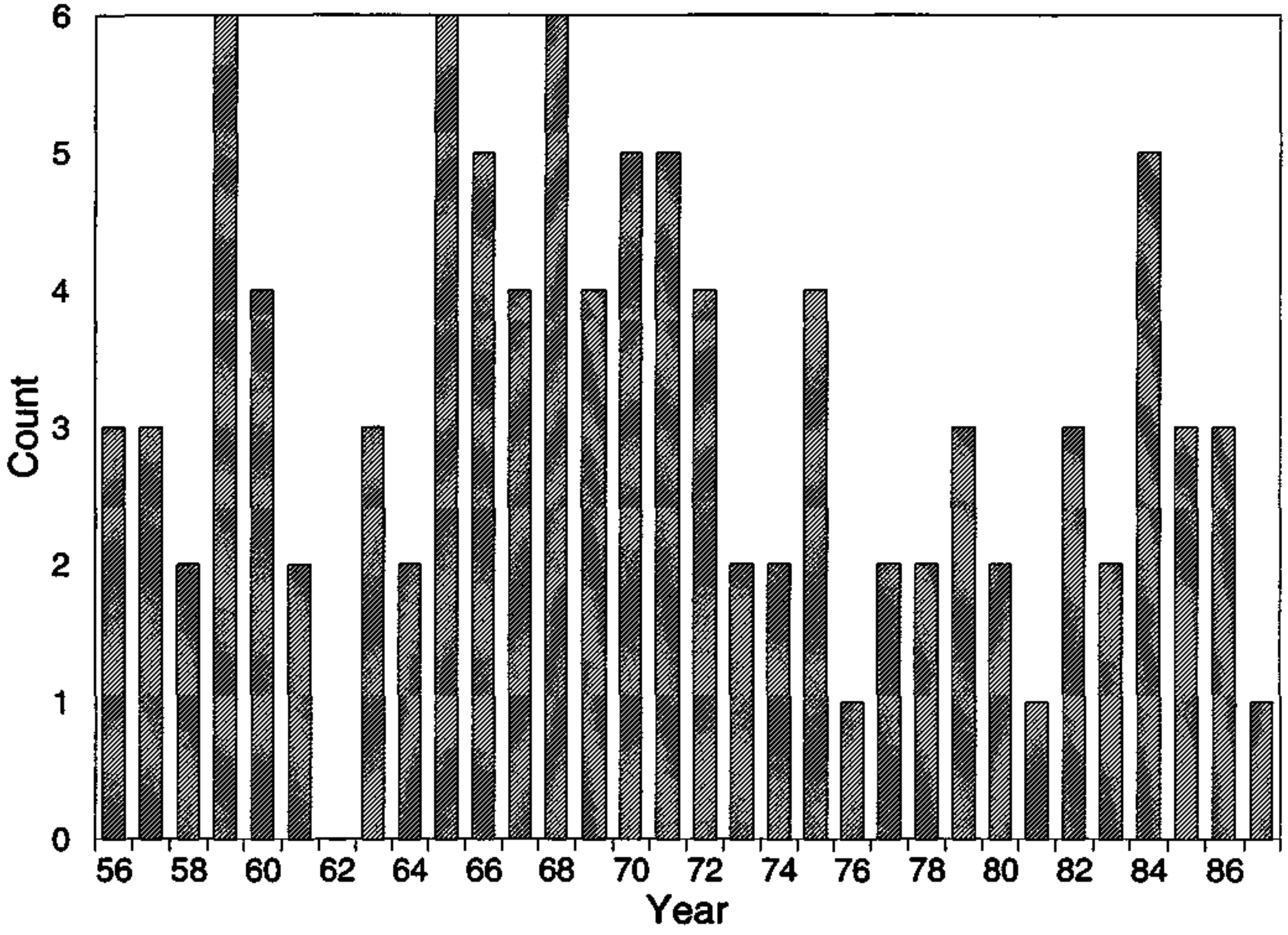


Fig. 3.8. The number of cyclones per year reporting wind speeds > 25.7 m/s, from Lewis (1987).

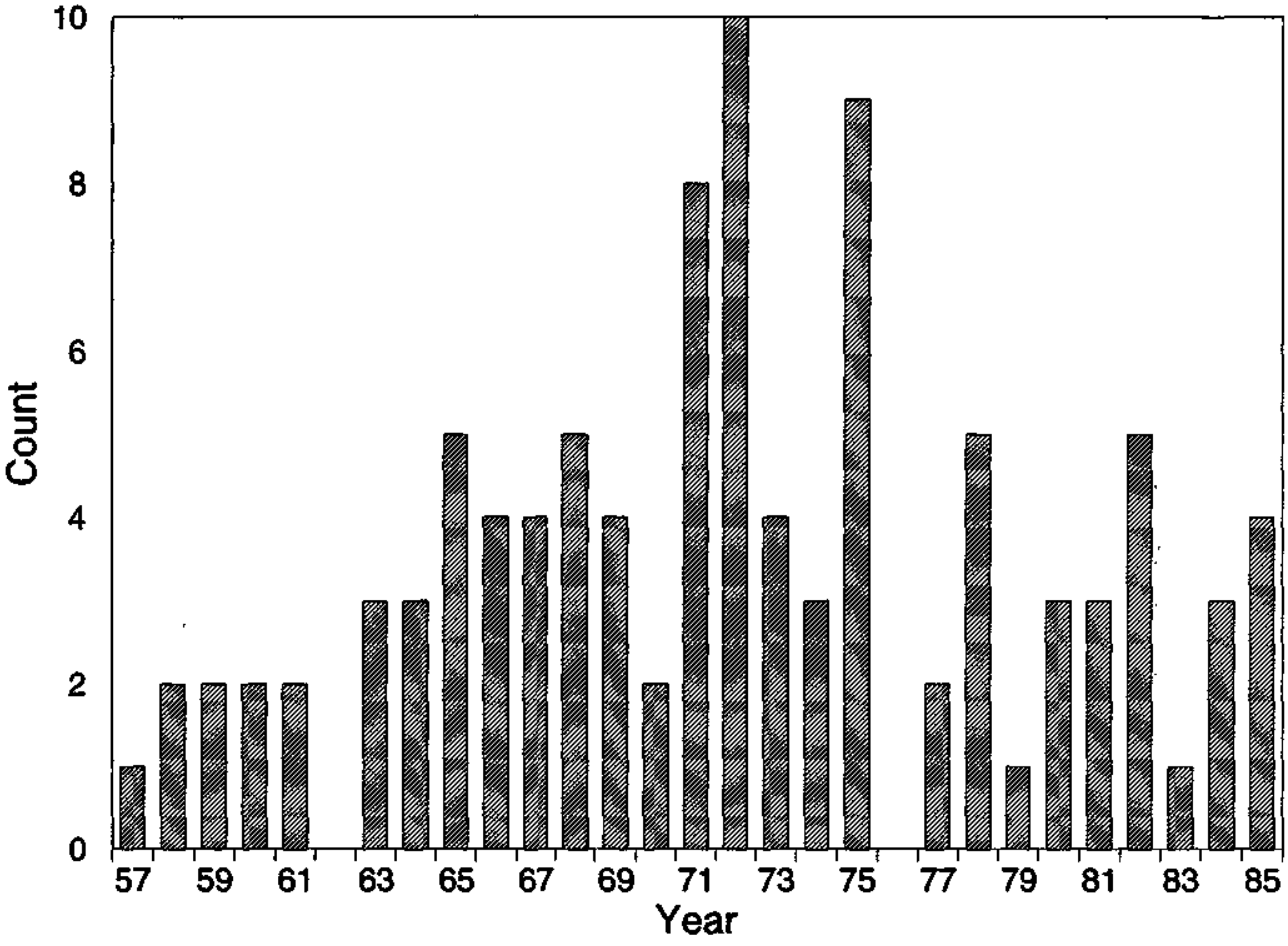


Table 3.5. Comparison of datasets using the percent with matching dates.

	NOAA *Storm Data*	Lewis (winds ≥ 25.7m/s)	WIS (wave criteria)	WIS (wind criteria)	MWL (cyclone tracks)
Lewis (winds ≥ 25.7 m/s)	18%	-	-	-	-
WIS (wave criteria)	28%	29%	-	-	-
WIS (wind criteria)	24%	30%	52%	-	-
MWL (cyclone tracks)	16%	24%	19%	24%	-
Chen (storm surge)	55%	64%	45%	41%	21%

ii) Lewis Study

Lewis (1987) selected 92 cyclones during the period between 1957 and 1985 that reported winds ≥ 25.7 m/s. Figure 3.8 shows the number of cyclones reported over time. The number of reports per year increases until 1972 with much variability through 1985. The variance increases notably during the period between 1970 and 1985, compared with earlier years, but there are no general trends in the number of reports per year. A breakdown by month shows a maximum in November with slightly lower frequencies for the rest of the cold season. Few events are recorded in late spring and summer. The report also shows that major cyclones occur during January-March, but cause little damage according to NOAA *Storm Data* reports (probably due to the protection of ice cover as discussed earlier).

c) Comparison of Datasets and Previous Studies

A comparison is made using the 100 "storms" based on the cyclone data and the two parts of the WIS study (wind and waves) plus the Chen (1988) and Lewis (1987) data to see how well the dates of these events matched. For Chen (1988), only the 24 events are examined. A good match between the dates of the events and the dates of the NOAA *Storm Data* would indicate that a particular dataset adequately explains the damage (Table 3.5). The percentages are calculated based on the maximum possible matches. For example, Chen (1988) has 24 potential matching dates compared with NOAA *Storm Data's* 112 dates so the number of matches is divided by 24. In all cases, the relationship between the selected studies and NOAA *Storm Data* is poor. The relationships between the selected studies is also poor.

The analyses based on previous research suggest that there is not a consistent criterion for judging the severity of the cyclone for generating damages using the currently available data. It is probable that each of these datasets are missing important factors that cause damage. It is also probable that the damage reports from NOAA *Storm Data* are not complete about reporting all damages.

d) Results of Criteria Selection

Because no clear-cut agreement exists between the datasets examined, an alternate approach based on the lowest central pressure and the pressure gradient of cyclones associated with NOAA *Storm Data* is examined. Because NOAA *Storm Data* are the only source of damage reports by cyclone, it is the standard for this comparison. Plotting the lowest central pressure for all cyclones passing over the Great Lakes versus the lowest central pressure associated with reports in NOAA *Storm Data* show distinctly different distributions (Fig. 3.9). The median central pressure of cyclones associated with damage reports is 992 mb. The pressure gradient of cyclones associated with NOAA *Storm Data* was calculated from the east-west change in pressure (the north-south changes were not measured because of the presence of accompanying fronts changed the isobar spacing). The distribution of the pressure gradients of cyclones associated with damage reports and the pressure gradients of all cyclones passing over the Great Lakes region for a period of five years are compared in the same fashion as the central pressure (Fig. 3.10). The resulting median pressure gradient of cyclones associated with NOAA *Storm Data* is 2.7 mb/100 km. A linear regression of the pressure gradient and the lowest central pressure (Fig. 3.11) shows that a pressure gradient of 2.7 mb/100 km yields a central pressure value of 991 mb, which is comparable to the results of the lowest central pressure analysis. Based on this information, and the fact that the central pressure is more straightforward to retrieve from the historical records, the median central pressure of 992 mb associated with NOAA *Storm Data* is selected as the threshold for strong cyclones. Using cyclone data from *Mariners Weather Log* for the years 1965 to 1990, this results in the selection of 18% of all cyclones. This is approximately 13 cyclones per year, which is comparable to the number of NOAA *Storm Data* reports and the results of Lewis (1987). As a side note, a comparison of the lowest central pressure and the cost index in the NOAA *Storm Data* yielded no strong relationship. This is probably due to the coarse nature of the cost index, the lack of comprehensive reports, and the importance of other factors such as lake levels.

Building the Historical Cyclone Dataset

Three datasets are used to construct the long-term records of cyclone strength and position. The first is compiled and analyzed cyclone track data by Klein (1957). This dataset was obtained in digital form from the National Climatic Data Center (NCDC) and covers the period 1899 to 1939. This daily dataset gives the central pressure, location of high and low pressure centers to the nearest whole degree of latitude and longitude, and information on movement and change in pressure. The reporting time is 0700 Eastern Standard Time (EST).

The second dataset was obtained from a NCDC "working tape" of cyclone track data digitized from *Mariners Weather Log* and covers the period from May of 1965 to the end of

Fig. 3.9. Box plot of the distribution of the lowest central pressures from all cyclones passing over the Great Lakes region compared with the distribution of the lowest central pressures of cyclones associated with NOAA *Storm Data* reports.

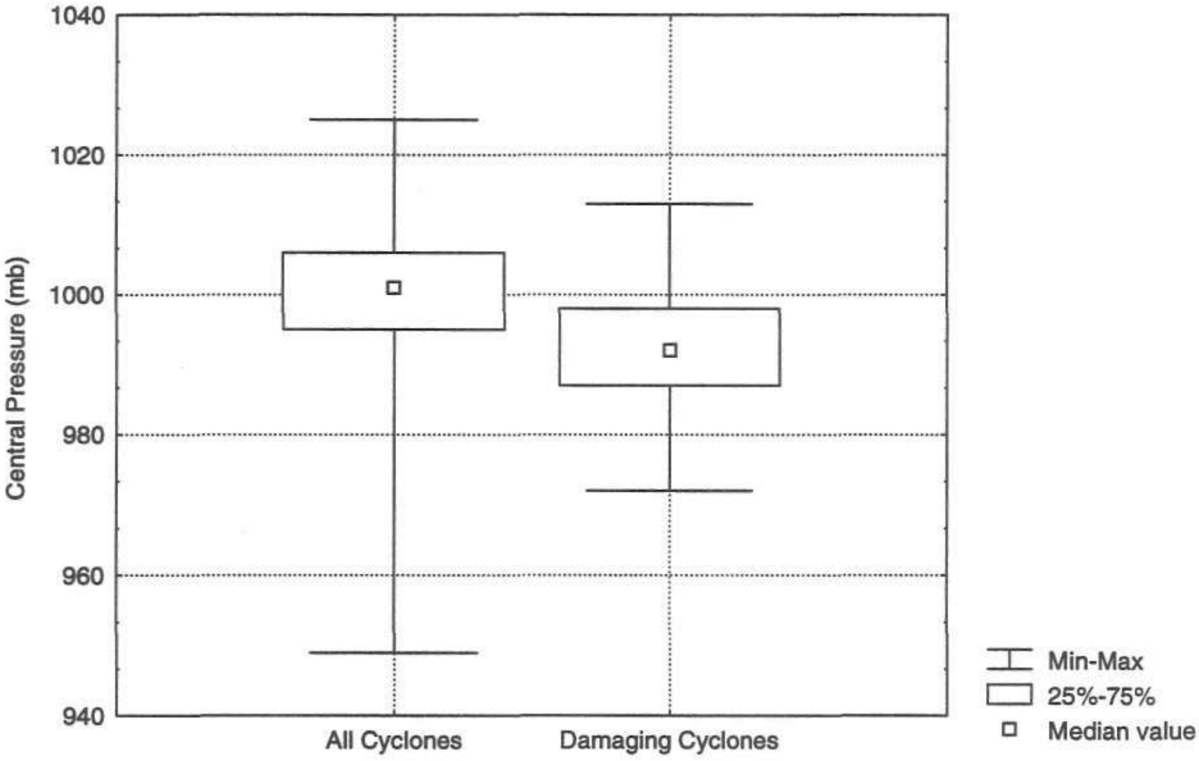


Fig. 3.10. Box plot of the distribution of the pressure gradients from all cyclones passing over the Great Lakes region compared with the distribution of the pressure gradients of cyclones associated with NOAA *Storm Data* reports.

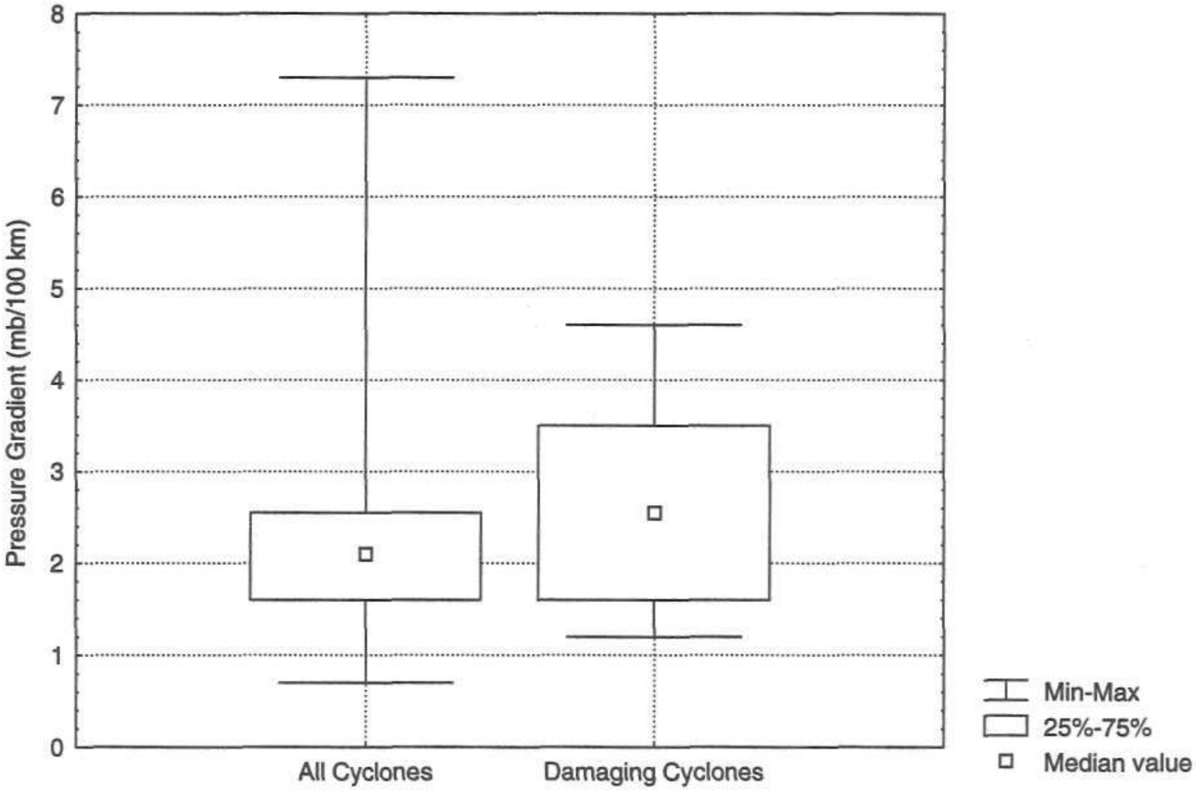


Fig. 3.11. Linear regression of the lowest central pressure and the pressure gradient of all cyclones passing over the Great Lakes.

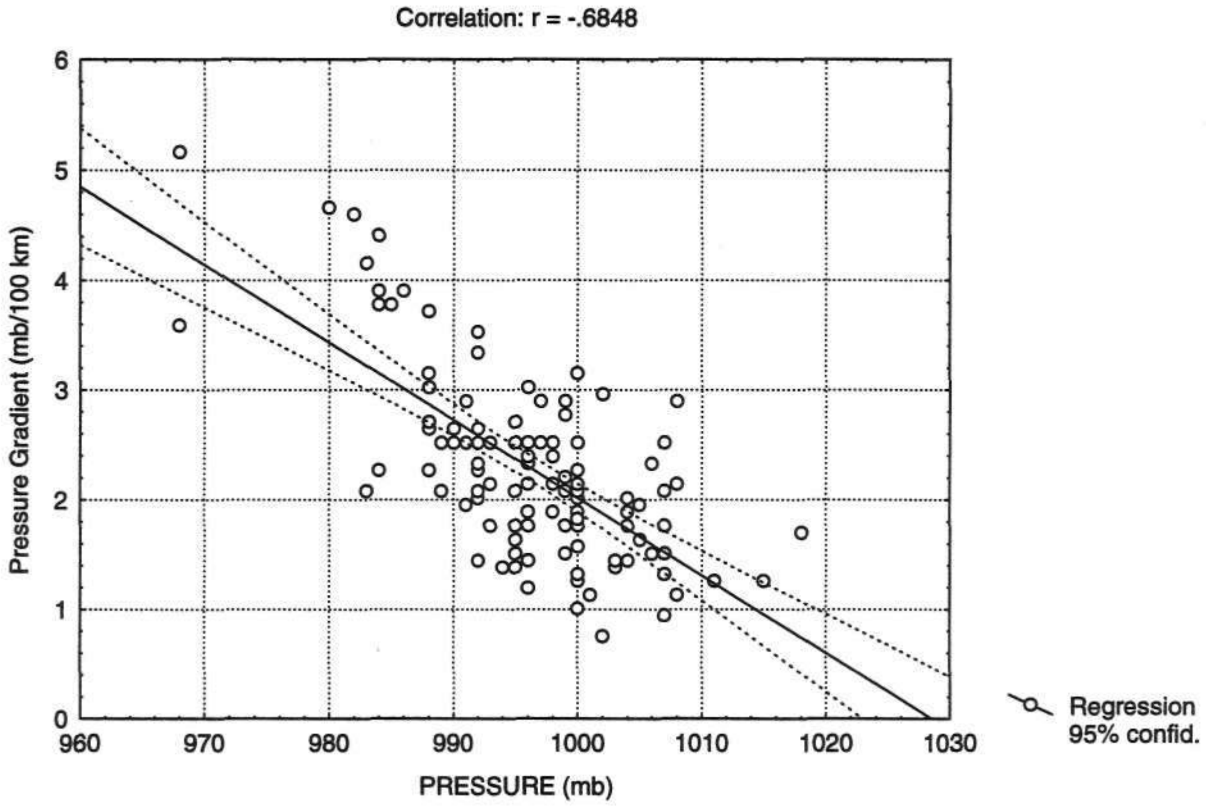


Table 3.6. Average monthly and annual cyclone frequencies for the three sources used to construct the historical data sets used in this study: Klein (1957), *Monthly Weather Review,* and *Mariners Weather Log.*

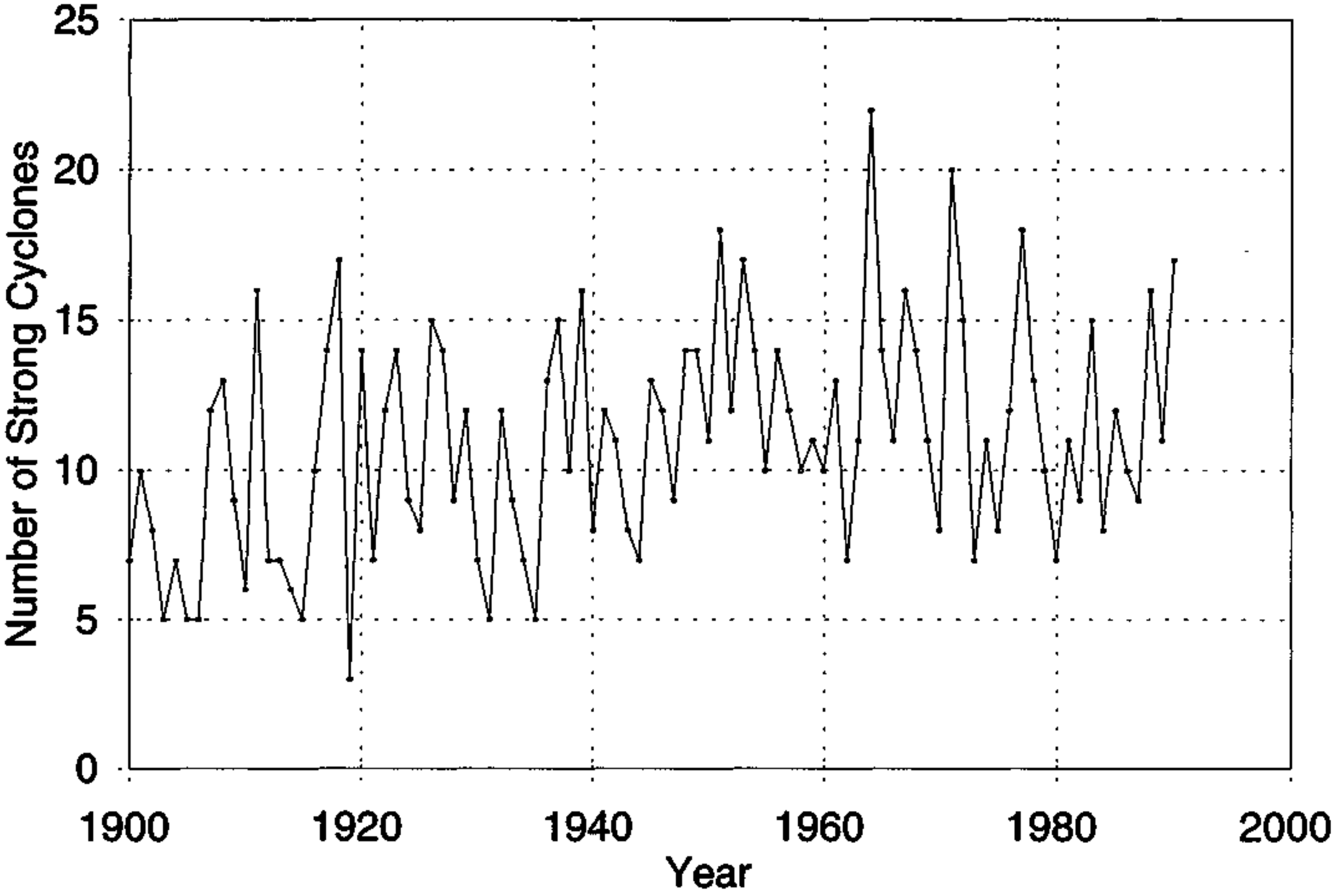
	Klein (1957)	*Monthly Weather Review*	*Mariners Weather Log*
January	1.78	1.52	1.84
February	0.88	1.37	1.16
March	1.78	2.04	1.80
April	0.88	1.44	1.28
May	0.48	0.59	0.68
June	0.30	0.48	0.24
July	0.05	0.15	0.16
August	0.05	0.04	0.04
September	0.33	0.70	0.44
October	0.73	0.70	0.92
November	1.03	1.74	1.52
December	1.23	1.44	1.88
Annual	9.48	12.22	11.96

1990. This dataset provides observations of cyclone location, speed, and central pressure at 6 hr intervals. Only the 12Z (0700 EST) observations are used to match the time of observation from Klein's dataset.

A daily time series of central pressure and location of the cyclone center is extracted from monthly weather maps summarizing cyclone tracks in the back *of Monthly Weather Review.* These data are used to fill the gap of 1940 to 1965 between the other two datasets. These tracks are also based on the location of the cyclone at 0700 EST.

To confirm that the combined records from three different sources results in a homogeneous time series the average frequencies are compared (Table 3.6). The average annual number of strong cyclones is lowest for the Klein data set. However, examination of several months of data from *Monthly Weather Review* shows that the earlier period did experience fewer of the strong cyclones. A comparison of the average number of strong cyclones per month yields essentially the same results as the average annual numbers, among the three data sets. The lowest numbers occur in the Klein dataset in 8 of the 12 months. An examination of the annual frequency of strong cyclones from 1900 to 1990 (Fig. 3.12) shows a period of reduced variability in the 1940s and 1950s. However, this is probably not an artifact of the analysis for several reasons. One, this pattern only appears on the annual time series and not on the seasonal or monthly time series. Two, Hosier and Gamage (1959) and Zishka and Smith (1980), whose two studies approximately spanned the same time period as this study, noted no changes in the monthly cyclone map series that would introduce biases in the cyclone frequencies. Three, it should also be noted that a simlar pattern in the variance of the annual frequency of strong cyclones developed in the 1980s. Despite the changes in variance discussed above, the standard deviations of the annual frequency of strong cyclones are the same for all three data sources (3.7, 3.5, 3.5 respectively). An upward trend in the frequency of strong cyclones is also evident in Figure 3.12.

Fig. 3.12. Annual frequency of strong cyclones used in this study, for the period 1900 to 1990.



4. CHANGES IN CHARACTERISTICS OF GREAT LAKE CYCLONES DURING THE TWENTIETH CENTURY

Introduction

In this chapter, trends and fluctuations in the characteristics of strong cyclones (<992 mb) over the Great Lakes during the 20th century will be examined including: frequency, intensity (as indicated by central pressure), and speed and direction of cyclone movement. The characteristics will be examined by month, the four traditional seasons (winter-December through February, spring - March through May, summer - June through August, and fall - September through November), and for the entire year. Documenting the characteristics of these time series is important, not only to note past trends and fluctuations but also to provide a benchmark from which to evaluate future changes in cyclone characteristics.

Previous studies have shown changes in the frequency of cyclones over time. One of the first studies to note this was Reitan (1979). He examined cyclone frequencies over North America for the period between 1949 and 1976 for four mid-season months (January, April, July, and October) and found a decrease in the number of cyclones over time. Brennan and Smith (1978) examined cyclones and anticyclones over the upper Mississippi and Ohio River Valleys and the Great Lakes region between 1950 and 1974. Their plot of both cyclones and anticyclones showed a general decline from a peak in 1959 through 1974. Zishka and Smith (1980) studied cyclones and anticyclones over North America for January and July for the period between 1950 and 1977. Their results show a statistically significant decline in the number and the mean central pressures of both cyclones and anticyclones for January and July. Agee (1991) examined the Zishka and Smith (1980) data and the Hosier and Gamage (1956) data for another comparison of cyclone and anticyclone trends. His analysis showed an increase in cyclone activity from 1900 to 1940, followed by a decrease through the 1970s. Using data from 1950 to 1993, Changnon et al. (1995) showed that the general decrease in cyclone frequency since 1950 for North America reversed in the mid-1980s and increased through 1993.

These studies show that changes in cyclone activity have occurred over North America in the recent past. It should be noted that all these studies were based on large-scale areas (e.g., North America) for relatively short periods (e.g., 1950-1977). This research will expand upon the work of these previous scholars. The historical database constructed for this thesis will span 1900 to 1990 and focus on the strong cyclones over the Great Lakes region. It will be used to investigate changes in frequency and intensity of strong cyclones, and changes in their speed and direction of movement.

Cyclone Characteristics for the Entire Great Lakes Region

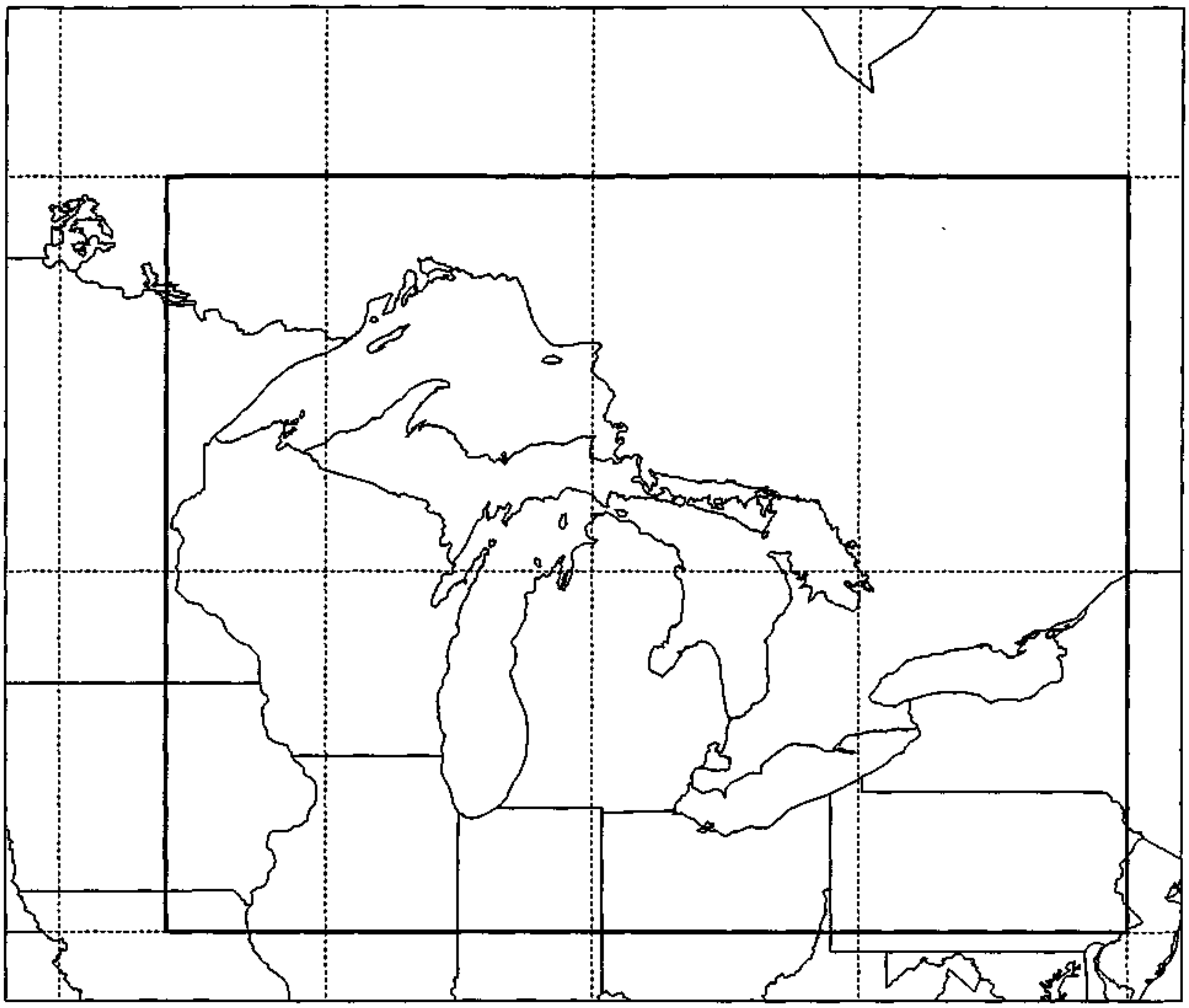
Data from the historical database are stratified by month, season, and year for the entire Great Lakes region. The frequency of the strong cyclones is determined by counting the number of cyclones passing through the region defined by 40°N to 50°N latitude and 93° W to 75° W longitude (Fig. 4.1). The migration speed of the cyclones is given as the average speed of the cyclone through the region. The lowest pressure of the cyclone is determined by averaging the lowest central pressure of each cyclone while it is in the region. The direction, or orientation, of the cyclone is the vector average of the entire cyclone track.

The median values of the four basic characteristics of strong cyclones by season for the 91 years of record are shown in Table 4.1 to serve as a benchmark for the analysis below. Winter (December-February) cyclones are the most frequent, move the fastest, and have the lowest pressure. Summer (June-August) cyclones are the rarest, weakest and slowest moving. Spring (March-May) and fall (September-November) cyclones are comparable, although there are typically more cyclones in spring. Although November is the month with the most cyclones, the number of cyclones is fewer in fall due to the very low frequency in September. The frequency of strong cyclones, their speed, pressure, and direction are aggregated into 5-year periods (pentads) for easier analysis. Linear regression is applied to the pentad data to detect any statistically significant trends (Table 4.2). There are statistically significant increases over time in the number of cyclones during the November, December, Fall, and annual time periods (Fig. 4.2). While not statistically significant, positive slopes were found in 11 out of the remaining 13 cases. As for the speed of the cyclones, there is a statistically significant increase over time in January and decrease in February (Fig 4.3). There are statistically significant decreases in central pressure (increased intensity) over time for Fall (Fig. 4.4). While not statistically significant, decreases in pressure over time were found in 11 of the remaining 16 cases. There is a .. statistically significant change in direction from the southwest to the west overtime in October and Fall (Fig. 4.5). Note that direction is calculated as an average vector and the direction notation refers to the direction from which the cyclones are moving.

Table 4.1. Median values of the basic characteristics of strong cyclones in the Great Lakes region by season.

Season	Number of Cyclones	Direction (degrees)	Pressure (mb)	Speed (km/day)
Winter	21	245.5	985.5	1149
Spring	18	246.5	986.9	965
Summer	2	248.5	989.2	859
Fall	12	247.0	986.5	1002

Fig. 4.1. The Great Lakes region defined in this study.



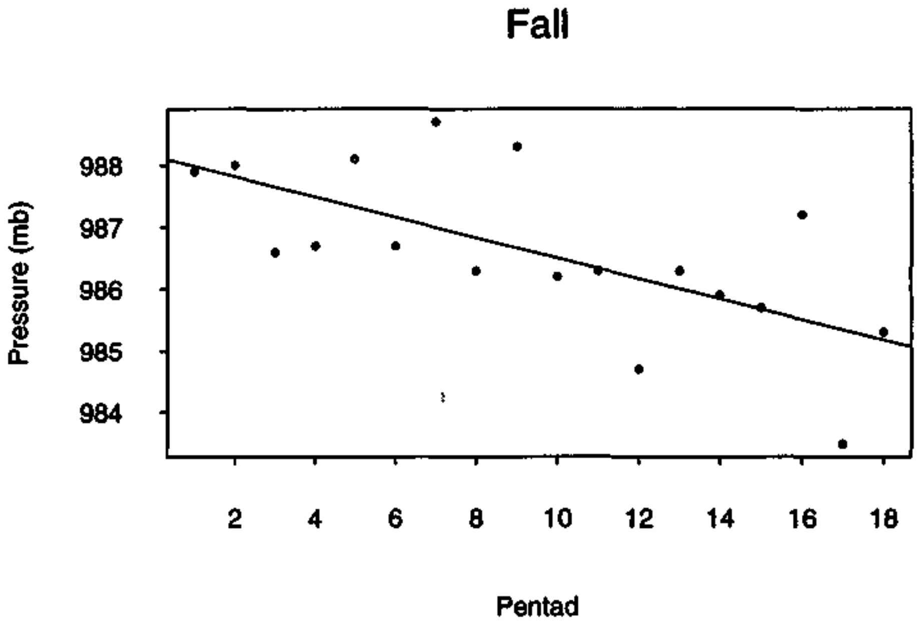

Fall

Fig. 4.4. Significant trends in the central pressure of strong cyclones (kPa) for the Great Lakes region (1900-1990).

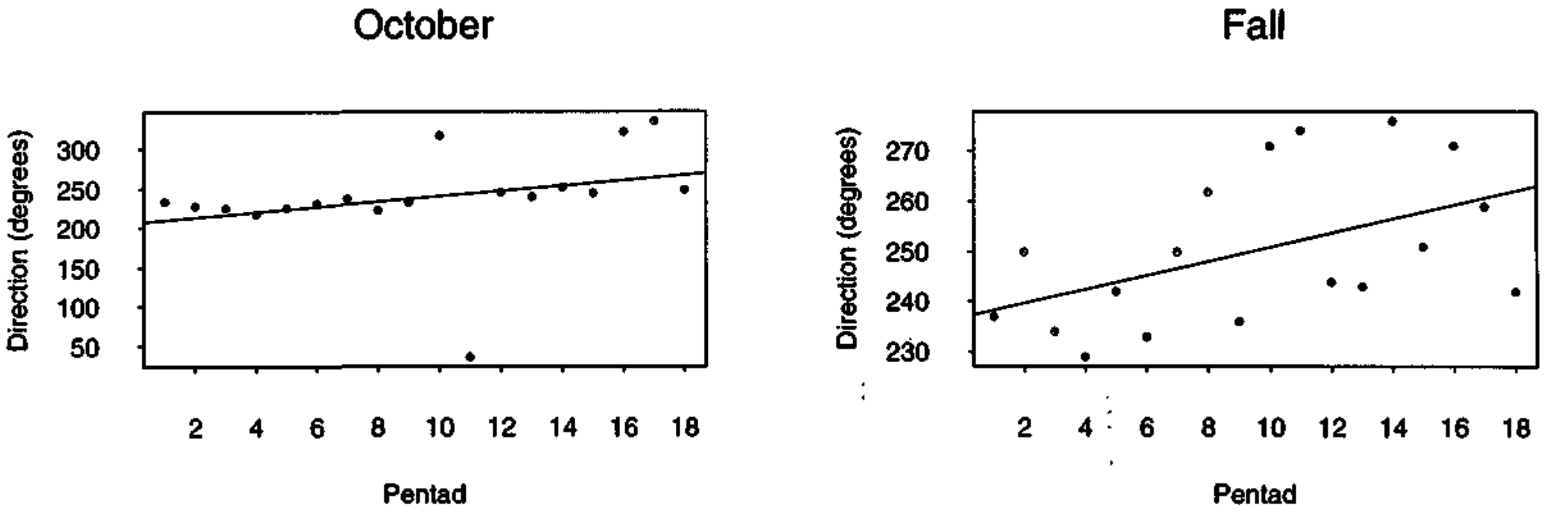


Fig. 4.5. Significant trends in the direction of strong cyclones (movement from) for the Great Lakes region (1900-1990).

Table 4.2. Results of the trend analysis for strong cyclones in the Great Lakes region, showing the *slope*. Statistically significant results at the 5% level, determined by the F-test, are denoted by an asterisk.

	Frequency	Direction	Pressure	Speed
Jan	-0.06	-0.18	-0.4	0.02*
Feb	1.07	0.00	-0.1	-0.01*
Mar	0.29	-0.08	-0.7	-0.01
Apr	0.49	-0.02	-0.8	-0.01
May	1.55	-0.15	0.1	-0.01
Jun	0.16	0.05	0.0	0.00
Jul	2.02	0.00	0.0	0.00
Aug	-0.64	0.01	0.0	0.00
Sep	1.08	0.00	0.0	0.00
Oct	0.73	0.05*	-0.8	0.00
Nov	0.95*	0.02	-0.8	-0.01
Dec	0.83*	-0.11	-0.4	-0.01
Winter	0.45	-0.27	-0.3	0.00
Spring	0.45	-0.19	-0.5	0.00
Summer	0.51	0.02	-0.8	0.01
Fall	0.58*	0.17*	-2.6*	-0.01
Annual	0.36*	-0.02	-2.2	-0.02

These results show that the frequency of strong cyclones has increased over time for most of the cold season. Evidence indicates that the central pressure of these systems has decreased over time (i.e., increased intensity) while the number of cyclones has increased over time during the Fall (this relationship will be explored further in the next chapter).

Inspection of all the time plots reveals a few instances of changes in the variance associated with these cyclone characteristics. For cyclone speed, the standard deviation doubles in the annual time series between the first and second half of the record. The change is largely due to an increase in the variation in cyclone speed during March (1.8 times greater) and September (2.9 times greater). The standard deviation of cyclone frequency increases from 3 to 13.1 for April and from 0.75 to 5.86 for October between the two halves of the time series. No other changes in cyclone characteristics are found for the entire Great Lakes region.

Cyclone Characteristics for Great Lakes Subregions

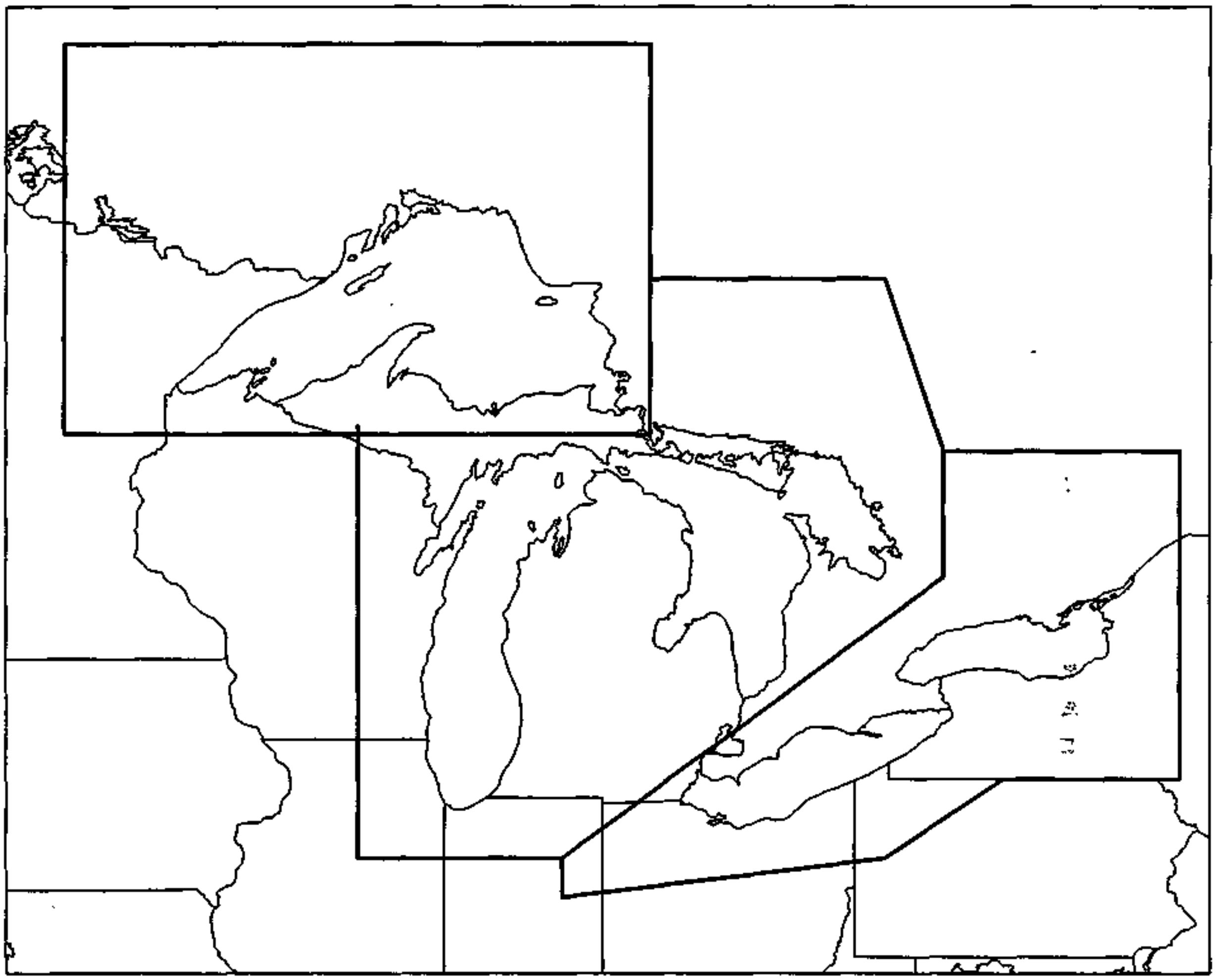
The Great Lakes region is divided into three subregions to examine any changes that are unique or stronger in a particular area of the Great Lakes region (Fig. 4.6). The three subregions are the Lake Superior subregion, the Lake Michigan-Huron subregion, and the Lake Erie-Ontario subregion, their approximate areas being 322,000 km^2, 437,000 km^2, and 277,000 km^2, respectively. The subregions closely follow the drainage region boundaries for the corresponding lakes. Because of the generally southwest to northeast track of the cyclones over the Great Lakes, dividing the study region into individual lake subregions is unwarranted. For example, the cyclones passing over Lake Ontario have most likely already passed over Lake Erie, making it difficult to develop independent samples of cyclones associated with each lake. Analysis of the trends in cyclone frequency, direction, pressure, and speed for the three subregions showed no significant results. A possible explanation for this is that the division of the region into three subregions reduces the sample size by approximately one-third, weakening the statistical significance of the results.

Discussion of Results

The results of the analyses of changes in direction and speed of cyclone movement across the Great Lakes region during the 20th century are not consistent across the region and for the seasons of the year. For direction of cyclone movement, statistically significant changes are found in the Great Lakes region for fall with October, in particular, showing a shift towards a more zonal flow. The results for speed of cyclone movement show statistically significant increases in speed in January and February for the Great Lakes region. In this study, statistically significant decreases in pressure over time (i.e., cyclones increasing in intensity over time) are found with a consistent signal in fall for the Great Lakes region.

The most notable findings of this analysis are the statistically significant increases in the frequency of strong cyclones from 1900 to 1990 for November and December, which together represent 21% of the annual total. The number of strong cyclones per pentad more than doubled from 4.5 to 9.6 for November and from 4.5 to 9.6 for December. The increases in November strongly contributed to the statistically significant increases for fall. The increases for both November and December strongly contributed to the statistically significant increases in the annual total. The variance explained by the linear regression for November, December, fall, and annual time periods is 28%, 23%, 28%, and 43% respectively. These results for strong cyclones are different from previous large-scale studies (e.g., Zishka and Smith, 1980), which showed a

Fig. 4.6. The Great Lakes region defined in this study.



decline in the frequency of all cyclones begun in the 1950s. Zishka and Smith (1980) noted a decline in cyclone pressure between 1950 and 1977 for cyclones over North America.

It should be noted that the increased frequency of strong cyclones along with the decline in frequency of all cyclones is similar to the results reported by Lambert (1995) for the Northern Hemisphere. Lambert used the Canadian Climate Centre GCM to simulate the 1000 mb geopotential height field for 1xCO_2 and 2xCO_2 levels and compared the "cyclone" characteristics between the two. A cyclone was defined as having a relative minimum grid point in the 1000 mb geopotential height field compared to the four surrounding grid points. He suggested that the reduction in the total number of cyclones in the Northern Hemisphere between the 1xCO_2 and 2xCO_2 runs was due to the reduced equator-to-pole temperature gradient, while the increase in the stronger cyclones (based on lows with departures of 200 m or more from the 1000 mb geopotential height field) was due to the increased availability of latent heat due to higher amounts of water vapor. The explanation for the increase in the frequency of strong cyclones, particularly in November and December, will be explored more in the next two chapters.

5. RELATIONSHIP BETWEEN CYCLONE FREQUENCY AND INTENSITY OVER THE GREAT LAKES

Introduction

In this chapter, the relationship between cyclone frequency and intensity (as measured by central pressure) is examined. On a planetary scale, the poleward transport of heat is generally assumed to be constant from one year to the next (if forcing such as changes in CO_2 levels or changes in the solar constant are ignored). Therefore, the transport of heat poleward by cyclone activity (as a function of both frequency and intensity) should also remain constant at this large scale (Lambert 1995). For the Great Lakes region, is there a balance between cyclone frequency and intensity such that as cyclones become more frequent they also become less intense? Is it also possible that anticyclone activity may partially balance the cyclone activity? Of course, a strict balance between cyclone frequency and intensity is not expected because cyclone activity outside the Great Lakes must also be considered.

Reitan (1979) did not make a direct comparison between frequency and intensity, but he did speculate on a mechanism for the decrease in cyclones that he found. He noted that a shift southward of the region of maximum cyclone activity could lead to fewer but stronger events. However, the data showed conflicting results with total frequency decreasing as the major area of cyclone activity shifted northward. A figure in Brennan and Smith (1978) demonstrates a general relationship between decreasing cyclone frequency and increasing cyclone central pressure, although it was not mentioned in the text. Zishka and Smith (1980) explicitly examined the relationship between cyclone frequency and pressure. For the period between 1950 and 1977, they found significant downward trends in both frequency and pressure for January and July. This supports the idea that decreased frequency is accompanied by increased intensity (i.e., lower central pressure).

Evidence of increased cyclone frequency and increased cyclone intensity (decreased central pressure) in the fall and annual time series of severe cyclones was presented in the previous chapter (Table 4.2). However, the use of the strong cyclone dataset (events with central pressures equal to or below 992 mb, a partial series) to fully analyze the relationship between cyclone frequency and intensity is inappropriate. For example, an increase in the frequency of weaker cyclones may compensate for a decrease in strong cyclones.

Relationship between Cyclone Frequency and Intensity for All Cyclones

To include *all* cyclones that tracked within the region, the more detailed data from the *Mariners Weather Log* database (1965-1990) is used. Including all cyclones that pass through the Great Lakes region (between 40°N and 50°N latitude and 93°W and 75°W longitude) for the period 1965-1990 leads to results that differ from those for the strong cyclone dataset. Table 5.1 shows statistically significant positive correlations between cyclone frequency and central pressure for winter, summer, and annual time periods. This result provides evidence of

Table 5.1. The correlation coefficients of cyclone frequency and intensity (central pressure) for *all* cyclones passing through the Great Lakes region (* - significant at 5% level).

Annual	0.41*
Winter (December - February)	0.27*
Spring (March - May)	0.17
Summer (June - August)	0.27*
Fall (September - November)	-0.10

compensation between cyclone frequency and strength. That is, as the central pressure of the cyclone increases (cyclones weaken) the frequency of cyclones also increases and vice versa.

Contribution of Anticyclones

The Klein (1957) study for 1899 to 1938 includes both cyclone and anticyclone data, which allows examination of the role that anticyclones play in the balance between cyclone frequency and intensity. In maintaining the long-term pressure field, anticyclones must compensate for the passage of cyclones (i.e., negative departures in the field must be balanced by positive departures if overall mass is to be conserved). Klein (1957) found a direct relationship between cyclone and anticyclone frequency. Using his original dataset, a reanalysis found a positive correlation of 0.42 between the annual number of cyclones and anticyclones that passed over the Great Lakes region for the period 1899-1938 (Fig. 5.1). As the number of cyclones increases (decreases), the number of anticyclones increases (decreases). The correlation is -0.69 between the average cyclone and anticyclone pressures within the Great Lakes region (Fig. 5.2). As the average cyclone pressure decreases (increases), the anticyclone pressure increases (decreases). In other words, both the cyclones and anticyclones become more intense.

Discussion of Results

These results show that for winter, summer and the entire year, a positive, statistically significant positive relationship exists between cyclone frequency and intensity. However, because the relationship is weak, it is possible that either cyclone activity outside the Great Lakes region is helping to compensate for the changes in frequency or the cyclone activity within the Great Lakes region is being compensated by anticyclone activity.

Fig. 5.1. Annual number of cyclones and anticyclones that passed over the Great Lakes region during the period 1899-1938.

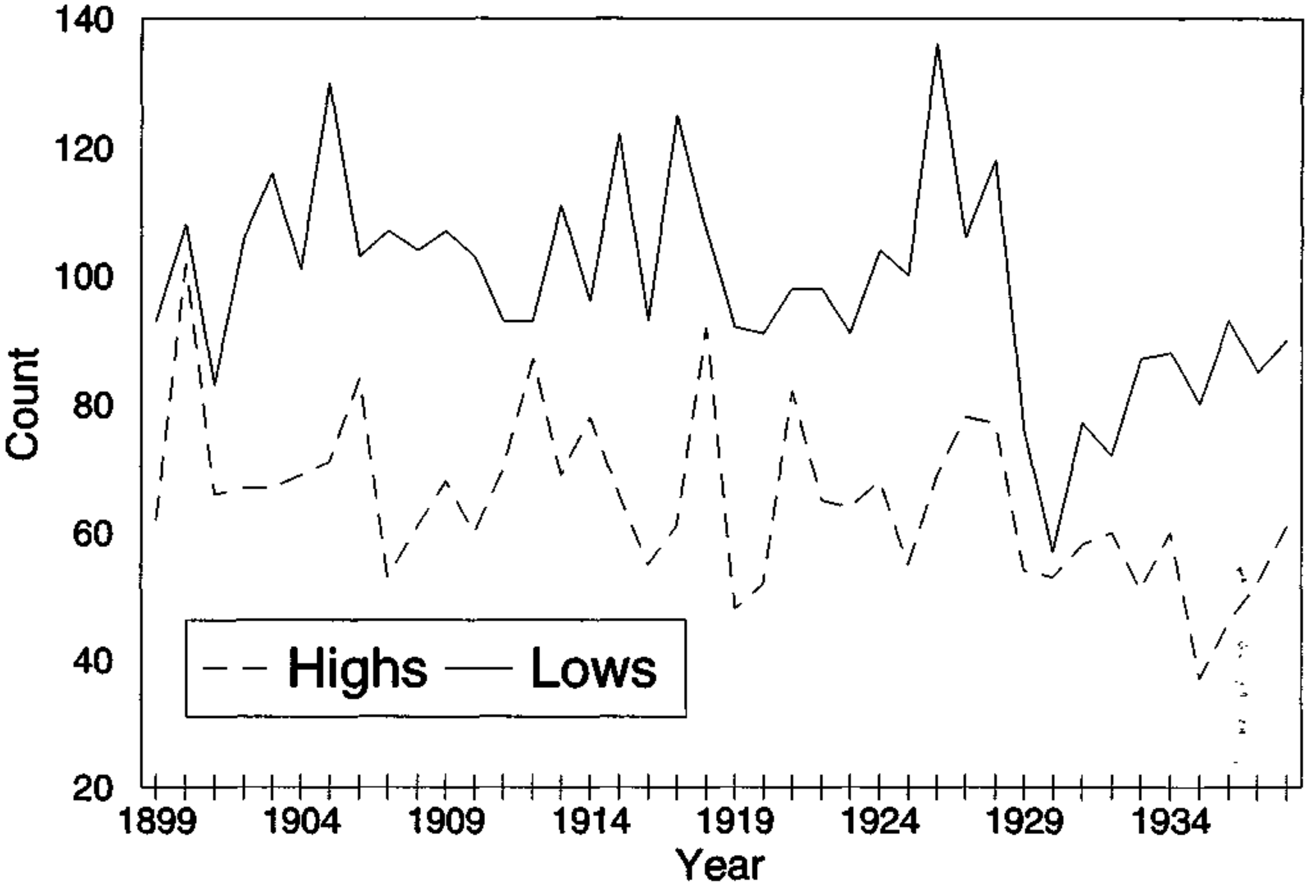
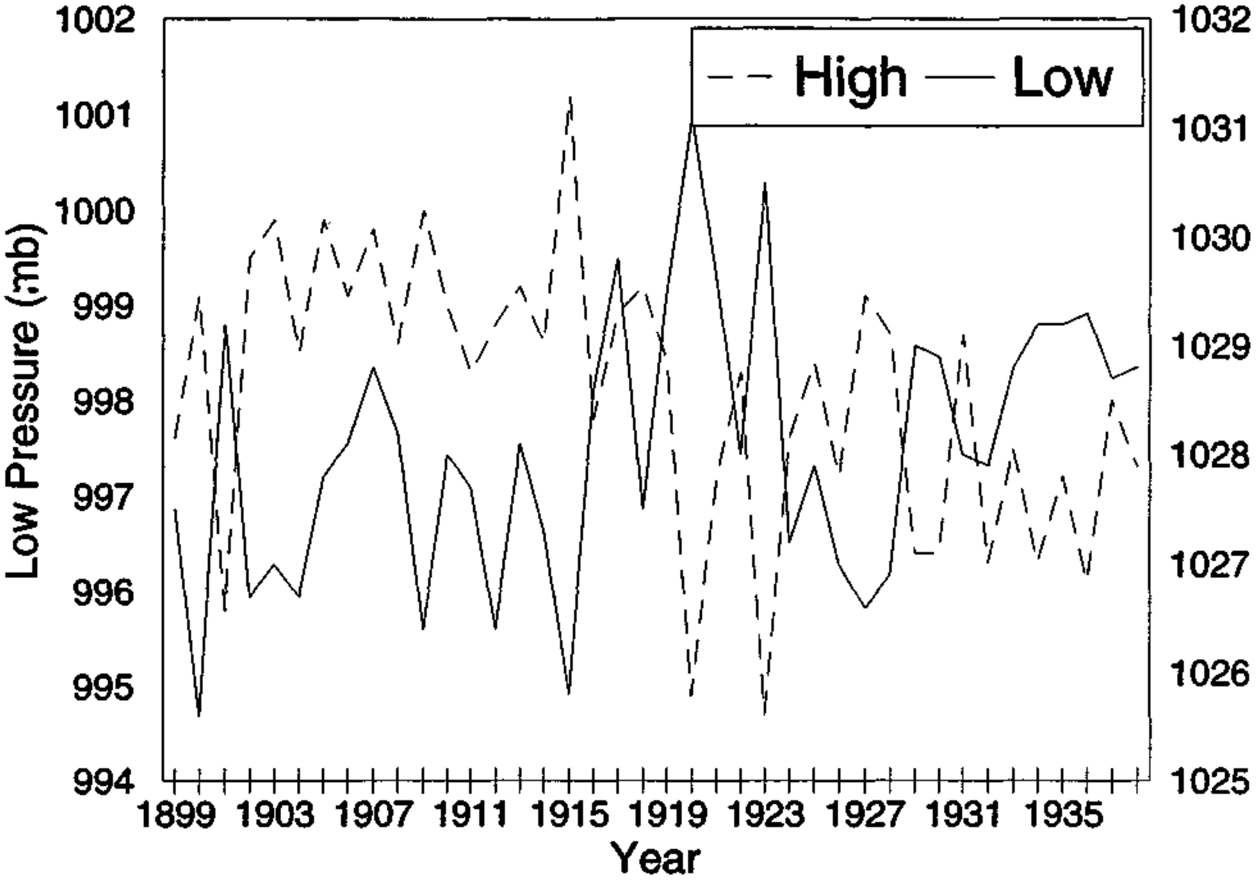


Fig. 5.2. Average annual cyclone and anticyclone central pressure over the Great Lakes region during the period 1899-1938.



6. RELATIONSHIPS BETWEEN CLIMATE VARIABLES AND THE CHARACTERISTICS OF CYCLONES IN THE GREAT LAKES REGION

Introduction

Establishing relationships between temperature and precipitation regimes and cyclone characteristics may provide a valuable tool for predicting cyclone characteristics. On a longer time scale, General Circulation Models (GCM) are used to predict the future temperature and precipitation patterns based on a doubling of greenhouse gasses in the atmosphere. A good relationship between temperature and precipitation regimes and cyclone characteristics could be used to project likely cyclone characteristics for the future, based on the temperature and precipitation patterns derived from the GCMs. On a shorter time scale, forecasts of temperature and precipitation out to one year in advance are now provided by the U.S. National Weather Service, and these values could be used to determine risks of cyclone activity for the upcoming season.

The first to note the temporal relationship between cyclone frequency and temperatures was Agee (1991). Using two previous cyclone studies (Zishka and Smith 1980; Hosier and Gamage 1956) and NASA temperature data, all for the Northern Hemisphere, Agee found a positive relationship between annual cyclone frequency and mean annual temperature. Agee speculated that the colder than normal temperatures were more likely associated with large-amplitude long waves (meridional flow), particularly over North America. During periods of meridional flow, fewer but stronger, cyclones would pass across the region. Warmer than normal temperatures were associated with shorter amplitude waves (zonal flow) with more frequent, but weaker, cyclones.

Rodionov (1994) examined the relationship between winter precipitation, lake levels, and atmospheric circulation patterns in the Great Lakes. As part of his analysis, he selected the 10 wettest and 10 driest Januarys in the Great Lakes region and compared cyclone frequency for the two groups. The change from the driest to wettest regimes was accompanied by an increase in cyclones from the Colorado region and a slight decrease in cyclones from the Alberta region, leading to a net increase in cyclone frequency through the region.

Some studies have looked at changes in cyclones using GCMs. The two drawbacks of these studies are that the GCMs do not generate surface pressure fields, as is used in historical studies, and the coarse spatial resolution of GCMs lead to underestimates of cyclone frequency. Konig et al. (1993) examined cyclone activity in GCM experiments based on three criteria: location of the geopotential height minimum at 1000 mb, its depth related to the surrounding grid points, and the location of the vorticity maximum at 850 mb. They found weak differences between the warming and the control runs. The difference was most pronounced for winter and associated with a northward shift of the major cyclone track in the North Atlantic and an eastward shift of the track in the North Pacific.

Zhang and Wang (1995) examined cyclone activity in GCM experiments based on the minimum 1000 mb geopotential height compared with the eight surrounding grid points, and the presence of strong vorticity at that grid point for 24 hours or more. They also calculated the Eady growth rate maximum, a suitable measure of baroclinic instability according to Lindzen and Farrell (1980). Zhang and Wang (1995) found decreases in cyclone and anticyclone activity between the control and global warming model runs as well as decreases in the baroclinicity of the basic flow. They attributed the decreased cyclone and anticyclone activity to a decrease in the temperature gradient from equator to poles and a decrease in the temperature differences between oceans and continents.

Lambert (1995) looked at $1XCO_2$ and $2XCO_2$ model simulations using the second generation of the Canadian Climate Centre GCM. Counting the relative lows in the 1000 mb geopotential height field on a global scale, he found statistically significant differences between the two model simulations. Overall, there was a reduction in the number of cyclones in the $2XCO_2$ model simulation. While the total number of cyclones decreased, the number of intense cyclones increased. Intense cyclones were defined by the as lows departing more than 200 m from the 1000 mb geopotential height field. Lambert speculated that a possible contributor to the increased frequency of intense cyclones was due to higher humidity (i.e., more latent heat) in the $2XCO_2$ simulation.

In this chapter, the four basic characteristics of strong cyclones (frequency, intensity, speed, and direction of movement) are compared with precipitation, temperature and temperature gradients within the Great Lakes region. The daily temperature and precipitation for the Great Lakes region were obtained from the Great Lakes Environmental Research Laboratory (GLERL) and cover the period 1900-1990. Both the temperature and precipitation data are spatially averaged from individual stations by a Thiessen weighting technique developed at GLERL by Croley and Hartmann (1985). The temperature gradient data are derived from Historical Climate Network (HCN) data for McLeansboro in southeast Illinois and Winnibigoshi Dam in north-central Minnesota for the period between 1900 and 1990. These two sites were selected for their few missing data and for their freedom from influence by the Great Lakes by being upwind of the region. Seven time periods will be examined; winter (December - February), spring (March - May), summer (June - August), fall (September - November), annual (January - December), cold (October - March), and warm (April - September). Daily temperatures and temperature gradients are averaged and precipitation summed for each time period during each year and then averaged for the 1900-1990 period of record.

Correlation Analysis between Temperature and Precipitation Regimes and Cyclone Characteristics for the Great Lakes

The results of the correlation analysis between the climate variables and cyclone characteristics for the seven time periods are shown in Table 6.1. The relationship between the temperature gradient and cyclone characteristics, an approximate measure of the baroclinicity in the region, yields a statistically significant inverse relationship with pressure in the spring. It is

Table 6.1. Correlation coefficient for relationships of cyclone characteristics with temperature and precipitation by season. Only those relationships that are significant at P≤0.05 are shown, and the P values are indicated.

	Winter	Spring	Summer	Fall	Annual	Cold Season	Warm Season
Frequency and Temperature							
Frequency and Precipitation		R=0.31 P=0.01		R=0.35 P=0.01			
Frequency and Temperature Gradient							
Direction and Temperature		R=-0.21 P=0.05					
Direction and Precipitation						R=0.26 P=0.01	
Direction and Temperature Gradient							
Speed and Temperature							
Speed and Precipitation							
Speed and Temperature Gradient							
Pressure and Temperature		R=-0.24 P=0.02				R=0.26 P=0.01	
Pressure and Precipitation							
Pressure and Temperature Gradient		R=-0.25 P=0.02					

expected that as the temperature gradient increases, the passing cyclones will become stronger (i.e., pressure decreases) due to increased baroclinicity. However, this relationship is not evident for time periods other than the spring.

While Agee (1991) showed an overall positive relationship between temperature and cyclone frequency on a larger scale for the Northern Hemisphere, no statistically significant relationship was found between temperature and cyclone frequency in this study. This difference may be due to Agee's use of all cyclones while this study focuses on strong cyclones. Strong positive relationships are found between precipitation and cyclone frequency for spring and fall. This result is expected due to the important role that cyclones play in transporting warm, moist air from the Gulf of Mexico into the region (Rodionov, 1994). An increase in cyclone frequency within the region should lead to increased precipitation.

An inverse relationship exists between temperature and the direction of cyclone movement for spring. During warmer than normal springs, cyclone direction is more southerly than during colder springs. This may correspond to an increase in cyclones from the Colorado region and a decrease in Alberta cyclones. However, there are positive relationships between cyclone direction and precipitation in the cold season (October-March). This finding appears contradictory because more precipitation is expected from cyclones that originated further to the south than those that originated in Canada. The relationship between temperature and the lowest central pressure of the cyclones is also strong. The relationship is positive for the cold season and inverse for spring. The positive relationships for the cold season correspond to Agee's (1991) finding that warmer than normal temperatures were associated with the frequent passage of weak cyclones. The inverse relationship between temperature and central pressure shown for spring; however, cannot be accounted for using this explanation.

Analysis of Variance Using Three Categories of Temperature and Precipitation

The relationship between temperature and precipitation regimes and cyclone characteristics is further examined using Analysis of Variance (ANOVA). The temperature and precipitation data sets are divided into three nearly-equal categories of above normal (33%), normal (34%), and below normal (33%). This division is the same as used by the NWS Climate Prediction Center in its long-range outlooks of temperature and precipitation. While the previous correlation analysis is used to measure the strength of the relationship among continuous variables, the ANOVA is used to identify additional relationships based on categorical variables of temperature and precipitation. Also, any resulting relationships could be directly applied to the current long-range outlooks of temperature and precipitation to give an outlook on cyclone activity. As in the previous correlation analysis, the data are divided into the seven time periods defined earlier in this chapter. The results are found in Table 6.2.

No statistically significant differences are found between and temperature and precipitation categories and cyclone movement. For pressure, there are statistically significant differences in the temperature categories for winter (below normal temperatures are associated with lower central pressures). While these differences may be statistically significant, their utility is reduced and their physical explanation is made difficult by occurring in only one or two seasons.

The strongest and most consistent relationships are found between precipitation categories and cyclone frequency. This was expected because of the close link between cyclone activity and precipitation in the Great Lakes region (Rodionov, 1994) and the results of the earlier correlation analysis. Statistically significant differences are found in the precipitation categories for winter, spring, summer, fall, and the cold season (October - March). For winter, above-normal precipitation is associated with a higher cyclone frequency (Fig. 6.1). For spring, below-normal precipitation is associated with a lower cyclone frequency (Fig. 6.2). For summer, there is a suggestion that above-normal precipitation is associated with a higher cyclone frequency (Fig. 6.3). For fall and the cold season, below-normal precipitation is associated with a lower cyclone frequency (Fig. 6.4-6.5). The relationship of precipitation and cyclone frequency is generally consistent in that either higher frequency is associated with above-normal precipitation or lower frequency is associated with below-normal precipitation.

Table 6.2 Results of the ANOVA of the cyclone characteristics for years of either below average, average, or above average temperature and precipitation. Only those effects that are significantly different at $P \leq .05$ are shown.

	Winter	Spring	Summer	Fall	Annual	Cold	Warm
Frequency and Temperature							
Frequency and Precipitation	P=0.01	P=0.04	P=0.03	P=0.01		P=0.02	
Direction and Temperature							
Direction and Precipitation							
Speed and Temperature							
Speed and Precipitation							
Pressure and Temperature	P=0.03						
Pressure and Precipitation							

Fig. 6.1 Box and whiskers plot showing the distribution of the frequency of strong cyclones in the Great Lakes region in winter for dry, normal, and wet years.

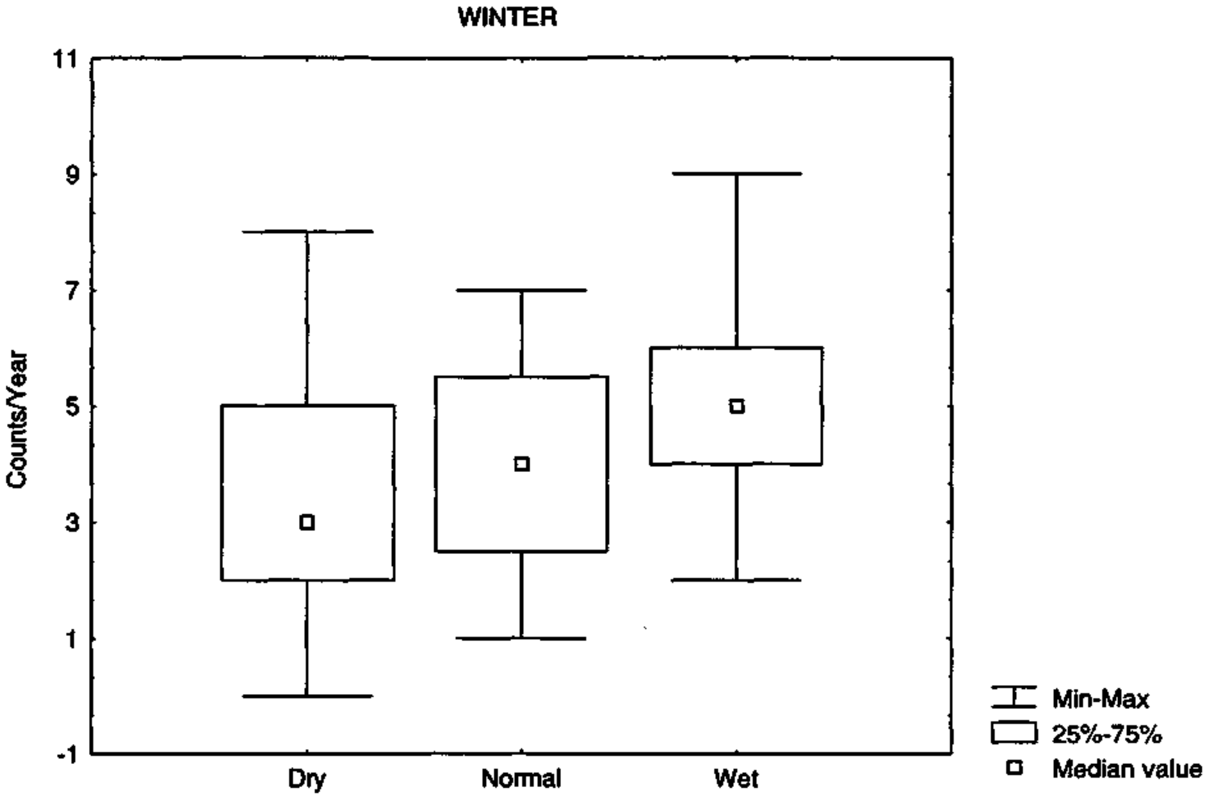


Fig. 6.2. Box and whiskers plot showing the distribution of the frequency of strong cyclones in the Great Lakes region in spring for dry, normal, and wet years.

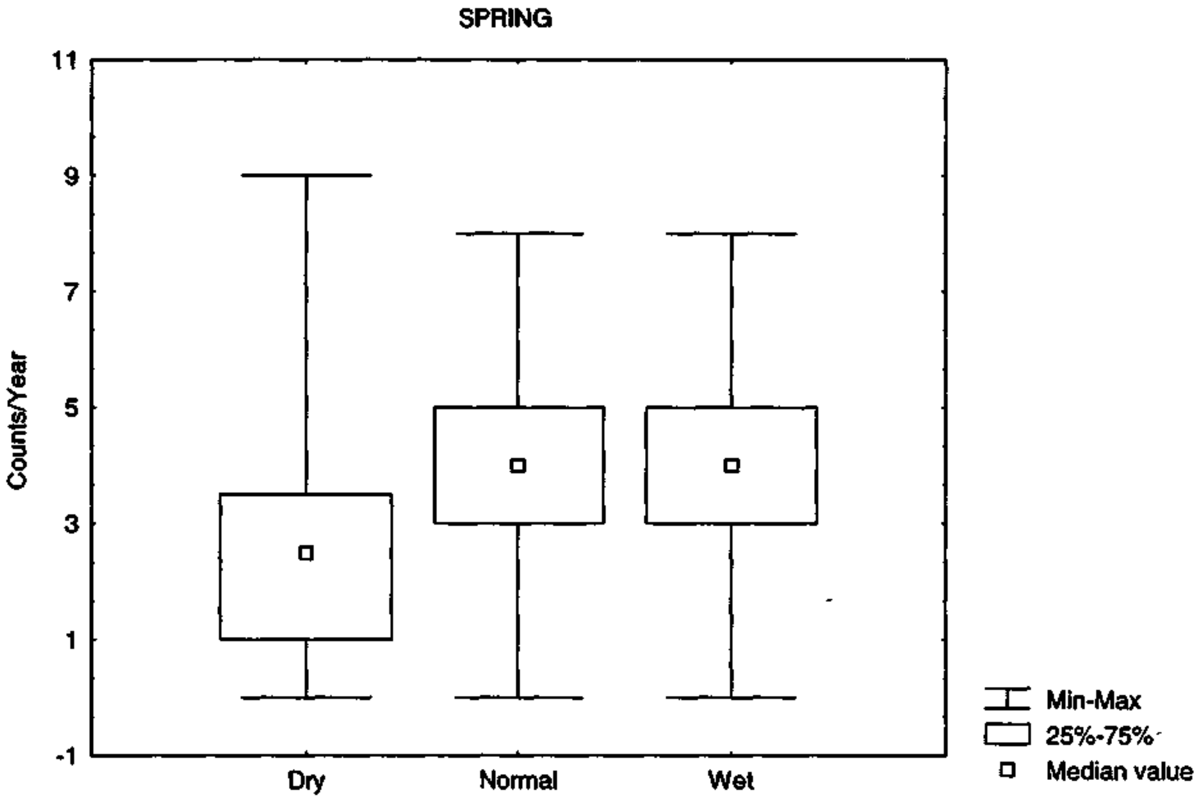


Fig. 6.3 Box and whiskers plot showing the distribution of the frequency of strong cyclones in the Great Lakes region in summer for dry, normal, and wet years.

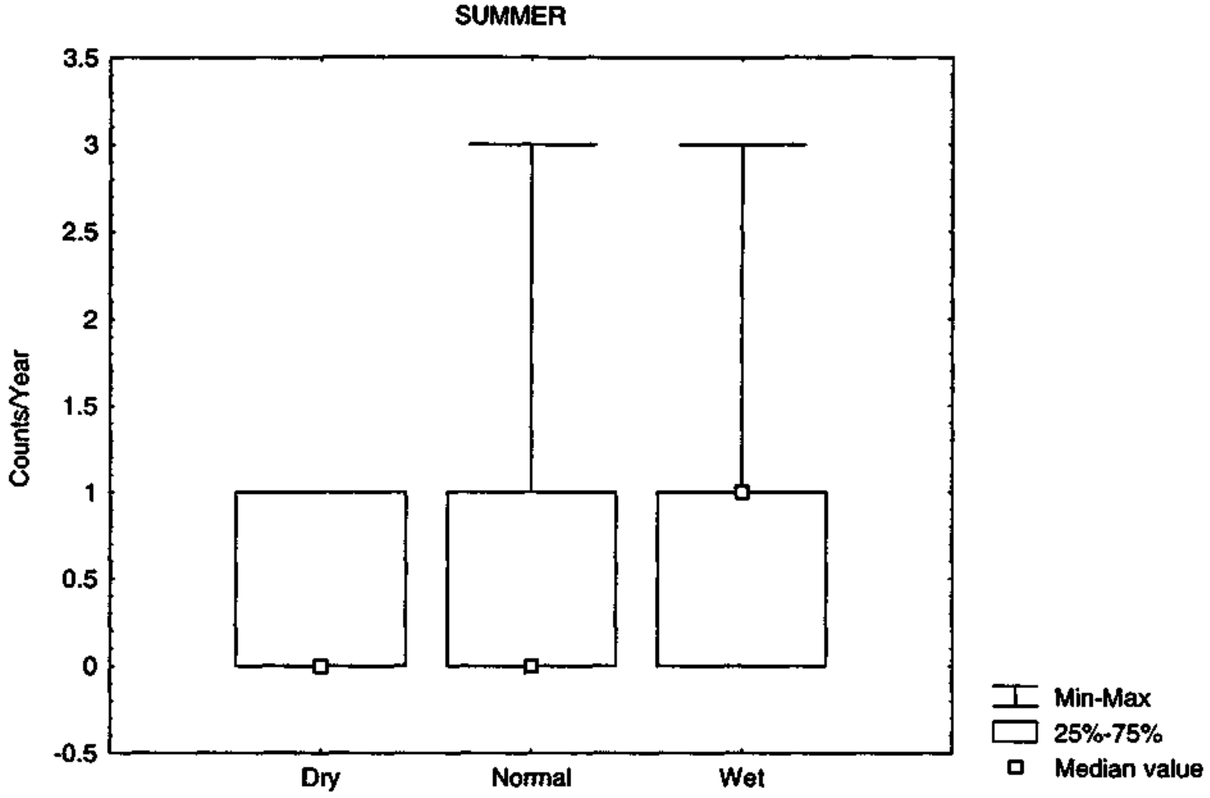


Fig. 6.4. Box and whiskers plot showing the distribution of the frequency of strong cyclones in the Great Lakes region in fall for dry, normal, and wet years.

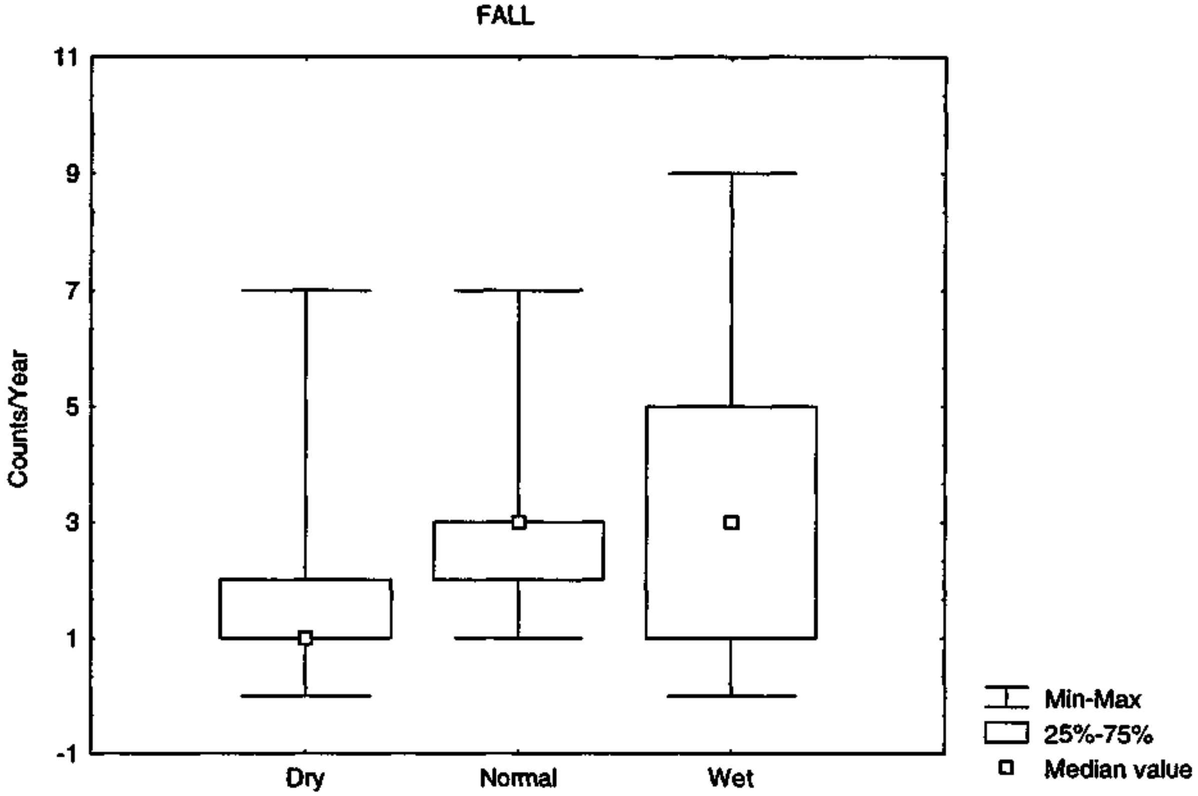
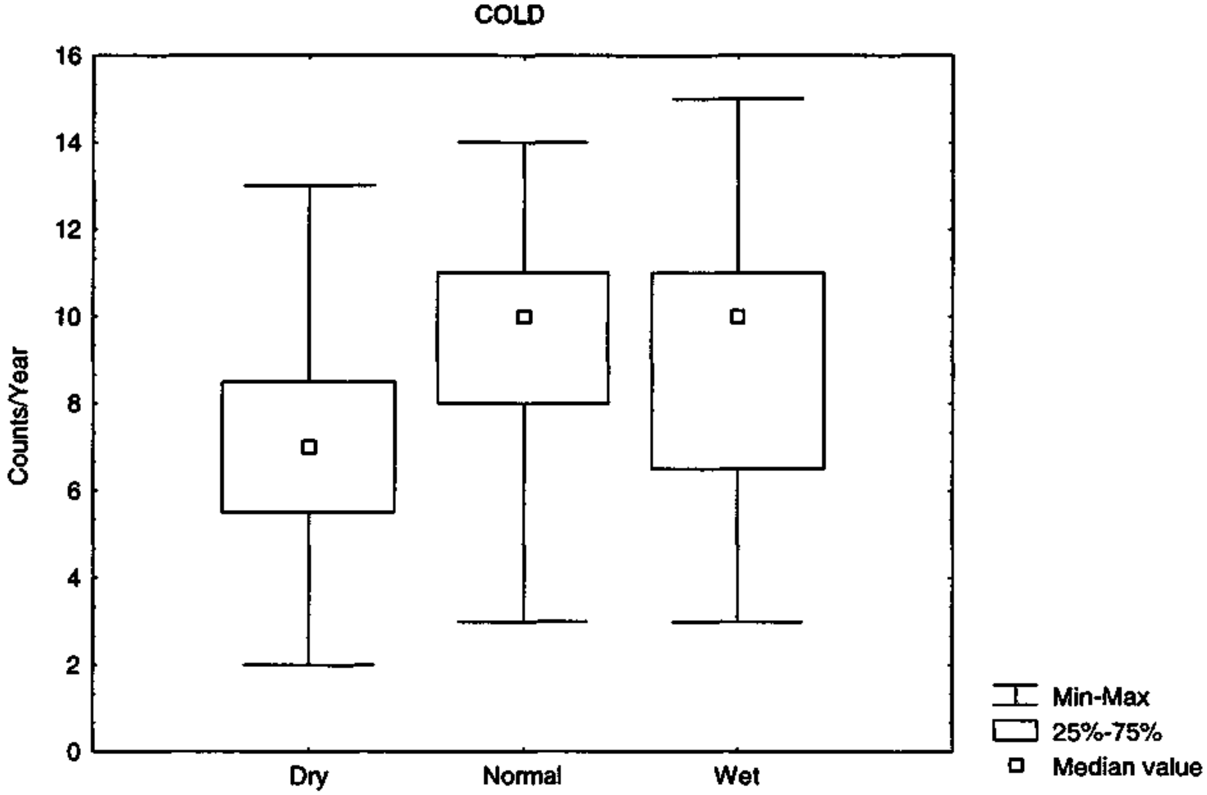


Fig. 6.5. Box and whiskers plot showing the distribution of the frequency of strong cyclones in the Great Lakes region in the cold season for dry, normal, and wet years.



Cyclone Characteristics Associated with Scenarios of Future Climates

Climate change induced by increased concentrations of greenhouse gasses in the atmosphere may have an important impact on cyclone activity in the Great Lakes. Correlation analysis and ANOVA show some linkages between cyclone characteristics and temperature and precipitation, especially between cyclone frequency and precipitation.

The U.S. EPA study (1988) applied climate scenarios to the Great Lakes region from three GCMs under a doubled CO_2 environment. The Oregon State model showed annual temperatures rising by 3.5° C with an increase in precipitation (+0.1 mm/day). The Goddard Institute for Space Studies model showed an increase of 1 ° C and precipitation increasing by 0.2 mm/day. The Geophysical Fluid Dynamics Laboratory showed the largest increase in temperature of 6.5° C and precipitation increasing by 0.05 mm/day. One limitation of these models is that the grid spacing is so coarse that the Great Lakes are not well represented in the model. Typical grid spacing was on the order of 4 to 5 degrees of latitude and longitude and thus the Great Lakes basin occupied between 6 and 8 grid squares.

Croley (1990) examined the impact of doubled CO_2 climate change on Great Lakes hydrology using later versions of the models used in the US EPA study. The resulting scenarios ranged from a 3 to 6° C warming and from a - 1 % to a +6% increase in precipitation. Both the US EPA (1988) and Croley (1990) studies show a general agreement of warming close to 4° C with precipitation amounts ranging from a slight decrease to increases up to 10%.

Using historical climate data, Croley et al. (1995) examined four spatial analog climates that might exist over the Great Lakes region under global warming. Overall, the temperature increases were from 4 to 11 ° C and precipitation ranged from -20% to +70% of the current climate. The spatial analogs were developed by selecting climates from different part of North America and transposing them over the Great Lakes region. For example, the climate of the Oklahoma-Texas region was selected to represent a warmer, drier climate. Forty years of daily data from the climate stations in that region were then transposed over the Great Lakes for use in a hydrological model.

To examine how strong cyclone frequency and pressure might change under such extreme conditions, the temperature and precipitation record for the Great Lakes region for the period 1900-1990 is extracted at the 10th and 90th percentile level. These percentiles are chosen because they represent relatively extreme conditions while retaining enough observations (nine in each case) to obtain reliable non-parametric statistics. Generally temperatures are 1 to 3 ° C

Table 6.3. Extreme temperatures and precipitation values in the Great Lakes region for selected season. Temperatures are departure from average and precipitation is percent of average.

Season	Minimum	10th Percentile	90th Percentile	Maximum
Winter - Temperature	-4.3° C	-2.6° C	2.3° C	4.5° C
Winter - Precipitation	60%	76%	123%	193%
Spring - Temperature	-2.6° C	-1.5° C	1.7° C	3.0° C
Spring - Precipitation	56%	78%	123%	149%
Fall - Temperature	-2.2° C	-1.2° C	1.2° C	3.1°C
Fall - Precipitation	55%	74%	127%	145%

cooler than the median at the 10th percentile and 1 to 3 °C warmer than the median at the 90th percentile. Precipitation is 25% below the median at the 10th percentile and 25% above the median at the 90th percentile (Table 6.3). To simplify the analysis, only the winter, spring, and fall seasons are examined. Summer is ignored because of the relatively small number of intense cyclones involved. After the years of extreme temperature and precipitation are selected, the corresponding cyclone frequency and lowest central pressure are collected with 9 years in each category. Differences in cyclone frequency and intensity are examined using box plots and are tested for significance using the non-parametric Mann-Whitney U test.

a) Cyclone Frequency

In winter, the cyclone frequency increases from a median value of 2 to 4 cyclones per season between the extreme dry and wet years (Fig. 6.6). This is a statistically significant increase at the 5% probability level. For temperature, the median increases from 3 to 6 cyclones per season between the extreme cold years and extreme warm years. However, due to the degree of scatter in the data points, this difference is not statistically significant.

In spring, the median cyclone frequency increases significantly (at the 5% probability level) from 1 to 4 cyclones per season between the extreme dry years and extreme wet years (Fig. 6.7). For temperature, the median cyclone frequency drops from 3 cyclones per year to 1 cyclone per year but again is not statistically significant due to the considerable overlap between the two distributions.

For fall, the median cyclone frequency increases from 1 to 5 cyclones per year for precipitation extremes although it is not statistically significant at the 5% probability level. For temperature, the median decreases from 3 to 1 with considerable overlap between the two distributions and the difference is not statistically significantly.

Fig. 6.6. Box and whiskers plot showing the distribution of the frequency of strong cyclones in the Great Lakes region in winter for extremely dry and wet years.

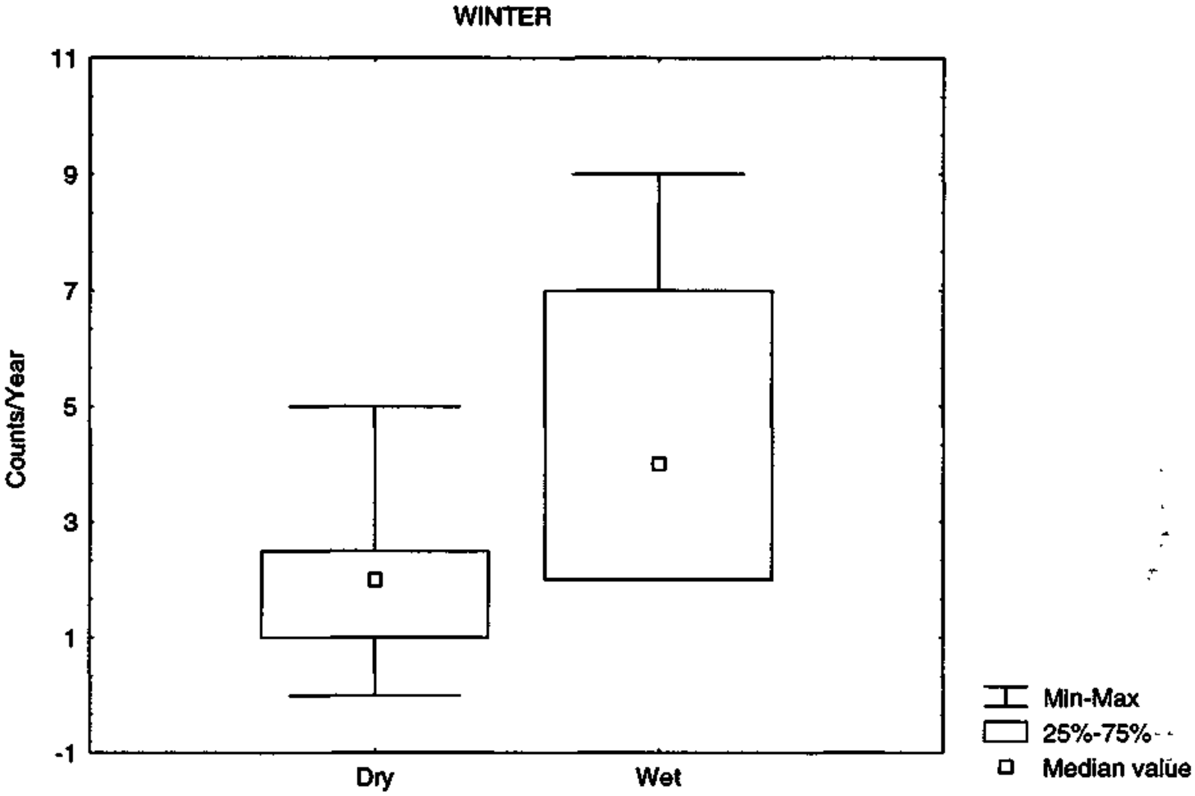
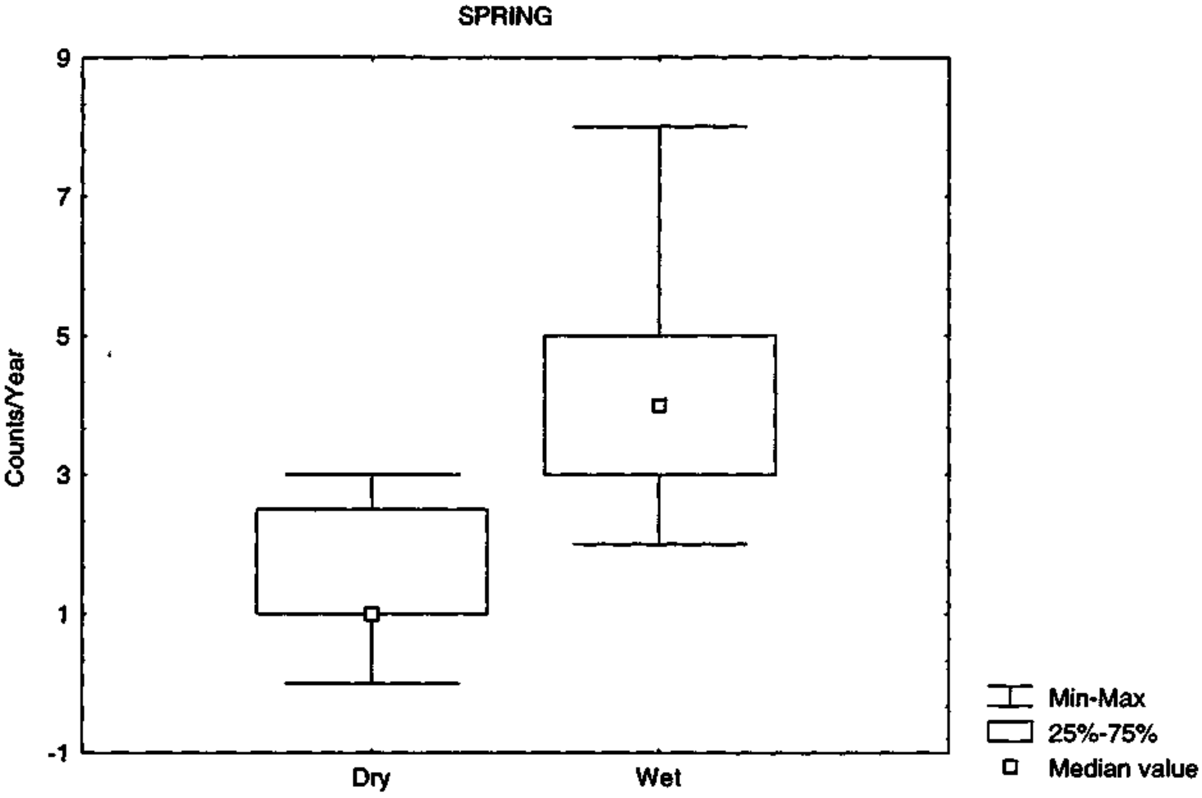


Fig. 6.7. Box and whiskers plot showing the distribution of the frequency of strong cyclones in the Great Lakes region in spring for extremely dry and wet years.



b) Central Pressure

The same type of analysis for the lowest central pressure of the strong cyclones as they pass through the Great Lakes region shows only one statistically significant difference between extreme temperatures and the lowest central pressure. This difference is for spring temperatures, with the central pressure decreasing from extremely cold to extremely warm springs. This analysis shows that extreme temperature and precipitation seasons do not affect the intensity (i.e., central pressure) of strong cyclones passing over the Great Lakes.

Cyclone Characteristics and Other Climate Variables

Noel and Changnon (1995) noted in their cyclone frequency study of North America that high cyclone frequency was associated with a more zonal flow at 500 mb, while a more meridional circulation was present during low cyclone frequency. There are no consistent patterns for the years with the lowest and highest cyclone frequencies in either the seasonal or monthly height fields. There are also no consistent patterns in either the seasonal or monthly height fields when the years with the lowest and highest cyclone pressure were selected.

El Niňo plays an important role in influencing temperature and precipitation anomaly patterns in parts of North America. One measure of the status of el Niňo is the Southern Oscillation Index (SOI). A correlation analysis between the SOI and monthly and seasonal cyclone frequency and central pressure data showed no statistically significant relationships for the period between 1900 and 1990.

In recent years another important teleconnection pattern to receive attention is the Pacific/North Atlantic (PNA) pattern. The mean pattern at 700 mb is a trough over east-central North Pacific, a ridge over the Rocky Mountains, and a trough over eastern North America (Fig. 6.8). The PNA index represents departures from this mean flow pattern. Departures from the mean pattern have been associated with changes in temperature and precipitation in the Great Lakes region by Leathers et al. (1991) and with changes in Great Lakes water levels by Rodionov (1994). The pattern and its extremes can be described by an index composed of standardized 700 mb height anomalies (Z) at grid points nearest the anomaly field centers. The 3-parameter form of the index used is given by:

$$\mathrm{PNA} = 1/3\ [-Z(50°\mathrm{N},170°\mathrm{W}) + Z(50°\mathrm{N},110°\mathrm{W}) - Z(30°\mathrm{N},90°\mathrm{W})] \tag{3}$$

Positive values of the index indicate a more meridional flow, near-zero values indicate normal flow, and negative values indicate a more zonal flow (Fig. 6.8).

Lau (1988) related cyclone track variability to low frequency changes in the circulation patterns. It is possible that the frequency of severe cyclones over the Great Lakes region may

Fig. 6.8. Illustration of the departures in the mean 700 mb flow pattern over the U.S. for positive (meridional) and negative (zonal) values of the Pacific/North American (PNA) teleconnection index.

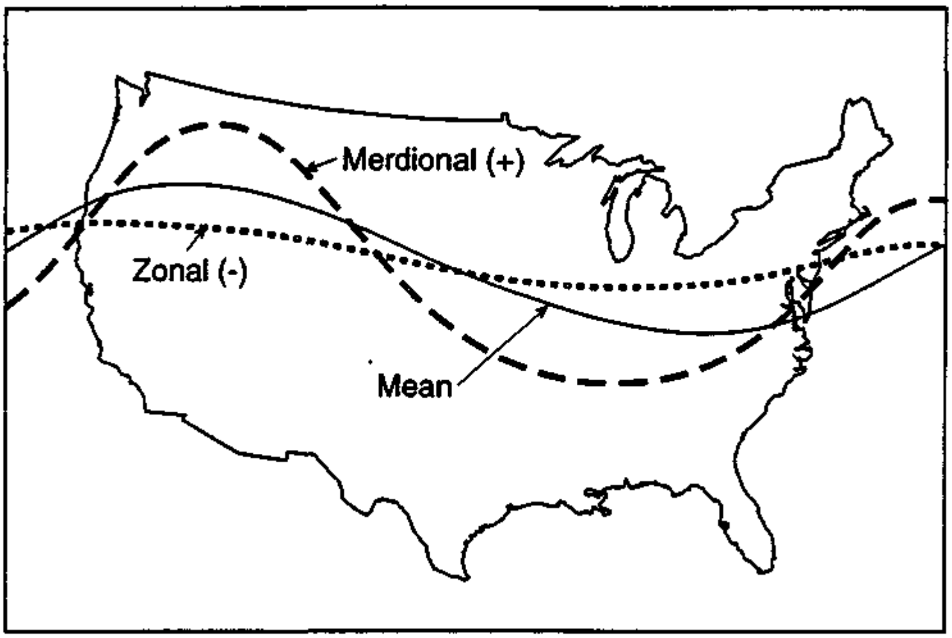


Table 6.4. The correlation coefficients, and their statistical significance, are shown between the PNA index and strong cyclone frequency over the Great Lakes region. The statistical significance is only shown if it is ≤ 0.05.

Time Period	Correlation	Statistical Significance
January	-032	0.05
February	-0.07	
March	-0.26	
April	-0.24	
May	-0.21	
June	-0.06	
July	+0.02	
August	+0.23	
September	-0.29	
October	+0.17	
November	-0.32	0.05
December	-0.36	0.05

also be sensitive to changes in the mean circulation patterns of the atmosphere over North America as represented by the PNA index.

Using correlation analysis, the monthly PNA index is compared with monthly strong cyclone frequencies over the Great Lakes region for the period when data were available between 1947 and 1984. Table 6.4 shows the results of the correlation. At the 5% significance level, negative correlations are found between the PNA index and cyclone frequency for November, December, and January. A negative correlation between cyclone frequency and PNA means that higher frequencies are associated with a negative PNA index (a more zonal flow) while lower frequencies are associated with a positive PNA index (a more meridional flow).

Based on earlier work by Reitan (1974) and by Zishka and Smith (1980), as well as their own work, Whittaker and Horn (1981) speculated that standing waves must accomplish an increasing amount of poleward energy and momentum transport to offset the significant decrease in cyclone activity in this century over the Northern Hemisphere. The negative correlations shown here appear to support their hypothesis. Lower cyclone frequency over the Great Lakes region is statistically associated with a standing wave pattern of higher amplitude (i.e., more meridional flow), while higher cyclone frequency is associated with a low amplitude standing wave (i.e., more zonal flow). The standing wave with a higher amplitude would represent an increase in poleward transport of energy to offset the lower cyclone frequency. More research is needed to examine the physical basis of this relationship.

Discussion of Results

The existence of relationships between the more intense cyclones over the Great Lakes region and other climate variables, in particular temperature and precipitation, should allow improved projections of future changes in the climate. Previous observational studies provide some historical evidence that the frequency of all cyclones increases with increasing temperature and precipitation, while other studies using GCMs in global warming scenarios show evidence that cyclone frequency decreases with increasing temperatures. Analysis of variance and correlation analyses revealed a statistically significant positive relationship between cyclone frequency and precipitation. An analysis of periods of extreme temperature and precipitation provides further evidence of a positive relationship between cyclone frequency and precipitation. Future climate changes involving increases in precipitation in the Great Lakes region will probably be associated with increases in cyclone frequency. The strong link between cyclone frequency and the 3-category precipitation scheme could lead to forecasting of strong cyclone frequency with the new National Weather Service long-range outlooks.

7. ANALYSIS OF PREFERRED TRACKS OF THE CYCLONES PASSING OVER THE GREAT LAKES

Introduction

In this chapter, the preferred tracks of strong cyclones, those with central pressure less than or equal to 992 mb, that cross the Great Lakes are examined. Previous studies by Klein (1957), Reitan (1974), Zishka and Smith (1980), and Whittaker and Horn (1984) have presented the preferred tracks of all cyclones passing over North America. In all these studies, the preferred tracks were calculated by counting all cyclones passing through a grid and contouring the resulting numbers to identify regions of high frequency. The resulting elongated regions are considered the preferred cyclone tracks. Despite the use of different sized grids and different periods of record, the results are similar among past studies. In January, there is a primary track from Alberta through the Great Lakes region, a Colorado track that also passes through the Great Lakes region, and an east coast track. In April, the dominant track is through the central plains of the US and thus passes through the Great Lakes region, while the Alberta track makes a smaller contribution. By July, most of the cyclone activity has moved northward into Canada and is not a significant factor in the Great Lakes. By October, cyclone activity has again migrated southward and the features are similar to those in January (Alberta, Colorado, and east coast tracks).

Eichenlaub (1979) and Lewis (1987) analyzed cyclone tracks for cyclones that affect the Great Lakes region. Although they identified more tracks, their results were similar to those of the larger scale studies. For example, they split the Colorado track into two or three more distinct tracks. Both studies also added an additional cyclone track moving out of Texas. Harman et al. (1980) identified two source regions for cyclones affecting the western Great Lakes (Lakes Superior, Huron, and Michigan), the northern and southern Great Plains. While previous studies have yielded similar results, an examination of cyclone tracks for strong cyclones over the Great Lakes may reveal that a particular track is dominant.

Data and Methodology

As mentioned earlier, the traditional approach to determining the preferred cyclone tracks is to divide the map into a grid based on latitude and longitude. The lines of longitude converge when approaching the poles such that the area within a grid box is reduced at higher latitudes. To adjust for this, many researchers (e.g., Whittaker and Horn, 1984) have used a scaling factor to give more weight to higher latitude grid boxes in proportion to their reduced size. Others have maintained (e.g., Hayden, 1981) that this just adds a latitude dependent bias to the data.

Another problem noted by Taylor (1986) is that square grids may preferentially weight certain cyclone track directions over other ones. The cross-section of the grid box in relationship to crossing track becomes important. For example, if all cyclones moved exactly west to east then the exposed cross-section of the grid box is the length of the western or eastern edge. If the cyclones move from southwest to northeast then the exposed cross-section of the box is the longer diagonal. Therefore, a box may count more southwesterly cyclones than westerly cyclones.

An alternate approach to solving the problems of square grids is to count cyclones within a certain radius of selected points. This approach is used by Changnon et al. (1995). The advantages are that the area remains the same at all latitudes and that no preferential treatment exists for cyclones from a particular direction.

The Changnon et al. (1995) approach is used here to develop areas of preferred strong cyclone activity. The radius is 111 km (60 nautical miles or 1° latitude) from selected points (Fig. 7.1). The circles extend from 26°N to 58°N and from 60°W to 120°W. The spacing is designed so that the circles just meet at 58 °N. A total of 272 circles are sampled. The track of each severe cyclone that passed over the Great Lakes for the period from 1900 to 1990 is described by a series of points representing the cyclone's position at 0700 EST. Whenever this track passes through a particular circle, it is added to the count of that circle. A linear interpolation is used to reconstruct the path in more detail. A more sophisticated interpolation scheme (e.g., spline curves) is not warranted because the major source of error is the departure of the cyclone from the mean path between any two 24-hour observations. Once the counting is completed, contour maps are drawn to show the regions of preferred strong cyclone activity. The primary tracks are along the axes of highest frequency, while secondary tracks are along axes of lesser frequency, as was done by Whittaker and Horn (1984). Because this study is focused on strong cyclones passing over the Great Lakes region, the highest frequencies will be in that region, as shown in Fig. 7.1.

Similar to earlier chapters, the severe cyclones are analyzed for the entire region plus the subregions of Superior, Michigan-Huron-St.Clair, and Erie-Ontario. The analyses are done for the four traditional seasons of winter (December-February), spring (March-May), summer (June-August), and fall (September-November).

Results

a) Great Lakes Region

For winter, the strong cyclone frequency map (Fig. 7.2a) shows two preferred tracks merging into one over the Great Lakes. The northern track extends to Alberta, Canada and closely follows the U.S. - Canada border. The southern track originates in the southwestern U.S. (Nevada, Utah, and southern Colorado) and passes through Kansas, Missouri, Iowa, and Illinois. These two tracks merge over the Great Lakes with the highest frequency immediately to the northeast of Lake Huron. The major track then passes through Ontario, Quebec, and the Gulf of St. Lawrence.

The spring pattern is similar to the winter pattern except that the contribution from the Alberta track has weakened (Fig. 7.2b). For summer, the number of severe cyclones has greatly

Fig. 7.1. Circles used to count the passage of strong cyclones in the Great Lakes region (box).

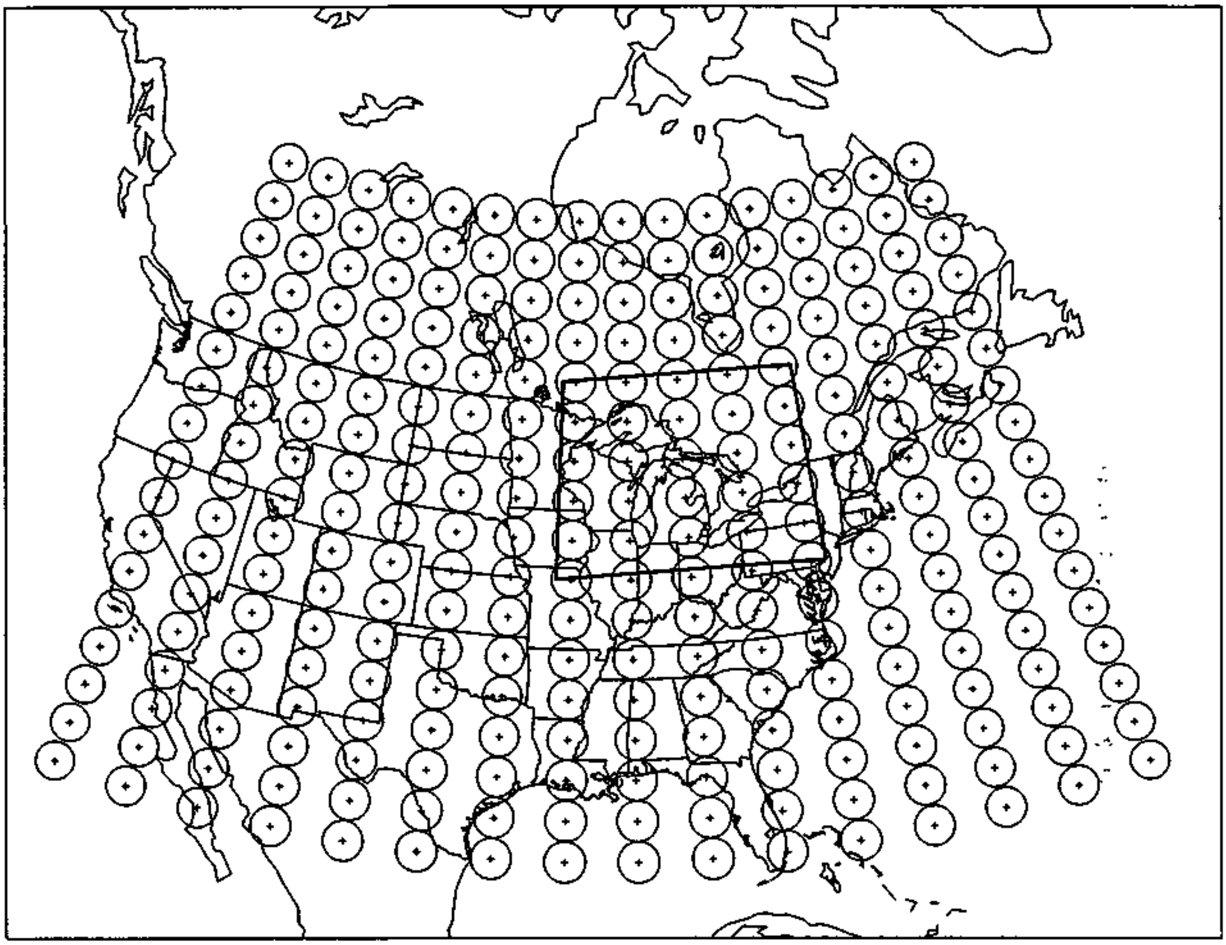


Fig. 7.2(a). Frequency of strong winter cyclones for the Great Lakes region. Solid lines indicate the primary tracks along the axes of high frequency.

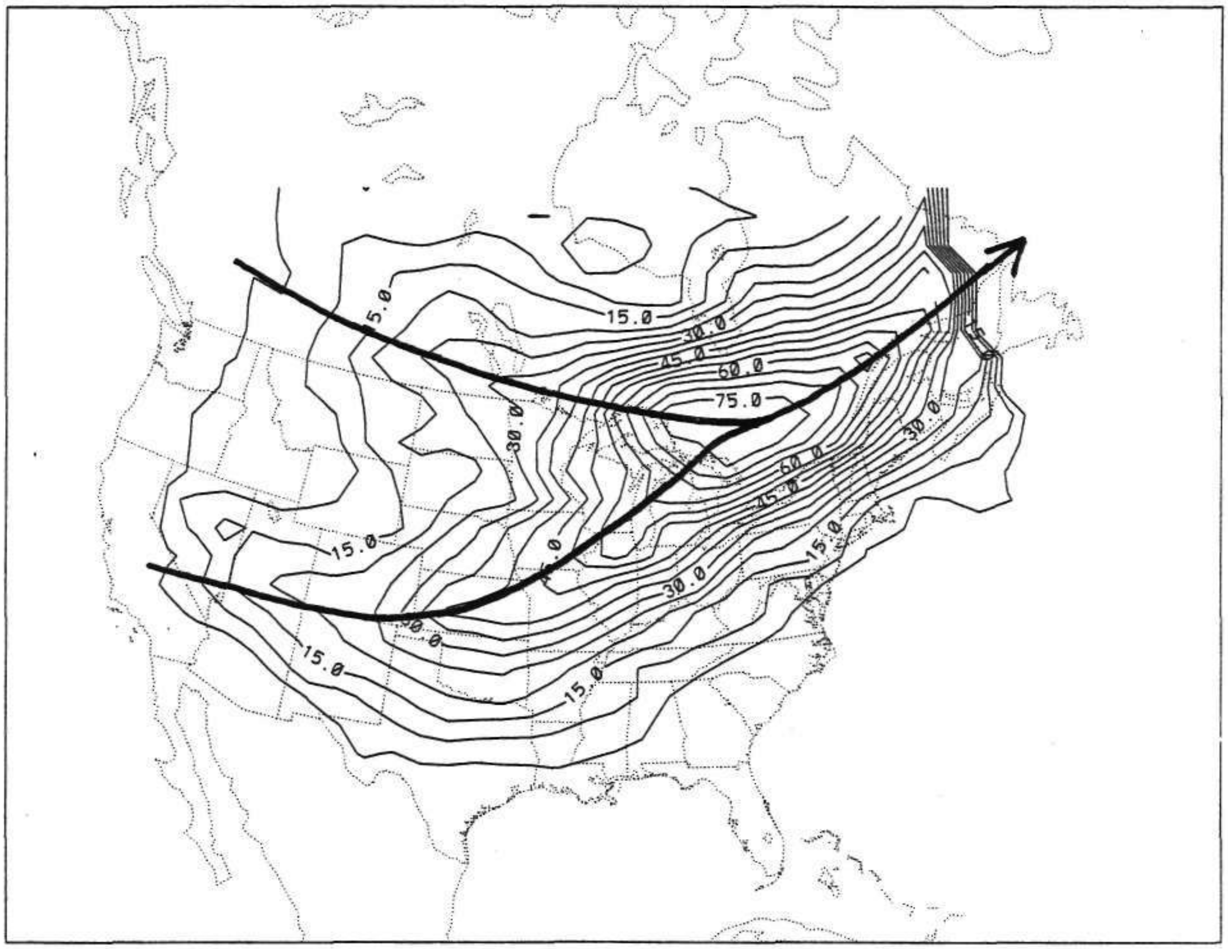
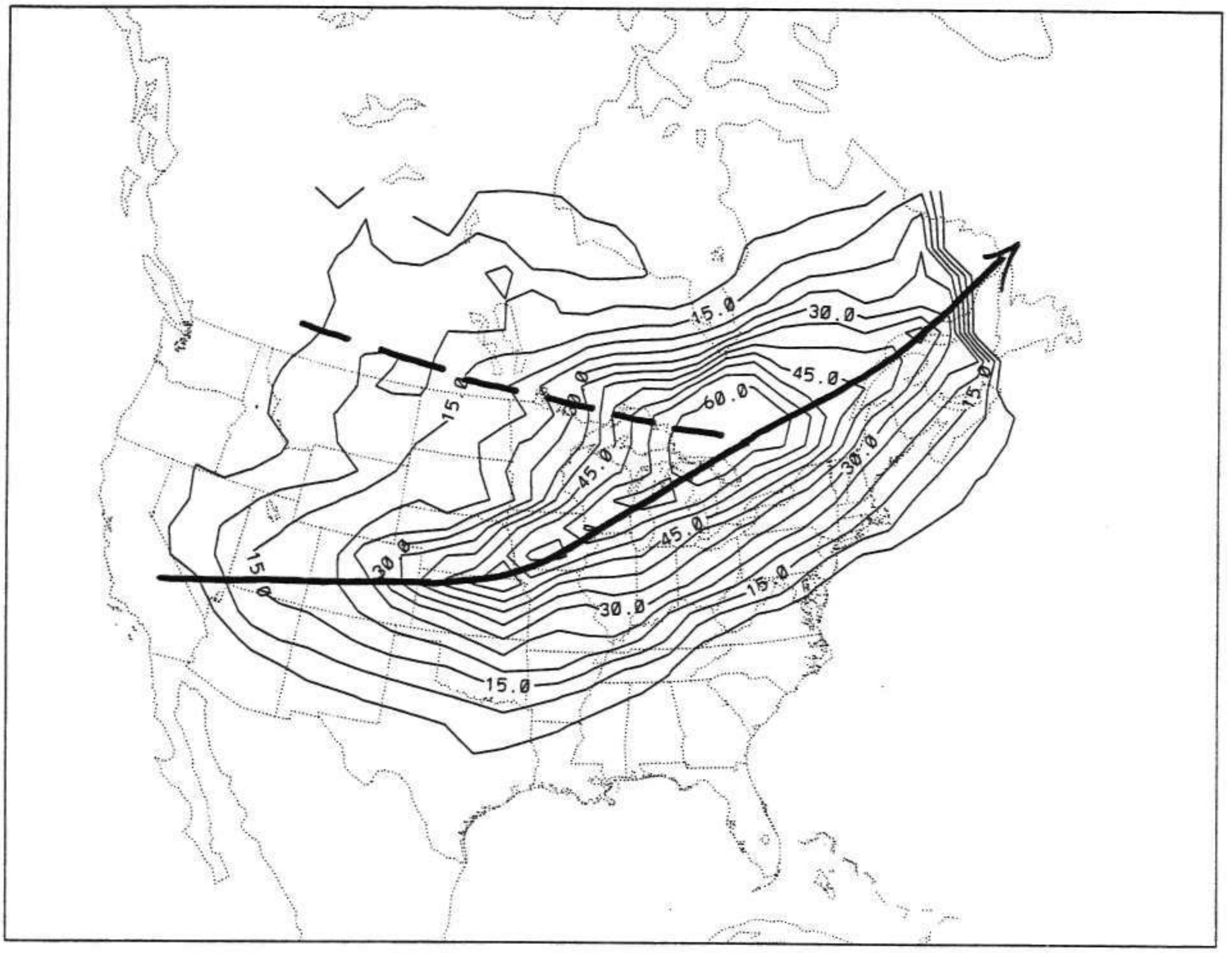


Fig. 7.2(b). Frequency of strong spring cyclones for the Great Lakes region. Solid lines indicate the primary tracks along the axes of high frequency. Secondary tracks (dashed lines) are along the axes of lesser frequency.



declined and the pattern is weak. The few cyclones that pass over the Great Lakes in summer originate in Colorado and move to the northeast (Fig. 7.2c).

The fall pattern is the most complex of the four seasons (Fig. 7.2d). The Alberta track is still present while the southern track has shifted northward by 300 to 400 kilometers. These two tracks converge east of Lake Superior, and diverge in eastern Canada. The southern track follows the same path as the winter track, parallel to the St. Lawrence River. The more northerly track extends in a northeasterly direction into northeastern Quebec and the Labrador Sea. An analysis of the Alberta and Colorado tracks separately, not shown, indicates that the Alberta track continues eastward out of the region, while the Colorado track continues northeastward.

b) Great Lakes Subregions (Superior, Michigan-Huron-St. Clair, and Erie-Ontario)

The Great Lakes region is divided into three subregions, as in Chapter 4, to evaluate variations in the sources of strong cyclone activity for the subregions. For winter (Fig. 7.3), the pattern is similar in all three subregions and similar to the pattern from the entire Great Lakes region (Fig. 7.2a). The Michigan-Huron-St.Clair and Erie-Ontario subregions do, however, have a weaker Alberta track than the Superior subregion.

For spring, the Superior subregion is very similar to the overall Great Lakes region pattern with a strong southeast U.S. track and a weakened Alberta track. The Michigan-Huron-St. Clair and Erie-Ontario subregions show only a strong southeast track (Fig. 7.4). For summer, the Superior subregion shows a weak track with a southwest-northeast orientation, while the other two subregions have no patterns (Fig. 7.5).

For fall, the pattern is similar to spring. The Superior subregion shows the Alberta track and a track extending directly from Nevada to the Great Lakes (a more northerly track than in spring). After departing the Great Lakes region, most of the strong cyclones pass into northeast Quebec and into the Labrador Sea (Fig. 7.6). For the Michigan-Huron-St.Clair and Erie-Ontario subregions, a single track extends from Colorado-Kansas into the Great Lakes region and parallels the St. Lawrence River. The Michigan-Huron-St.Clair subregion has a maximum of activity centered at Sault Ste. Marie, MI while the Erie-Ontario subregion reaches a maximum in southern Ontario.

Based on these results, the cyclones are divided into two categories, those cyclones originating north of 43°N and those originating south of 43 °N, to determine the relative contribution of the two major source regions. For convenience, cyclones originating south of 43°N will be referred to as "Colorado" cyclones, and cyclones originating north of 43 °N will be referred to as "Alberta" cyclones because most of the cyclones originate from those two regions. For the Great Lakes as a whole, the contribution of the two regions is evenly divided between the Colorado and Alberta source regions. However, this is not the case for the three subregions. The Lake Superior subregion is dominated by the Alberta track 66% of the time. The Michigan-Huron-St.Clair and Erie-Ontario subregions are dominated by the Colorado track 67% and 62% of the time, respectively.

Fig. 7.2(c). Frequency of strong summer cyclones for the Great Lakes region.

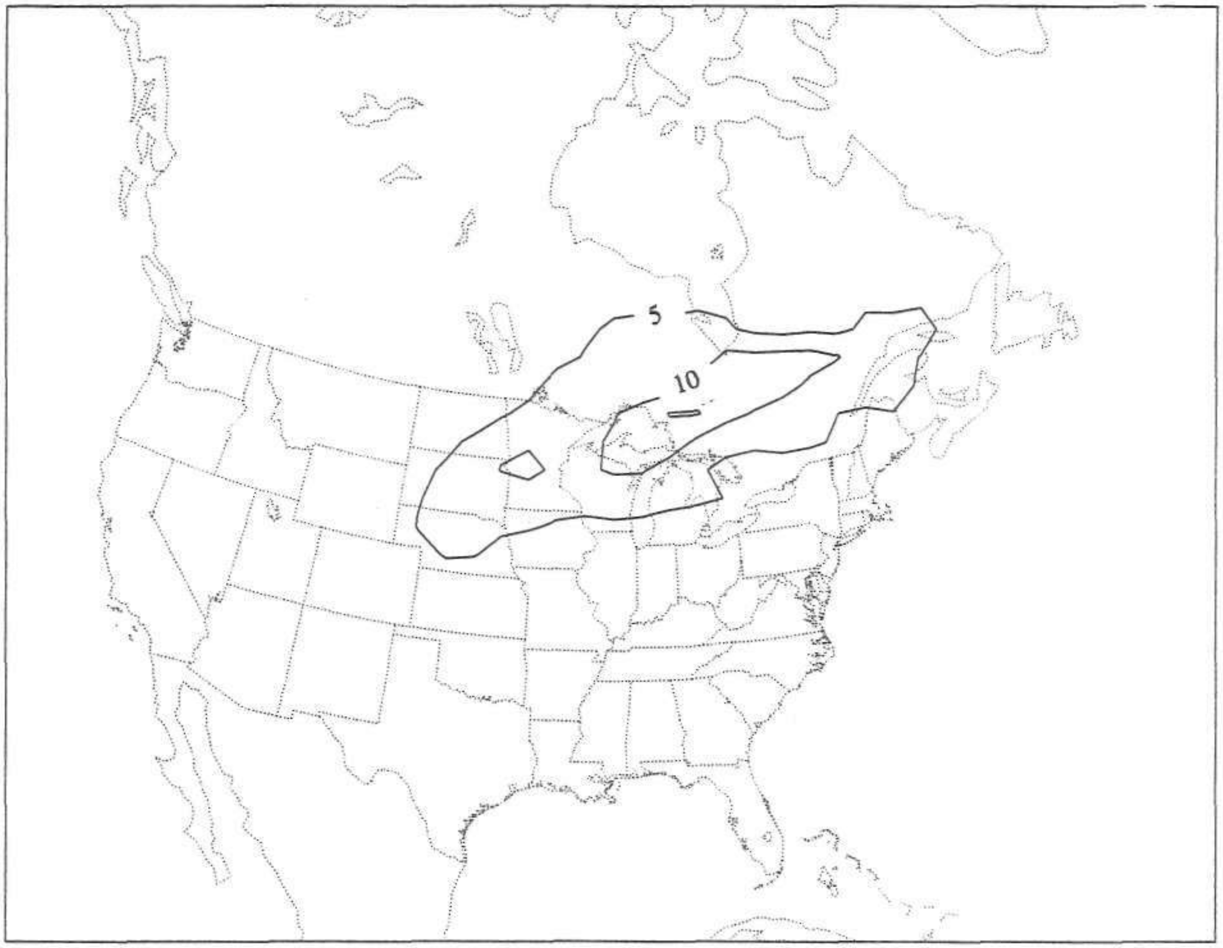


Fig. 7.2(d). Frequency of strong fall cyclones for the Great Lakes region. Solid lines indicate the primary tracks along the axes of high frequency. The Alberta track continues eastward out of the region, while the Colorado track continues northeastward.

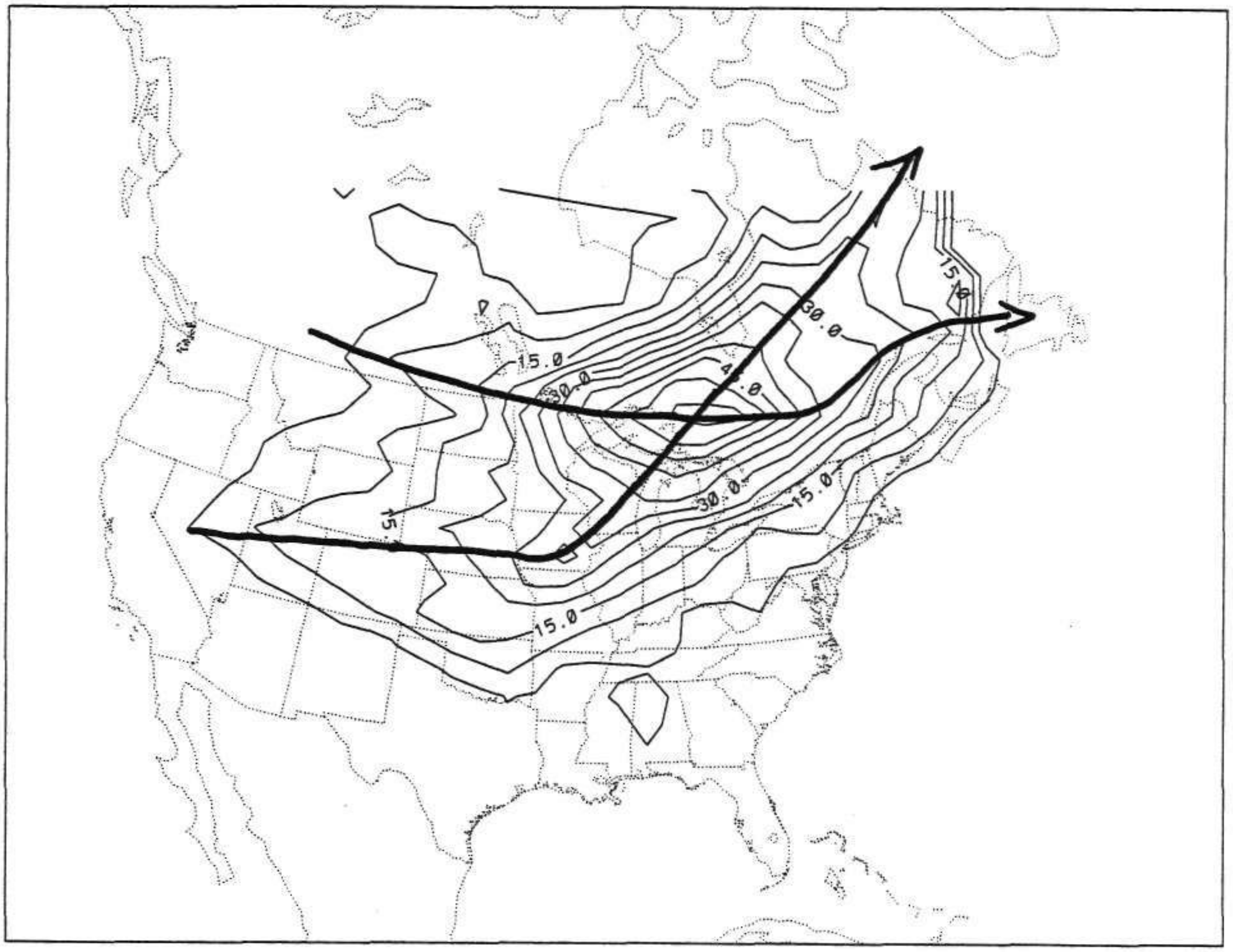


Fig. 7.3(a). Frequency of strong winter cyclones for the Superior region. Solid lines indicate the primary tracks along the axes of high frequency.

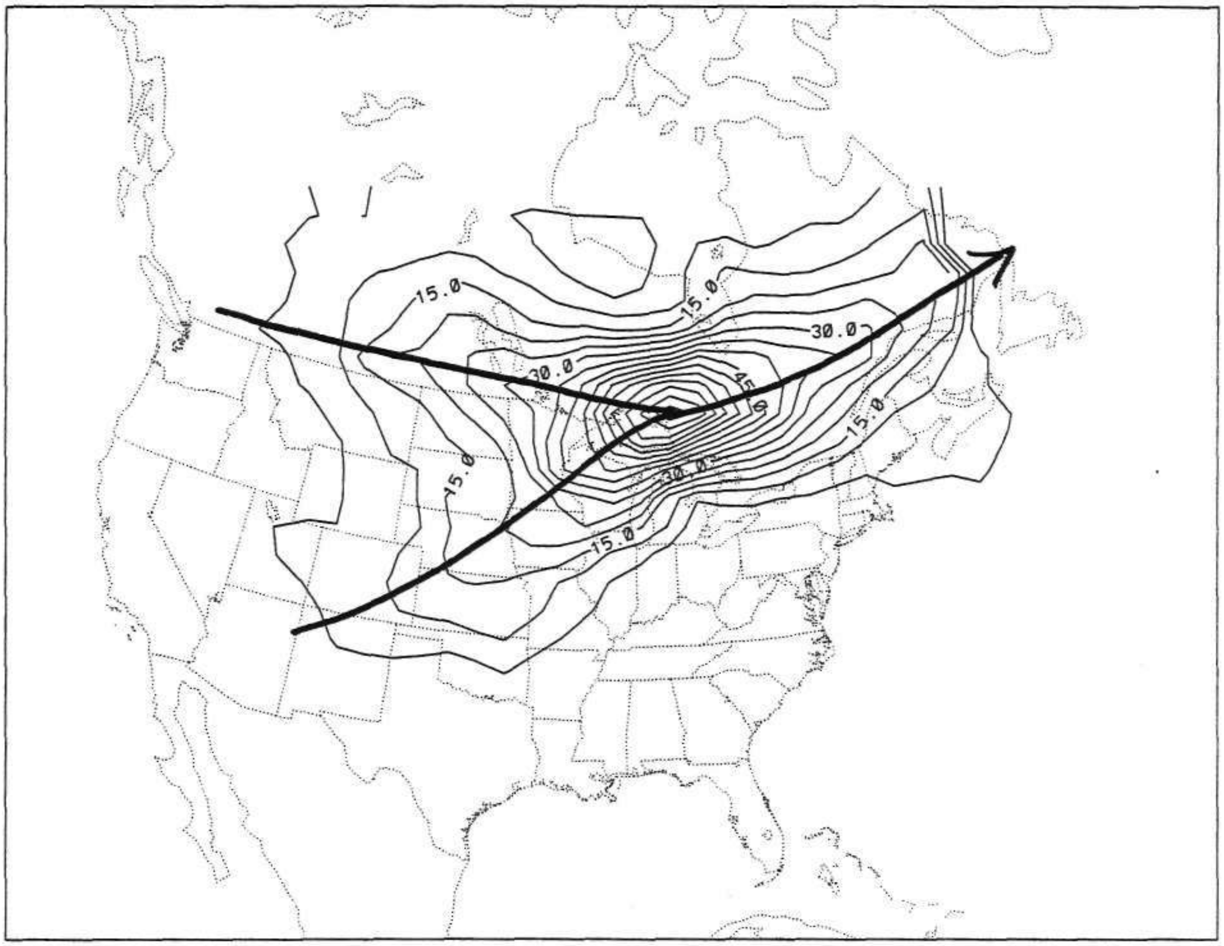


Fig. 7.3(b). Frequency of strong winter cyclones for the Michigan-Huron-St.Clair region. Solid lines indicate the primary tracks along the axes of high frequency. Secondary tracks (dashed lines) are along the axes of lesser frequency.

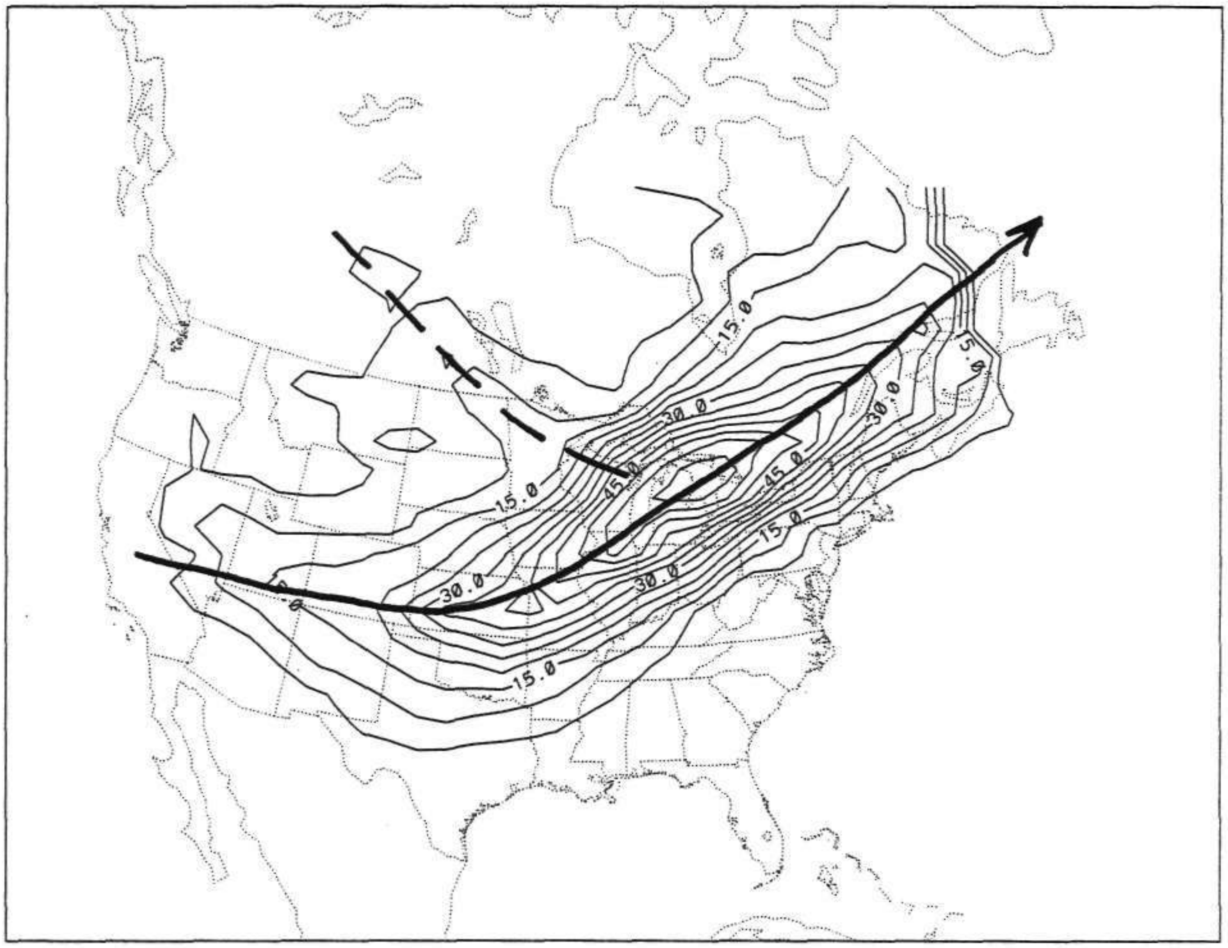


Fig. 7.3(c). Frequency of strong winter cyclones for the Erie-Ontario region. Solid lines indicate the primary tracks along the axes of high frequency. Secondary tracks (dashed lines) are along the axes of lesser frequency.

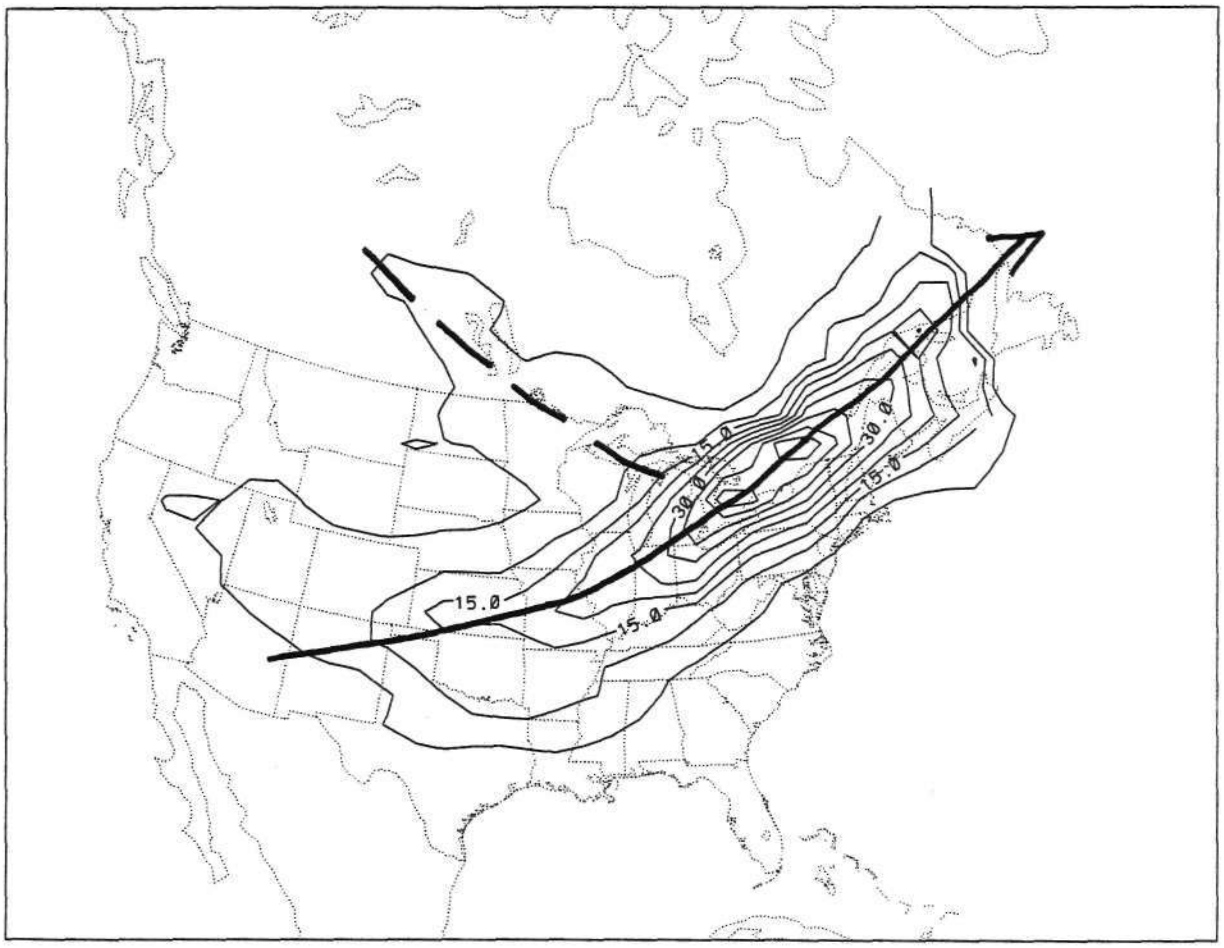


Fig. 7.4(a). Frequency of strong spring cyclones for the Superior region. Solid lines indicate the primary tracks along the axes of high frequency. Secondary tracks (dashed lines) are along the axes of lesser frequency.

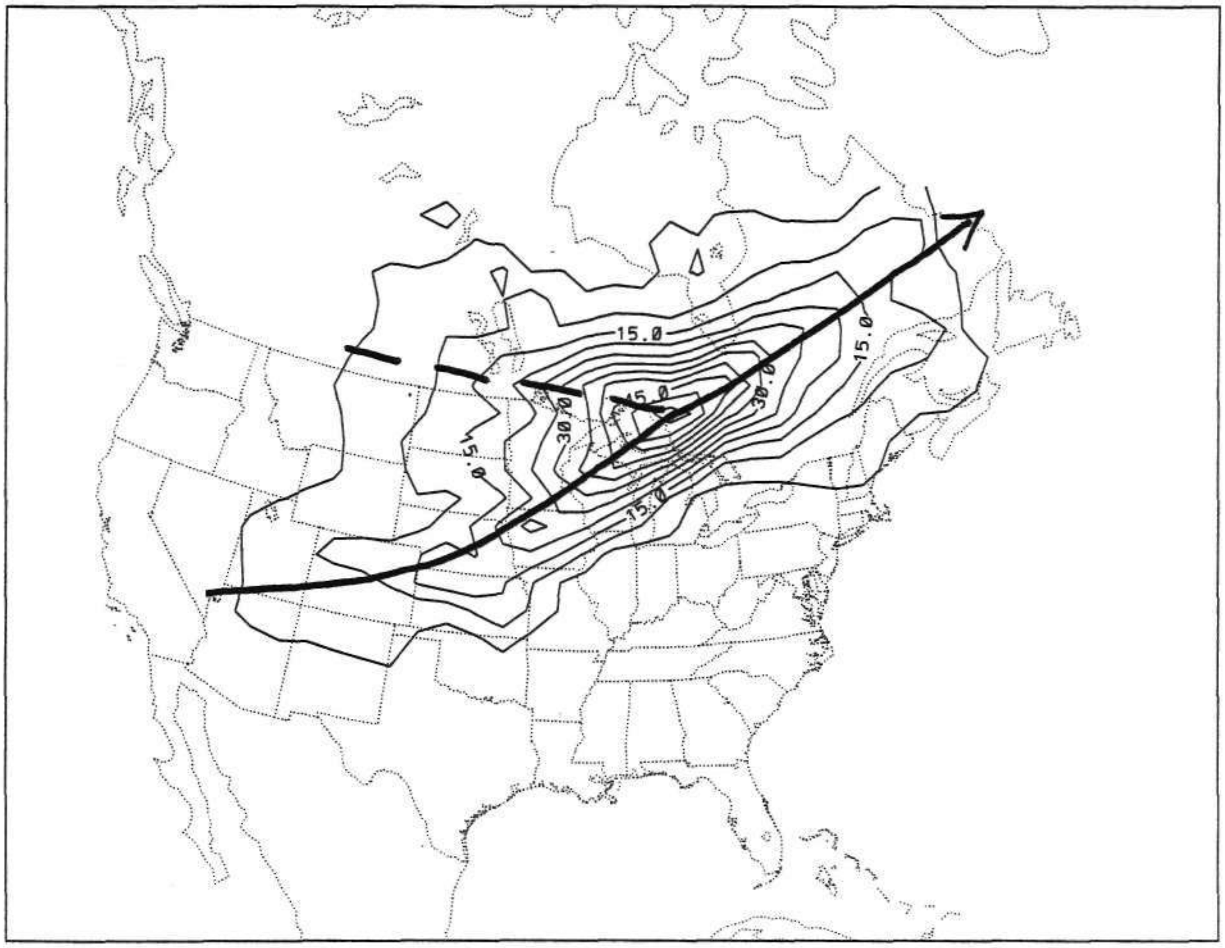


Fig. 7.4(b). Frequency of strong spring cyclones for the Michigan-Huron-St.Clair region. Solid lines indicate the primary tracks along the axes of high frequency.

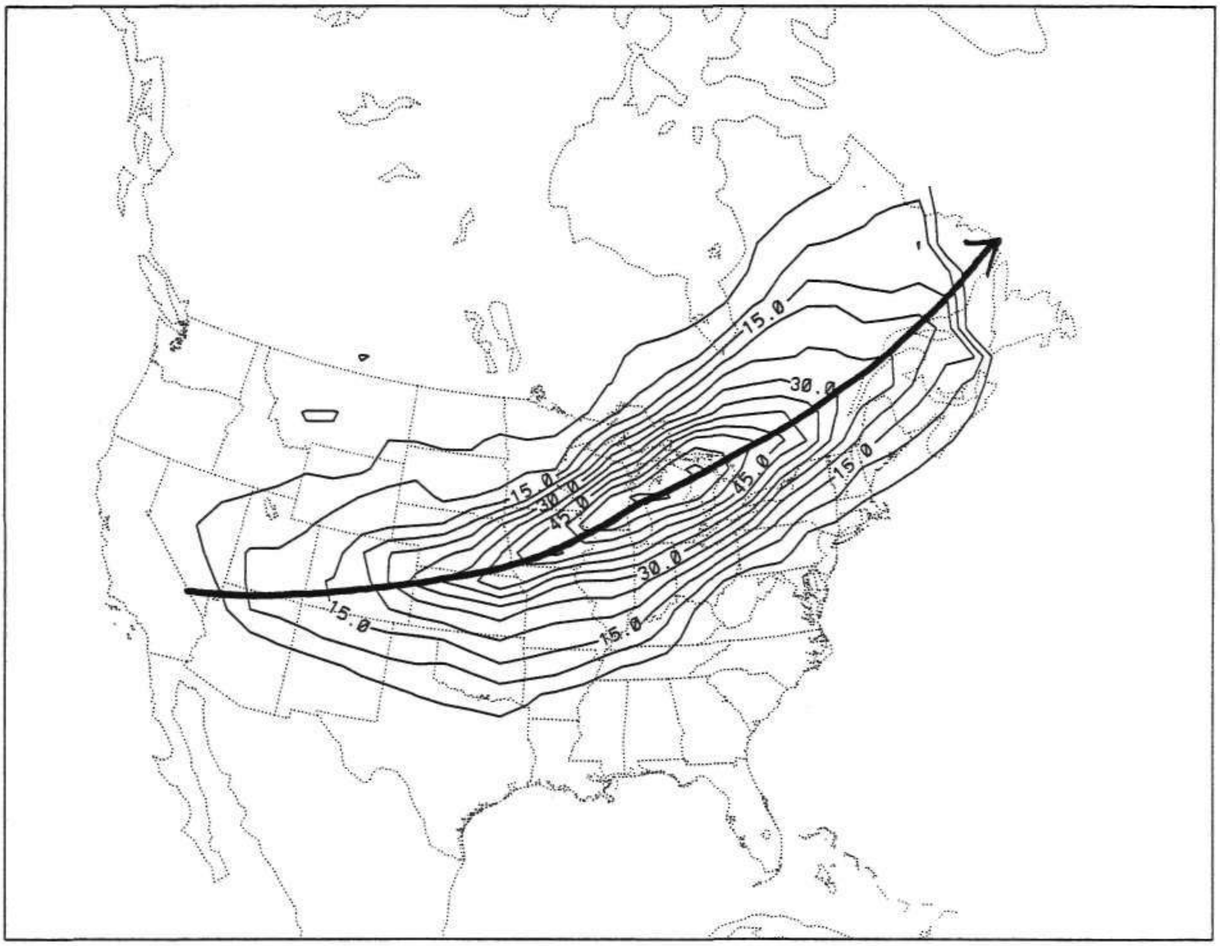


Fig. 7.4(c). Frequency of strong spring cyclones for the Erie-Ontario region. Solid lines indicate the primary tracks along the axes of high frequency.

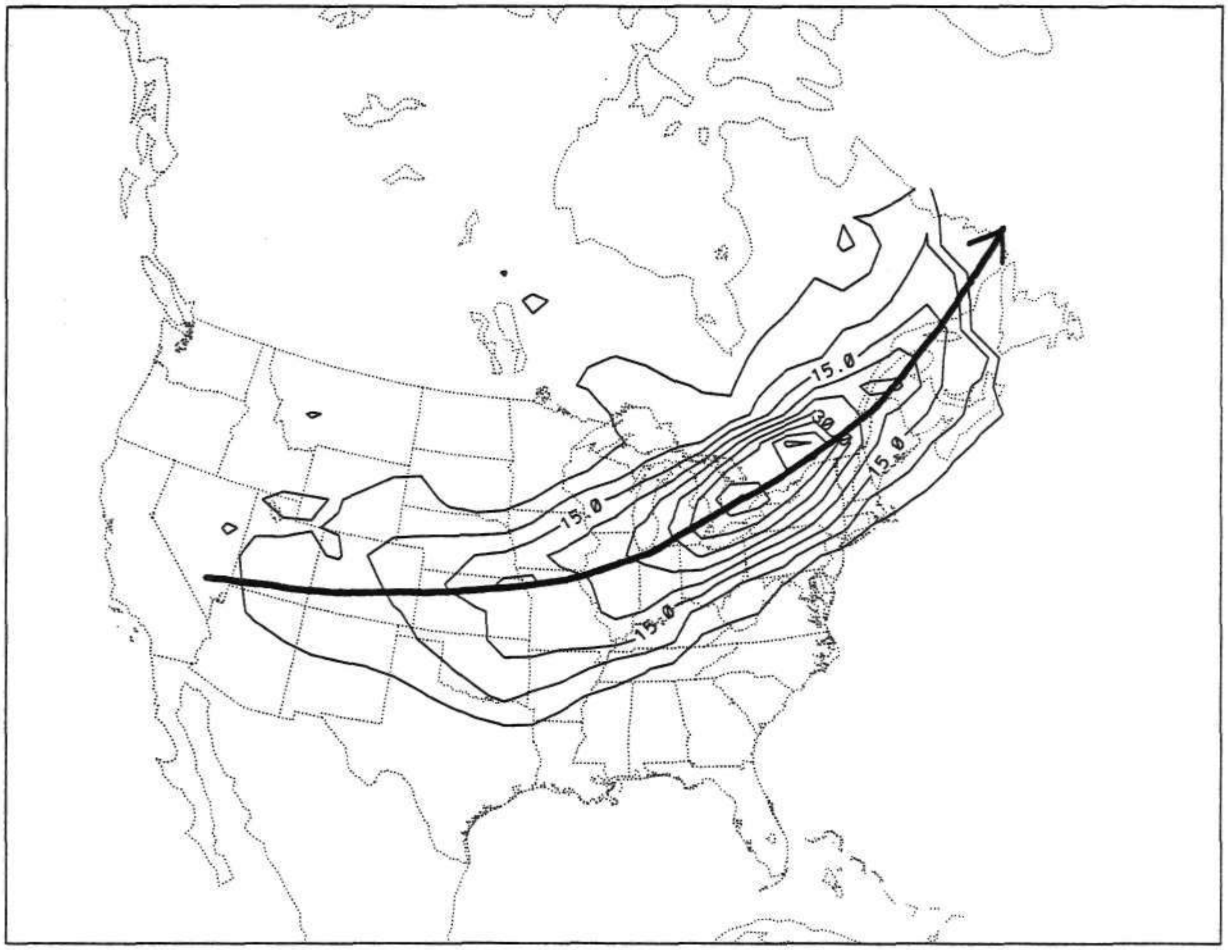


Fig. 7.5(a). Frequency of strong summer cyclones for the Superior region.

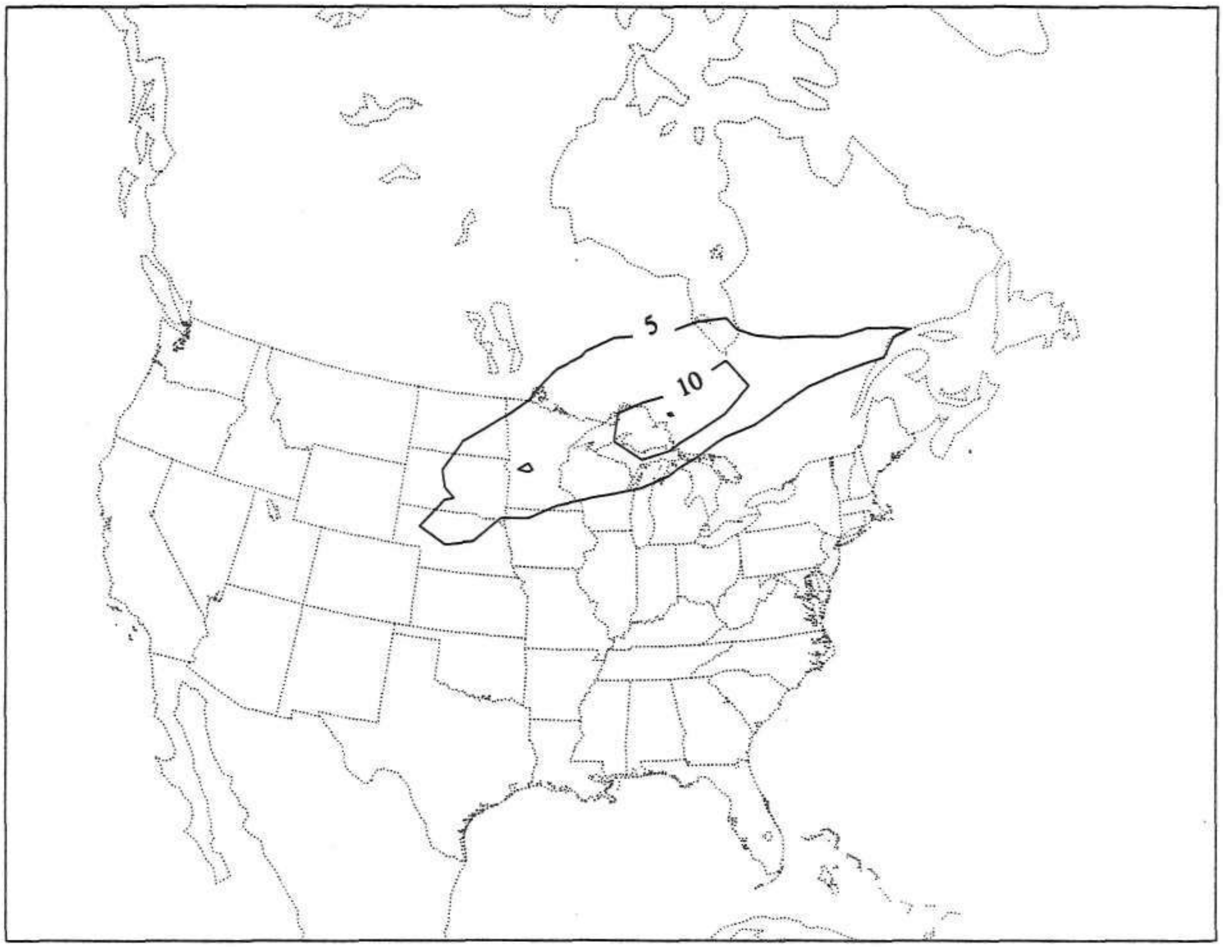


Fig. 7.5(b). Frequency of strong summer cyclones for the Michigan-Huron-St.Clair region.

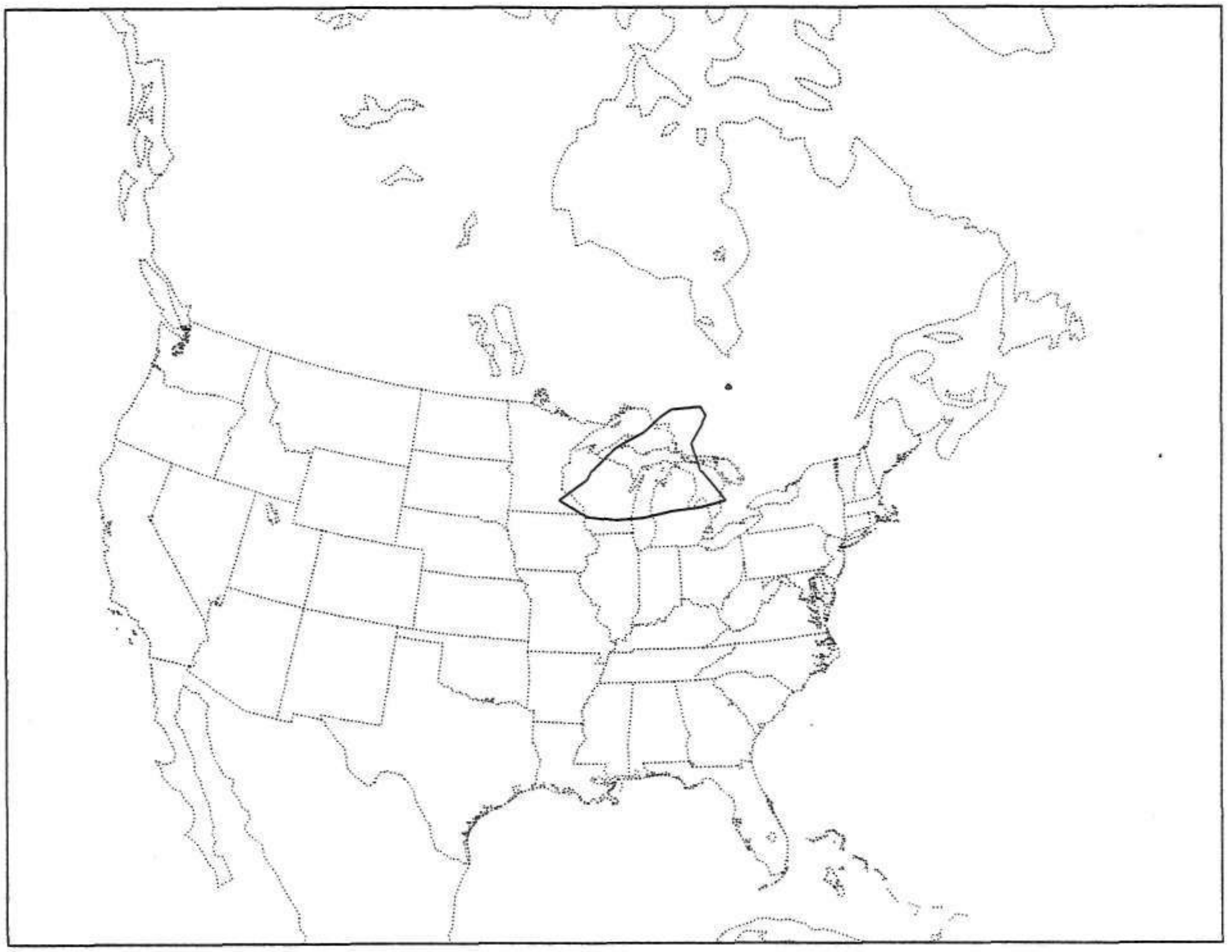


Fig. 7.5(c). Frequency of strong summer cyclones for the Erie-Ontario region.

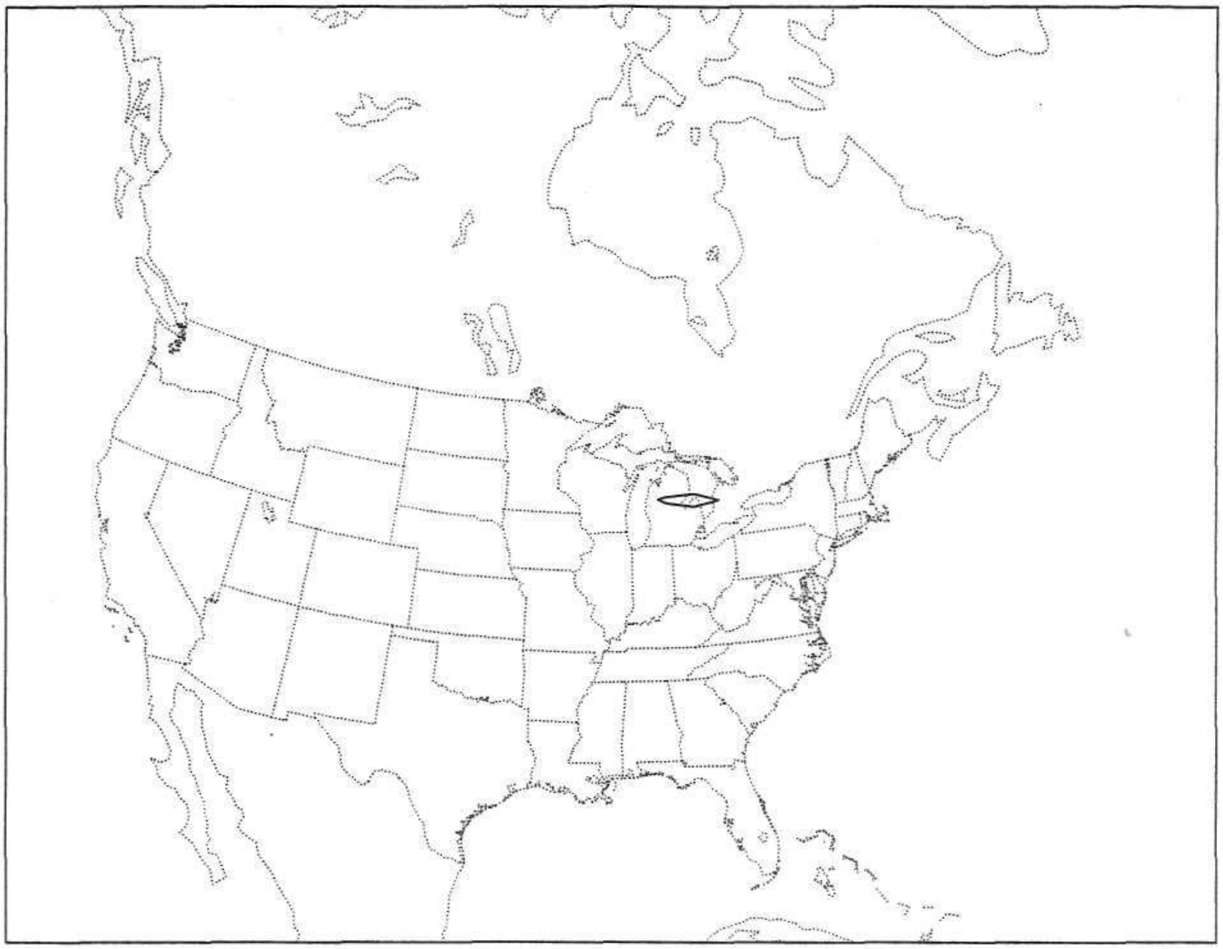


Fig. 7.6(a). Frequency of strong fall cyclones for the Superior region. Solid lines indicate the primary tracks along the axes of high frequency.

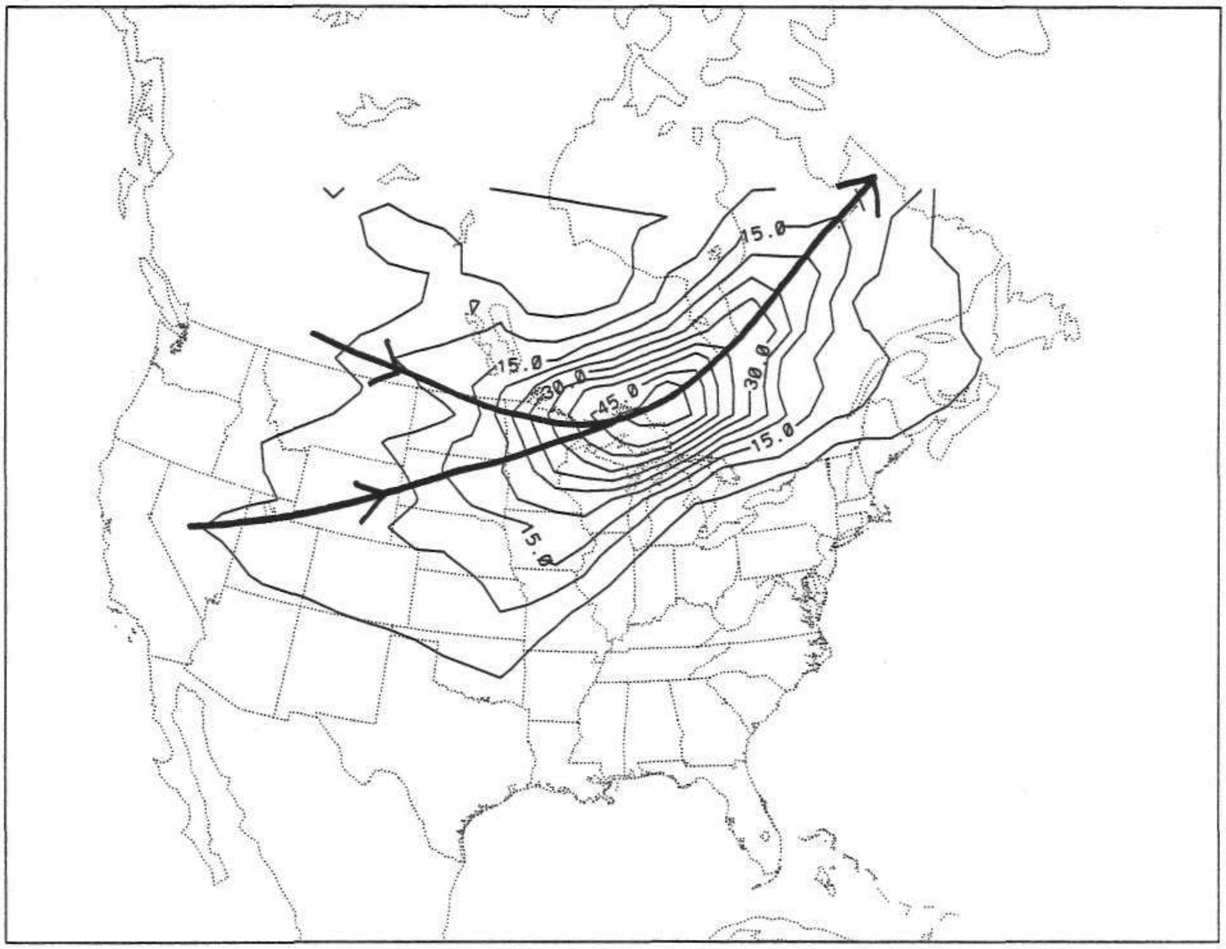


Fig. 7.6(b). Frequency of strong fall cyclones for the Michigan-Huron-St.Clair region. Solid lines indicate the primary tracks along the axes of high frequency.

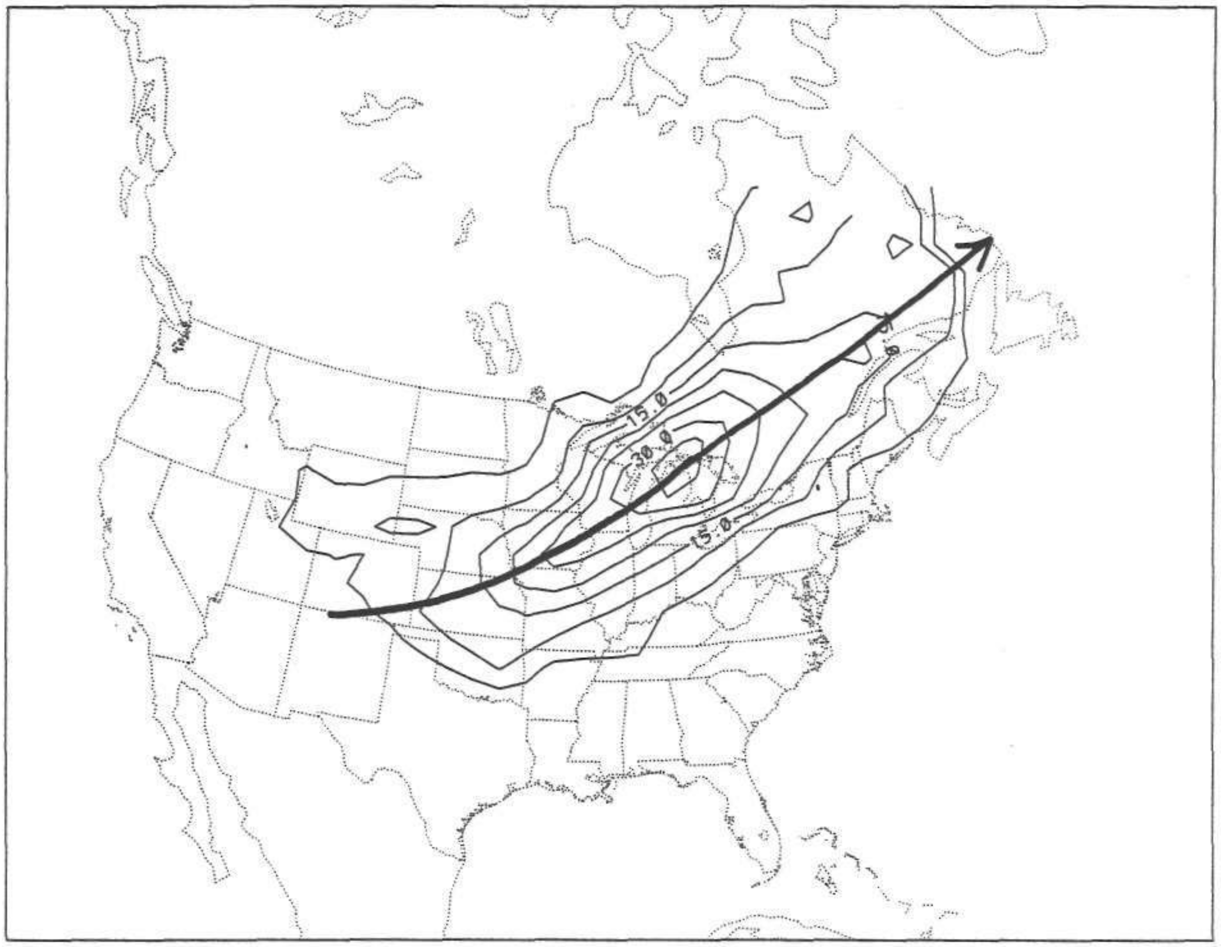
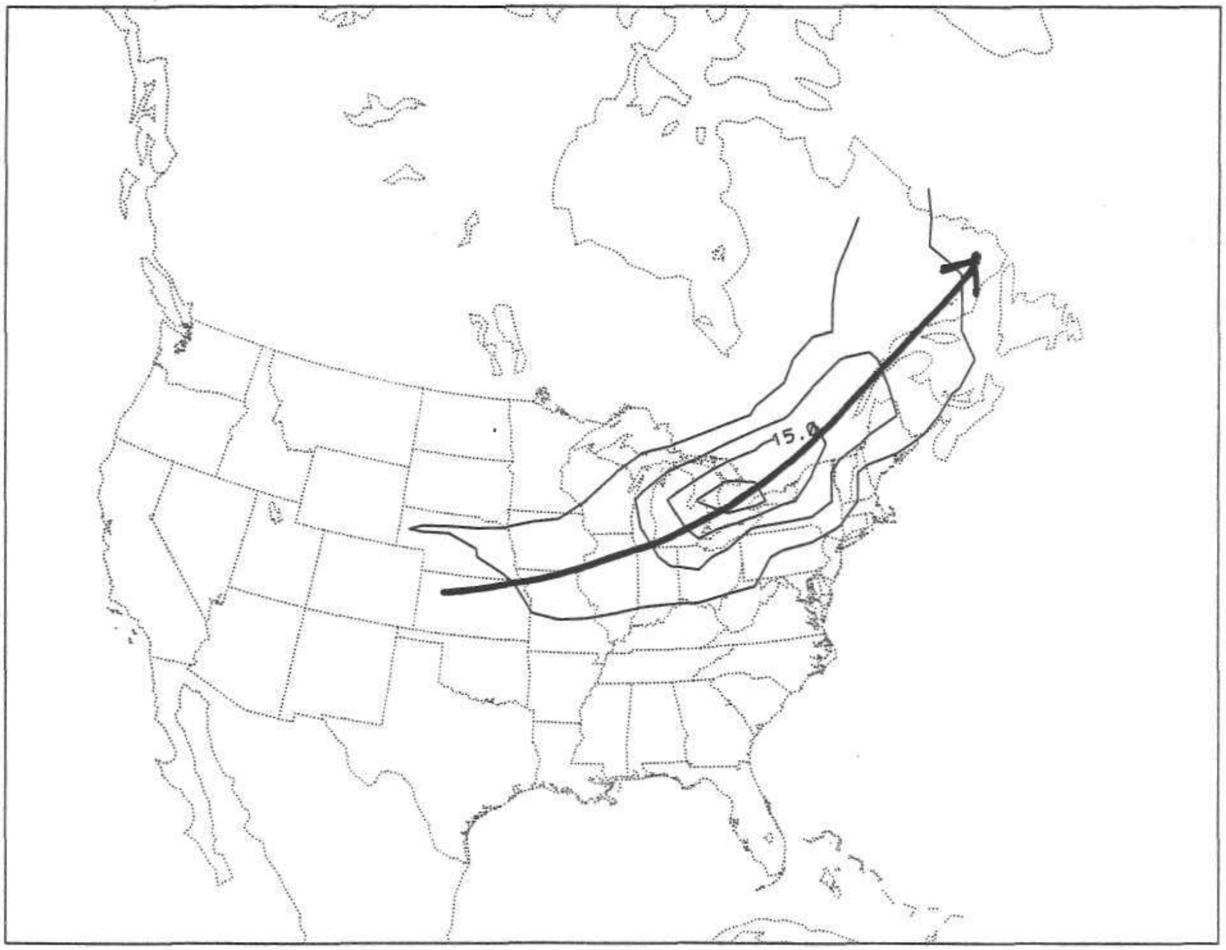


Fig. 7.6(c). Frequency of strong fall cyclones for the Erie-Ontario region. Solid lines indicate the primary tracks along the axes of high frequency.



Spatial Changes in Cyclone Frequency over Time

Results in Chapter 4 suggest that strong cyclone frequency in the Great Lakes region increased through the 20th century. In an attempt to define the spatial nature of these changes, the strong cyclones are divided into two periods, 1901 to 1945 and 1946 to 1990. The data are then processed using the Changnon et al. (1995) method, just as before, and the counts are subtracted between the two periods to detect any differences. Positive values show an increase in strong cyclone frequency over time.

For winter, an increase is found in the strong cyclone frequency for an elongated area from Montana to the Hudson Bay (Fig 7.7a). Using a two-tailed *t-test*, some grid points show statistically significant change at the 5% confidence level (denoted by asterisks on the map). Areas of decrease over time are also found in the western region of the U.S. (Idaho, Nevada, Utah, and Colorado) and in the northeastern U.S. and the maritime provinces of Canada. This suggests that the Alberta cyclone track has become more active in the last 45 years for winter, while the Colorado and east coast cyclones have become less active.

For spring, an area of increased strong cyclone frequency is noted from the upper Midwest through the Hudson Bay (Fig. 7.7b). One area with decreases is the Utah-Colorado region. This agrees with the finding of Bierly and Harrington (1995) that transition season (spring and fall) cyclone activity in the Colorado region has declined over time. At the same time, increased activity occurred from Nebraska eastward, suggesting a shift in cyclogenesis to the east along this track. Other areas with decreases are the prairie provinces of Canada, and the maritime provinces of Canada. There are no noteworthy changes between the 1901-1945 and 1946-1990 time periods for summer (Fig. 7.7c). For fall, a large area of increases over time is seen extending from Montana-South Dakota through the upper Midwest and into the Hudson Bay region. An area of decreased strong cyclone frequency is noted in the maritime provinces of Canada (Fig. 7.7d).

Fig. 7.7(a). Changes in the strong cyclone frequency from 1901-45 to 1946-90 for winter for the Great Lakes region. Solid contours indicate increases in frequency. Dashed contours indicate decreases in frequency. Asterisks indicate grid points with significant changes at the 5% level according to a two-tailed *t-test*.

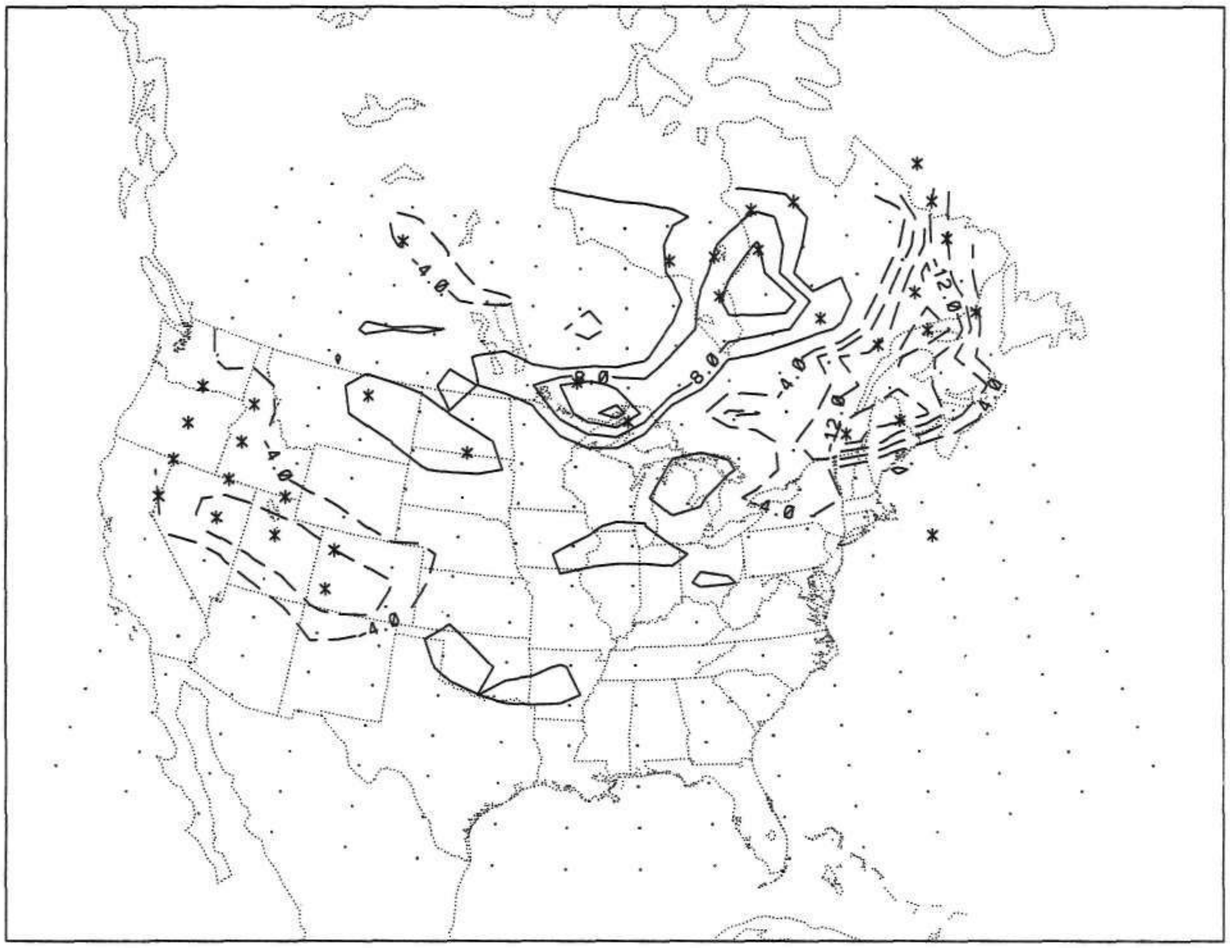


Fig. 7.7(b). Changes in the strong cyclone frequency from 1901-45 to 1946-90 for spring for the Great Lakes region. Solid contours indicate increases in frequency. Dashed contours indicate decreases in frequency. Asterisks indicate grid points with significant changes at the 5% level according to a two-tailed *t-test*.

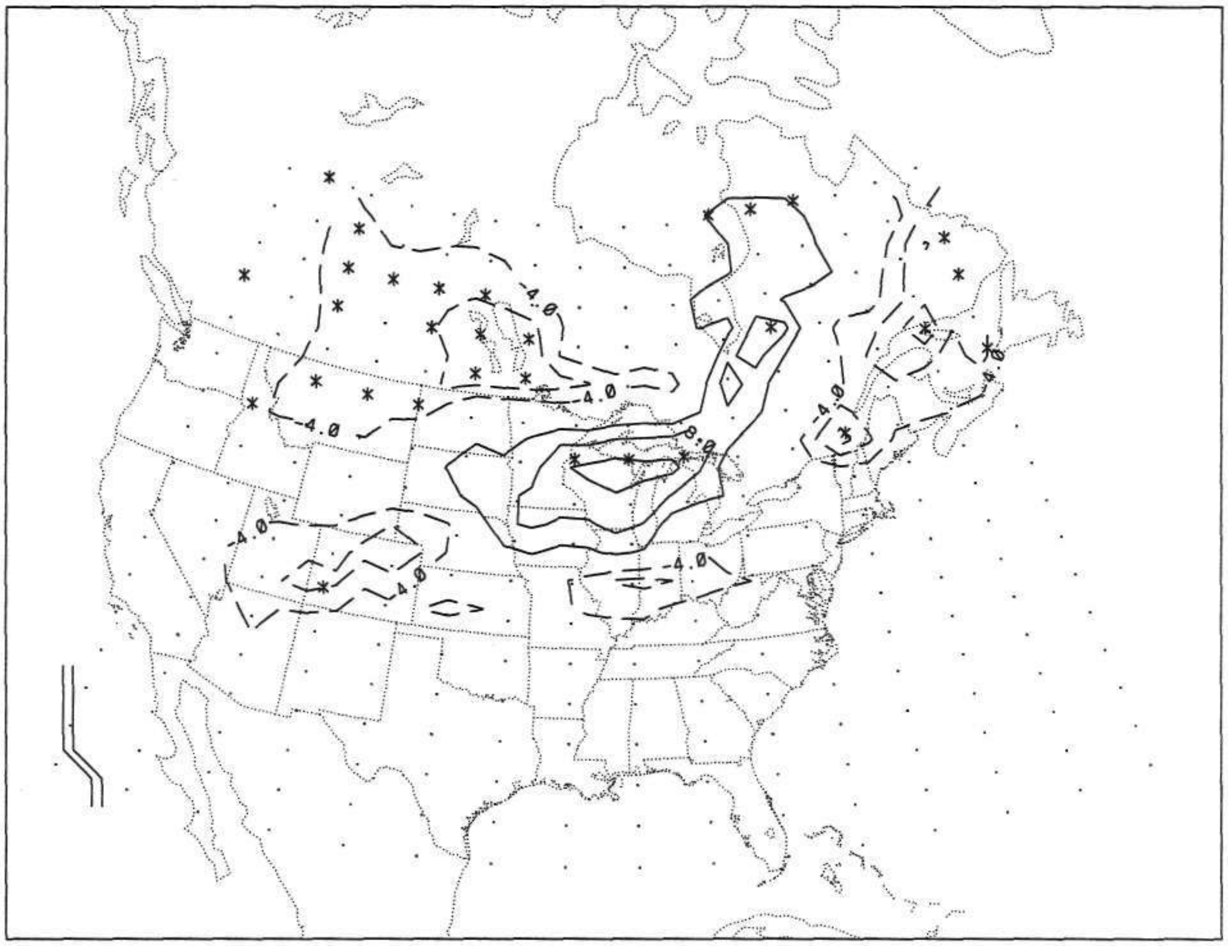


Fig. 7.7(c). Changes in the strong cyclone frequency from 1901-45 to 1946-90 for summer for the Great Lakes region. Solid contours indicate increases in frequency. Dashed contours indicate decreases in frequency. Asterisks indicate grid points with significant changes at the *5%* level according to a two-tailed *t-test*.

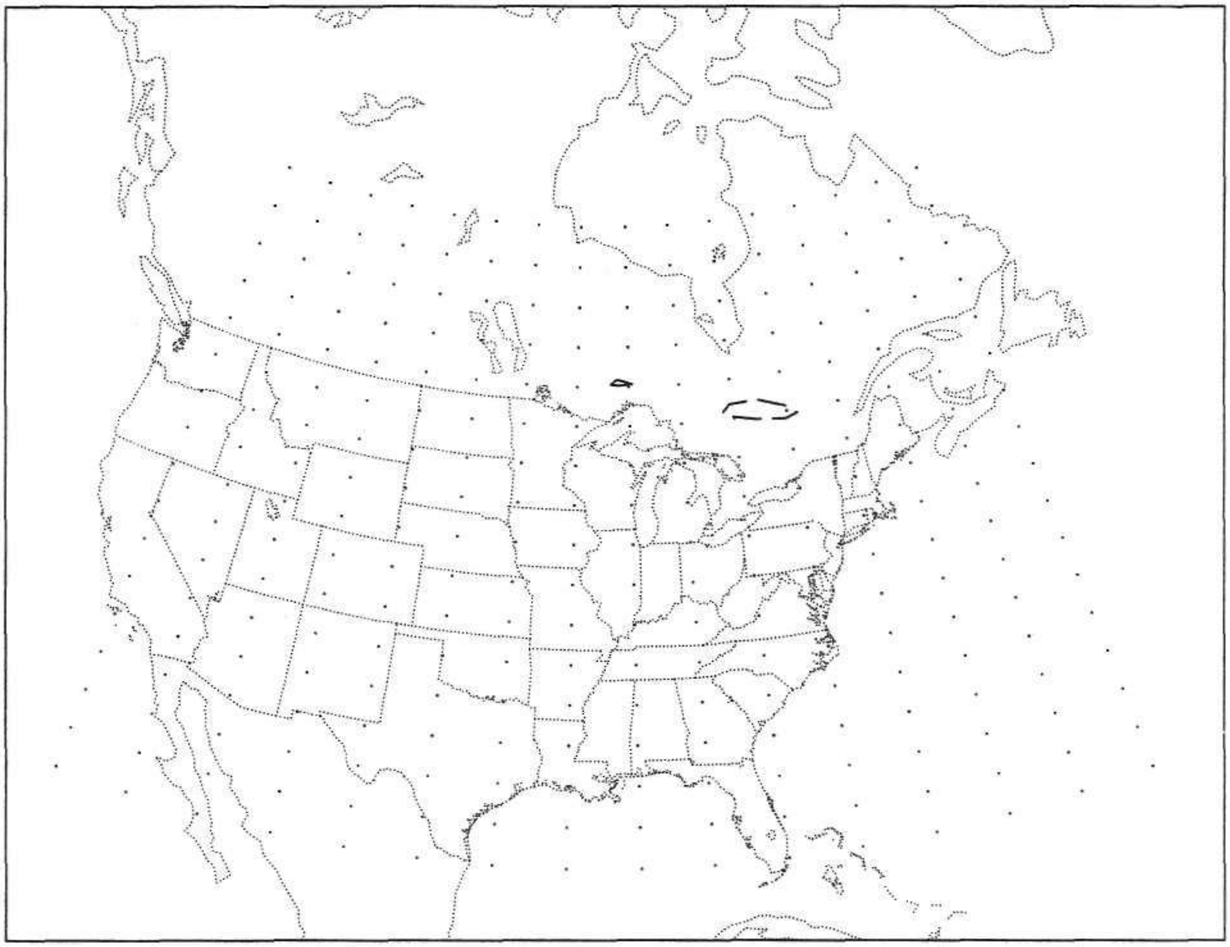
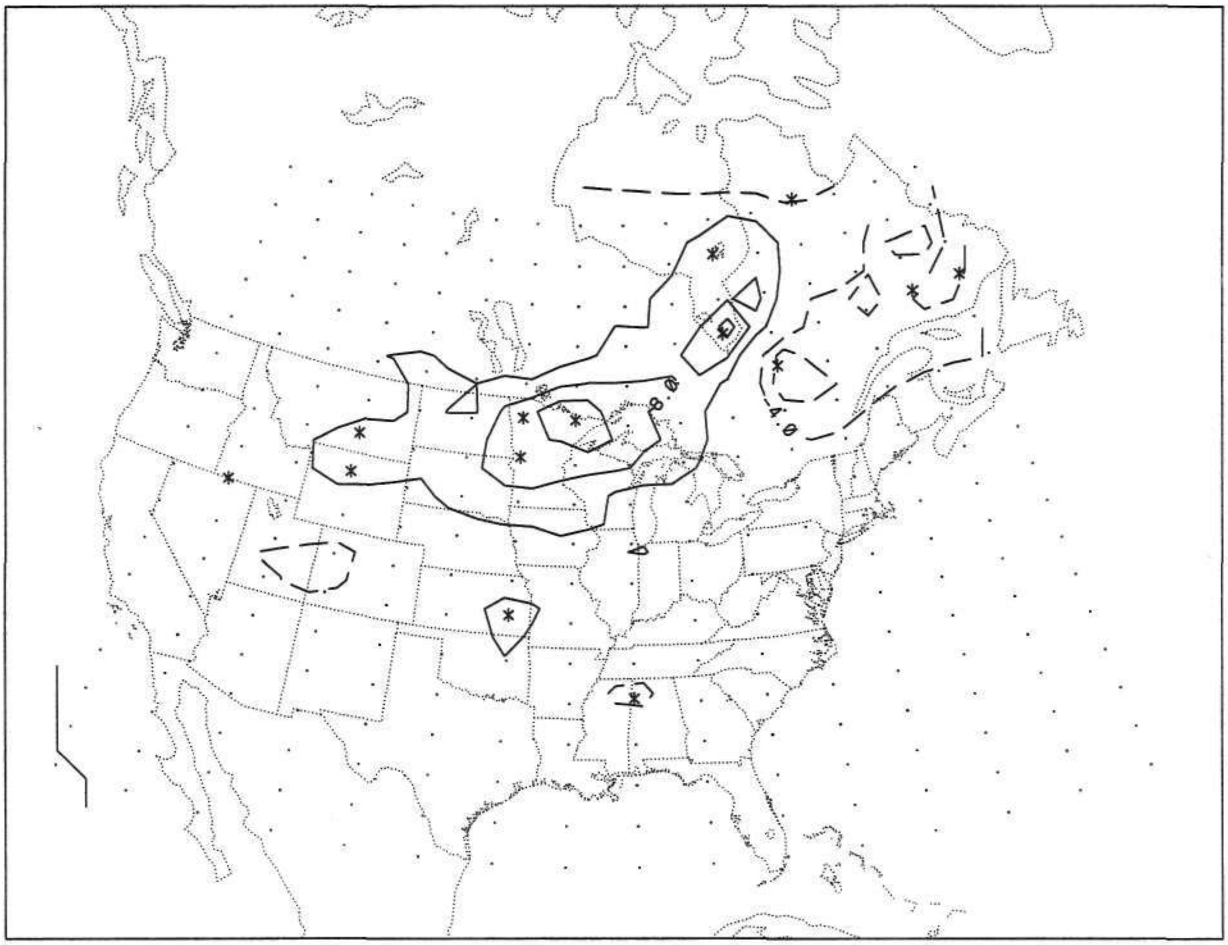


Fig. 7.7(d). Changes in the strong cyclone frequency from 1901-45 to 1946-90 for fall for the Great Lakes region. Solid contours indicate increases in frequency. Dashed contours indicate decreases in frequency. Asterisks indicate grid points with significant changes at the 5% level according to a two-tailed *t-test*.



Discussion of Results

The approach used by Changnon et al. (1995) is employed to summarize the strong cyclone tracks from 1900 to 1990. The dominant incoming tracks are from the Colorado-Utah region and Alberta in Canada. This agrees with the results of earlier studies of all cyclones in North America and the results of Harman et al. (1980) for the western Great Lakes. After passing over the Great Lakes region, the dominant track passes through the Canadian provinces of Ontario and Quebec. Dividing the Great Lakes region into three subregions (Superior, Michigan-Huron-St.Clair, and Erie-Ontario), the tracks in the three subregions are similar for winter. For spring and fall, the Michigan-Huron-St.Clair and Erie-Ontario region do not show the Alberta track.

For the entire Great Lakes region, the cyclones are evenly divided between the two major source regions of Colorado and Alberta. However, the western Great Lakes (Lake Superior) is dominated by the Alberta track, while the middle and eastern regions of the Great Lakes are dominated by the Colorado track.

Regarding changes in cyclone activity between 1901-1945 and 1946-1990 time periods, three features are outstanding: a) an area of decrease in the strong cyclone frequency along the eastern coast of Canada and Maine, b) an increase in strong cyclone activity across the upper Midwest and into the Hudson Bay area, and c) a decrease in frequency of strong cyclones in the west central portion of the U.S. This suggests a shift in frequency away from the earlier source regions for Great Lakes cyclones of Alberta and Colorado over the last 45 years. In addition, the cyclones that pass over the Great Lakes region generally track further north over eastern Canada than they did in the 1901-1945 period.

8. THE EFFECT OF THE GREAT LAKES ON PASSING CYCLONES

Introduction

Large inland water bodies such as the Great Lakes can strongly influence the weather systems in their vicinity (Petterssen and Calabrese 1959), and when the lakes intensify passing cyclones, the effect can extend far downstream in the atmosphere (Fritsch et al. 1989). This influence is attributed primarily to differential heating between water and land. Because the surface waters of large lakes warm and cool more slowly than surrounding land surfaces, the Great Lakes are either cooler or warmer than the air advecting over them for long periods each year. The period when surface water temperature is warmer than that of the overlying air is called the unstable season because the relatively warm water provides sensible and latent heat, which intensify vertical motions within overlying airmasses (Eichenlaub 1979). The unstable season in the Great Lakes region varies from lake to lake due to size and latitude. Generally, it extends from September to February or until the lake surface water freezes. The remainder of the year, when the temperature of the surface water in the lakes is cooler than that of the air advected over them, is considered the stable season. The lake water cools the air immediately above its surface, decreasing the lapse rate of temperature in the overlying airmasses and often causing inversions. During the stable season, the Great Lakes are not considered an important source of energy for passing cyclones (Eichenlaub 1979).

While lake-effect snowstorms are well-known and have been studied extensively (e.g., Reinking et al. 1993), few studies have examined the larger scale effects of the Great Lakes on passing weather systems. Cox (1917) was one of the first to note that the Great Lakes amplify low pressure centers that pass over them in winter. Petterssen and Calabrese (1959) stated that in a steady- state situation, when no other processes were active, the Great Lakes would provide enough heat to the overlying air mass, in winter, to result in horizontal convergence of air near the lakes' surface and lead to the development of cyclonic circulation. They calculated the pressure field corresponding to rotational motion and compared it with the actual surface pressure fields for two case studies of cyclones. The contribution of the warming by the Great Lakes to the passing cyclone appeared to account for a 6 mb drop in the surface pressure field.

Danard and Rao (1972) simulated the intense cyclone of February 24-26,1965 with a mesoscale (8-layers with 190 km grid spacing) primitive equation model, both with and without the Great Lakes present. A comparison of the Lake and No-Lake model runs showed a 1000 mb height difference of 70 m over the Great Lakes. They noted that this is comparable to the 6 mb drop in the surface pressure field calculated by Petterssen and Calabrese (1959). For the situation where cold dry air is advected over relatively warm waters, their model indicated that the Great Lakes can contribute to cyclone intensification in three important ways. First, the warm Great Lakes emit radiant energy to the air passing above them. Second, they provide sensible heat to the air. Finally, the Great Lakes provide water vapor (latent heat) to the airmass that acts to intensify the cyclone when the water vapor condenses.

Danard and McMillan (1974) refined the Danard and Rao (1972) model by improving the treatment of the heat and water vapor fluxes and incorporating a more sophisticated parameterization of the earth's surface (amount of land/water in each grid cell). These changes reduced the influence of the Great Lakes on passing cyclones. For the February 24-26,1965, cyclone case study, the differences in 1000 mb heights between Lake and No Lake model runs decreased to 27 m, equivalent to a 2 mb drop in the surface pressure field.

Boudra (1981) used a primitive equation model of higher resolution (45 km grid spacing with 15 layers) to examine the meteorological effects that the Great Lakes have on the atmosphere in early winter. In a case study of the December 9-10,1977 cyclone, a drop of 4.5 mb in the surface pressure field was attributed to the influence of the Great Lakes on the passing storm.

Fritsch et al. (1989) used both surface observations and model data to show how the Great Lakes can alter the strength and path of relatively weak cyclones as they pass through the region. In a case study of the period November 14-15,1992, the cyclone center advanced rapidly to the Great Lakes region from the southwest, slowed over the lakes, and then accelerated again as it moved away from the lakes and into eastern Canada. In contrast, the model run with the Limited Fine Mesh (LFM) model, which does not explicitly include the Great Lakes, moved the November 14-15,1992, cyclone at a more uniform speed across the region.

Sousounis and Fritsch (1994) used a high-resolution (30 km grid spacing with 36 levels) numerical model to examine the combined effect of all five Great Lakes on passing cyclones. Model simulations, using a Lake/No-Lake scheme, for the November 14-15,1992, cyclone case study confirmed the results of the earlier Fritsch et al. (1989) study. As the cyclone approached the Great Lakes, it accelerated rapidly into the region, slowed for 12 hours and deepened by 5 mb over the lakes before moving to the east. The authors noted that this disturbance of low-level flow with the addition of sensible and latent heat from the Great Lakes exerted a secondary (weak) influence that continued over the East Coast.

Unfortunately, the conclusions of these studies were based on a total of five cyclones (one in November, one in December, and three in February). While it was speculated by Fritsch et al. (1989) that the influence of the Great Lakes is largest on the weaker cyclones, no conclusions can be drawn from such a small sample. Nor can conclusions be drawn about the change in the influence of the Great Lakes throughout the year.

Data and Methodology

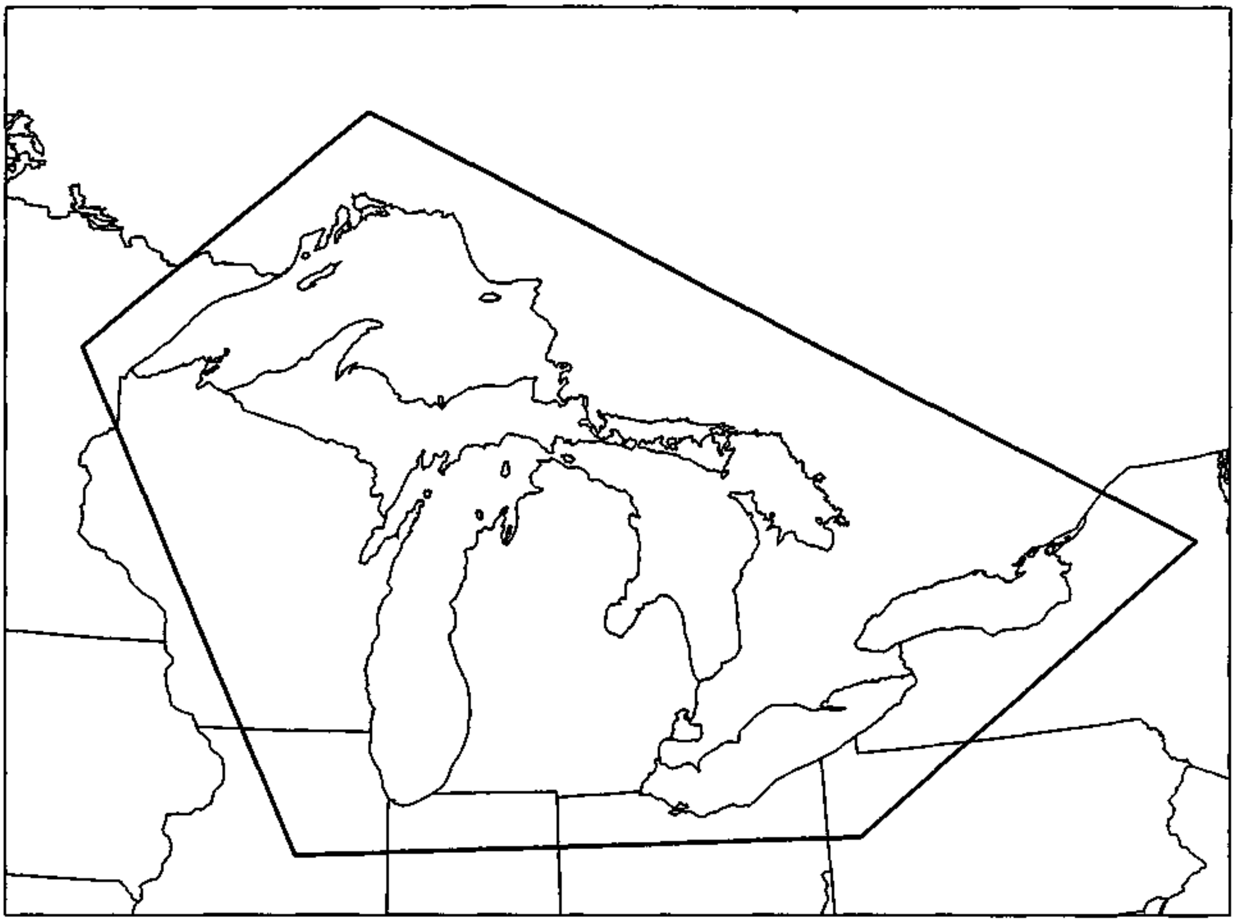
This chapter will evaluate the hypothesis that the Great Lakes exert a systematic influence on passing cyclones. Previous observation and modeling case studies suggest that during the unstable season cyclones: 1) accelerate into the region, 2) intensify within the Great Lakes region, 3) slow down within the region, 4) accelerate after leaving the region, and 5) return to lower cyclone deepening rates after leaving the region. During the stable season, cyclone: 6) speed should be maintained while passing through the region, and 7) pressure should remain steady or weaken (rise) while passing over the Great Lakes. The high temporal resolution digital dataset of cyclones from 1965 to 1990 (see Chapter 3) is used to examine the effect of the Great Lakes on all passing cyclones. This dataset provides location, central pressure, and cyclone speed at 6-hr intervals as the cyclones approach and pass over the Great Lakes region.

For this analysis, the Great Lakes region is redefined from previous chapters in a way that includes all of the surface water while excluding most of the land surface in the basin (Fig. 8.1). The focus is on the Great Lakes region as a whole and not the land-water interactions of the individual lakes for two reasons. First, the typical diameter (measured within the area of closed isobars) of cyclones passing over the Great Lakes is on the order of 1000 km. Therefore, at any particular time, a cyclone can be influenced by more than one lake. Second, Sousounis and Fritsch (1994) found in their model simulation that the influence of the Great Lakes manifest itself in the form of a 4 km deep, 2000 km wide, lake-aggregate disturbance. Therefore, only the larger scale effects will be examined here.

The influence of the Great Lakes will be evaluated by comparing differences between observations outside and inside the Great Lakes region in cyclone speed (distance traveled with respect to time) and in the cyclone deepening rate (change of central pressure with respect to time). Differences in cyclone deepening rates is selected over differences in cyclone pressure because many cyclones passing over the Great Lakes are already deepening to some extent. Therefore, the influence of the Great Lakes would not be to cause a cyclone to deepen, but to deepen at a greater rate than before. In some cases, a cyclone entering the region may be filling (an increase in central pressure with respect to time) and the Great Lakes may cause the filling to decrease or change signs and start to deepen, as will be shown. The cyclone deepening rate, AP/At, is measured in mb per day, an unusual At, but it better corresponds to the observational time interval.

Seven measures are constructed to evaluate the effect of the Great Lakes on passing cyclones that correspond to the seven components (propositions) of the hypothesis specified above. The first measure is related to the acceleration of the cyclone before entry into the region and is computed as the difference between the cyclone speed of the second to the last observation before entry and the last observation before entry into the region. The last two observations before entry are chosen because the results of Sousounis and Fritsch (1994) indicate that the cyclone acceleration occurs in the 3 to 6 hours prior to entry into the Great Lakes region. The second measure is an index of the change in the cyclone deepening rate as the cyclone passes over the Great Lakes calculated as the difference between the cyclone deepening rate in the last observation before entry into the region and the largest observed cyclone deepening rate that occurred in the region. The third measure is related to the change in speed of the cyclone as it enters into the region and is computed as the difference between the speed in the last observation before entry and the lowest 6-hour speed inside the Great Lakes region. The fourth measure is related to the acceleration of the cyclone after leaving the region and is computed as the difference between the lowest observation of speed within the region and the second observation

Fig. 8.1. A more restrictive definition of the Great Lakes region than in previous chapters.



after exiting the Great Lakes region. With an average distance of 320 km between the first observation and second observation after leaving the area, it is likely that the cyclones are largely beyond the influence of the Great Lakes by the second observation after leaving the region. The fifth measure is related to the maintenance of the cyclone deepening rate after leaving the region and is computed as the difference between the largest observed change in central pressure within the region and the second observation after exiting the Great Lakes region. The sixth measure is related to the influence of the Great Lakes on cyclone speed during the stable season. This measure is computed as the difference between the cyclone speed of the last observation before entry into the region and the lowest cyclone speed within the Great Lakes region. The seventh measure is related to the cyclone deepening rate during the stable season. It is computed as the difference between the cyclone deepening rate of the last observation before entry into the region and the largest cyclone deepening rate within the Great Lakes region. The statistical significance of each of these measures of the effect of the Great Lakes on passing cyclones is evaluated using the *t-test* at the 95% confidence level ($\alpha=0.05$).

To evaluate the hypothesis that the Great Lakes have a systematic effect on passing cyclones, the dataset is classified in different ways. The unstable season is defined as September to February and the stable season is defined as March through June. Due to the small number of cyclones, July and August are not included in the analysis.

The first division of the data is by strength of the cyclone using the threshold developed in Chapter 3. Cyclones exhibiting a central pressure ≤992 mb over the Great Lakes are classified as strong. Alternatively, all cyclones exhibiting a central pressure >992 mb are considered weak. Using this system for the period 1965 to 1990, 122 cyclones are classified as strong and 324 cyclones are classified as weak during the unstable season. During the stable season, 49 cyclones are classified as strong and 217 cyclones are classified as weak.

The second division of the data is between the cyclones that developed north of 43 °N and those that developed south of 43°N. This classification differentiates between those cyclones originating in the Alberta region of Canada and those originating in the Colorado/southwestern U.S. region, as noted in Chapter 7. This division yields 243 and 203 cases for all cyclones of the two source regions respectively for the unstable season. For convenience, cyclones that originate poleward of 43°N are referred to as Alberta cyclones, while those that originate equatorward of 43 °N are referred to as Colorado cyclones. For the stable season, 119 cyclones are classified as Alberta cyclones, and 147 are classified as Colorado cyclones.

The third division of all the data is by month. During the unstable season, this classification yields 51, 63, 86, 93, 95, and 58 cyclones for the months of September through February respectively. During the stable season, this classification yields 76, 68, 63, and 59 cyclones for the months of March through June respectively.

a) Acceleration of Cyclones into the Great Lakes Region during the Unstable Season

To examine the proposition that cyclones accelerate into the Great Lakes region in late fall and winter, the speed of the second to last observation before entry into the Great Lakes region is compared with the speed of the last observation before entry. The results of this analysis are presented in Table 8.1 classified by cyclone strength, source region, and month, as defined earlier.

Statistically significant increases (α=0.05) in cyclone speed are found for weak cyclones (+2.0 m/s), Alberta cyclones (+1.5 m/s), and Colorado cyclones (+2.2 m/s) as they approach the Great Lakes during the unstable season. While the speed of strong ($\leq$992 mb) cyclones increase as they approach the Great Lakes region, these accelerations are not statistically significant. Statistically significant increases in speed are also found for cyclones that pass over the Great Lakes in September (+3.2 m/s) and November (+2.1 m/s) when all categories of cyclones are included in the analysis. Although not statistically significant, increases in speed are noted for the remaining unstable months of October, December, January, and February. The average increases in the speed of cyclones as they approached the Great Lakes region is 2.0 m/s during the unstable season.

b) Increased Intensification within the Great Lakes Region during the Unstable Season

The results of the comparison of the differences in cyclone deepening rates of the last observation before entry and while they are in the Great Lakes region during fall and winter can be found in Table 8.2. The differences in the cyclone deepening rate in the Great Lakes region show increased deepening that is statistically significant for strong cyclones (-3.9 mb per day), for weak cyclones (-5.6 mb per day), for Alberta cyclones (-5.3 mb per day) and for Colorado cyclones (-5.0 mb per day), thus supporting the proposition that cyclones intensify more rapidly over the Great Lakes in fall and winter. The cyclone deepening rate of cyclones (all strength and source region categories) increases by a statistically significant amount as they entered the Great Lakes region for every month during the unstable season. The average difference in the cyclone deepening rate for all cyclones during the unstable season is an increased deepening of 5.2 mb per day.

Table 8.1. A comparison of cyclone speeds (m/s) of the second to the last observation and the last observation before entry into the Great Lakes region during the unstable season. Bold indicates a significant change at the 5% significance level.

Category	Number of Cyclones	Second to last observation before entry	Last observation before entry	Difference
Strength (regardless of region or month)				
Strong Cyclones (central pressure ≤ 992 mb)	122	14.0	15.6	+1.5
Weak Cyclones (central pressure > 992 mb)	324	12.0	14.0	+2.0
Region (regardless of strength or month)				
Alberta Cyclones	243	13.2	14.8	+1.5
Colorado Cyclones	203	11.8	14.0	+2.2
Month (regardless of strength or region)				
September	51	8.6	11.9	+3.2
October	63	11.1	12.9	+1.9
November	86	12.6	14.8	+2.1
December	93	13.7	14.2	+0.6
January	95	13.8	15.7	+1.9
February	58	13.8	15.9	+2.2

Table 8.2. A comparison of cyclone pressure deepening rate in mb/day between the last observation before entry into the Great Lakes region with the lowest 6-hour observation within the region during the unstable season. Bold indicates a significant change at the 5% significance level. A negative difference indicates an increase in the rate of deepening.

Category	Number of Cyclones	Entering Region	Within Region	Difference
	Strength (regardless of region or month)			
Strong Cyclones (central pressure ≤ 992 mb)	122	-7.8	-11.7	-3.9
Weak Cyclones (central pressure > 992 mb)	324	-0.1	-5.7	-5.6
	Region (regardless of strength or month)			
Alberta Cyclones	243	-0.8	-6.1	-5.3
Colorado Cyclones	203	-4.0	-8.9	-4.9
	Month (regardless of strength or region)			
September	51	-0.8	-6.2	-5.4
October	63	-2.5	-7.6	-5.1
November	86	-2.6	-7.8	-5.2
December	93	-2.4	-7.5	-5.1
January	95	-2.2	-7.4	-5.2
February	58	-2.2	-7.4	-5.2

Table 8.3. A comparison of cyclone speeds (m/s) of the last observation before entry into the Great Lakes region with the lowest 6-hour observation within the region during the unstable season. Bold indicates a significant change at the 5% significance level.

Category	Number of Cyclones	Entering Region	Within Region	Difference
Strength (regardless of region or month)				
Strong Cyclones (central pressure ≤ 992 mb)	122	15.6	12.6	-2.9
Weak Cyclones (central pressure > 992 mb)	324	14.0	12.6	-*13*
Region (regardless of strength or month)				
Alberta Cyclones	243	14.8	12.0	-2.7
Colorado Cyclones	203	14.0	13.8	-0.6
Month (regardless of strength or region)				
September	51	11.9	10.6	-1.2
October	63	12.9	10.7	-2.2
November	86	14.8	13.0	-1.7
December	93	14.2	13.4	-0.8
January	95	15.7	13.6	-2.1
February	58	15.9	13.0	-2.9

c) Decrease in Cyclone Speed within the Great Lakes Region during the Unstable Season

The speed of cyclone movement in the last observation before entry into the Great Lakes region is compared with the lowest cyclone speed while the storm is within the region to evaluate the proposition that these storms linger in the Great Lakes region. The results are shown in Table 8.3. For strong cyclones, weak cyclones, Alberta cyclones and Colorado cyclones the average speed of the cyclones decreases by 2.9, 1.3, 2.7, and 0.6 m/s in the Great Lakes region respectively. Only the results for Colorado cyclones are not statistically significant.

The speed of cyclone movement (all strengths and source region categories) decreases as they enter the Great Lakes region for every month during the unstable season. However, only the decreases for October (-2.2 m/s), November (-1.7 m/s), January (-2.1 m/s), and February (-2.9 m/s) are statistically significant. The average decrease in speed of cyclone movement for all cyclones is 1.9 m/s.

Table 8.4. A comparison of cyclone speed (m/s) of the lowest 6-hour observation within the region with the second observation after exiting the Great Lakes region during the unstable season. Bold indicates a significant change at the 5% significance level.

Category	Number of Cyclones	Within Region	Exiting Region	Difference
Strength (regardless of region or month)				
Strong Cyclones (central pressure ≤ 992 mb)	122	12.6	14.1	+1.4
Weak Cyclones (central pressure > 992 mb)	324	12.6	14.9	+*23*
Region (regardless of strength or month)				
Alberta Cyclones	243	12.0	13.9	+1.9
Colorado Cyclones	203	13.4	15.6	+2.2
Month (regardless of strength or region)				
September	51	10.6	13.8	+3.1
October	63	10.7	12.4	+1.7
November	86	13.0	14.5	+1.5
December	93	13.4	15.0	+1.5
January	95	13.6	15.6	+2.0
February	58	13.0	16.1	+3.1

d) Acceleration of the Cyclones after Departing the Great Lakes Region during the Unstable Season

As mentioned above, cyclone speeds decrease in the Great Lakes region during fall and winter. The proposition that cyclone speed increases after departing the region is evaluated by comparing the lowest speed within the region with the speed in the second observation after the cyclone leaves the region (Table 8.4). Statistically significant increases in cyclone speed are found for both strong cyclones (+1.4 m/s) and weak cyclones (+2.3 m/s). Statistically significant increases are found for both Alberta cyclones (+1.9 m/s) and Colorado cyclones (+2.2 m/s). Statistically significant increases are also found for September (+3.1 m/s), January (+2.0 m/s), and February (+3.1 m/s). While not statistically significant, increases are noted in the remaining months of the unstable season. The average increase in cyclone speed after departing the region for all cyclones is 2.2 m/s.

Table 8.5. A comparison of cyclone pressure deepening rate in mb per day between the lowest 6-hour observation within the region and the second observation after exiting the Great Lakes region during the unstable season. Bold indicates a significant change at the 5% significance level. A positive difference indicates a decrease in the deepening rate after leaving the region.

Category	Number of Cyclones	Within Region	Exiting Region	Difference
Strength (regardless of region or month)				
Strong Cyclones (central pressure ≤ 992 mb)	122	-11.7	-0.4	113
Weak Cyclones (central pressure > 992 mb)	324	-5.7	-4.0	1.7
Region (regardless of strength or month)				
Alberta Cyclones	243	-6.1	-2.2	3.9
Colorado Cyclones	203	-8.9	-4.0	4.9
Month (regardless of strength or region)				
September	51	-6.2	-3.5	2.7
October	63	-7.5	-3.0	4.6
November	86	-7.8	-1.9	5.9
December	93	-7.5	-3.8	3.6
January	95	-7.4	-2.5	4.8
February	58	-7.4	-3.8	3.6

e) Return to Reduced Cyclone Deepening Rates after Departing the Great Lakes Region during the Unstable Season

The proposition that the cyclone deepening rate returns to a lower value after the storms depart the region and is no longer under the influence of the Great Lakes is evaluated by comparing the cyclone deepening rates within the region with that at the second observation after the cyclone left the Great Lakes region (Table 8.5). All divisions, except for September in the division by month, show a statistically significant decrease in the cyclone deepening rate after leaving the Great Lakes region. Except for the division by cyclone strength, the deepening rates after leaving the region are comparable to the rates before entering the region.

Table 8.6. A comparison of cyclone speeds (m/s) of the last observation before entry into the Great Lakes region with the lowest 6-hour observation within the region during the stable season. Bold indicates a significant change at the 5% significance level.

Category	Number of Cyclones	Entering Region	Within Region	Difference
Strength (regardless of region or month)				
Strong Cyclones (central pressure ≤ 992 mb)	49	12.5	10.4	-2.1
Weak Cyclones (central pressure > 992 mb)	217	12.4	11.5	-0.9
Region (regardless of strength or month)				
Alberta Cyclones	119	12.0	11.2	-0.8
Colorado Cyclones	147	12.7	11.4	-13
Month (regardless of strength or region)				
March	76	13.5	12.4	-1.1
April	68	13.2	10.2	-3.0
May	63	11.1	10.3	-0.5
June	59	11.5	11.9	-0.4

f) Changes in Cyclone Speed in the Great Lakes Region during the Stable Season

During the stable season, defined here as March through June, the Great Lakes should have little influence on the speed of passing cyclones. To test this proposition, cyclone speed of the last observation before entry into the region is compared with the lowest speed within the region (Table 8.6). The only statistically significant decreases in cyclone speed are for the Colorado cyclones (-1.3 m/s) and cyclones in April (-3.0 m/s). For all other divisions, there is a decline in cyclone speed over the Great Lakes but it is not statistically significant.

Table 8.7. A comparison of cyclone pressure deepening rate in mb per day between the observation just before entry into the Great Lakes region with the lowest 6-hour observation within the region during the stable season. Bold indicates a significant change at the 5% significance level. A negative difference indicates an increase in the rate of deepening.

Category	Number of Cyclones	Entering Region	Within Region	Difference
Strength (regardless of region or month)				
Strong Cyclones (central pressure ≤ 992 mb)	49	-7.1	-10.8	-3.7
Weak Cyclones (central pressure > 992 mb)	217	0.5	-4.5	-5.0
Region (regardless of strength or month)				
Alberta Cyclones	119	-0.3	-5.9	-5.6
Colorado Cyclones	147	-1.4	-5.4	-4.0
Month (regardless of strength or region)				
March	76	-1.6	-7.3	-5.6
April	68	-1.1	-6.0	-4.9
May	63	-0.2	-3.9	-3.7
June	59	-0.5	-5.1	-4.6

g) Changes in Cyclone Pressure in the Great Lakes Region during the Stable Season

The proposition that the Great Lakes weaken passing cyclones during the stable season is evaluated by comparing the cyclone deepening rates of the last observation before entering the Great Lakes region with the largest deepening rate within the region (Table 8.7). Statistically significant increases in cyclone deepening rate (i.e., increases in intensity) are found for both strong and weak cyclones, both Alberta and Colorado cyclones, and all months of the stable season. In general, the difference in the cyclone deepening rates are somewhat smaller than during the unstable season. In the case of weak cyclones, they were filling, on average, before entering the region and began to deepen significantly while in the region. These results indicate that the Great Lakes continue to have a major influence during the stable season.

Discussion of Results

Using cyclone data from 1965 to 1990 recorded at 6-hour intervals, seven propositions or components of the hypothesis that the Great Lakes exert a systematic influence on cyclones passing over them are examined. The first proposition is that cyclones accelerate as they enter the Great Lakes region. The acceleration was assessed by comparing cyclone speeds for the two observations just before entry into the Great Lakes region. Statistically significant accelerations are found for weak cyclones (>992 mb), for all cyclones along both the Alberta and Colorado tracks, and all cyclones during September and November. While not statistically significant, increases were noted in all the other divisions. This indicates that cyclones do accelerate into the region.

The second proposition tested is that cyclone deepening rates increase (cyclones intensify) while the cyclone is in the Great Lakes region. Statistically significant results were found in all divisions with differences on the order of 4.8 mb per day, indicating that the Great Lakes have a strong influence on pressure during the unstable season.

The third proposition evaluated is that cyclone speed decreases as the storms enter the Great Lakes region. The change in speed is examined by comparing cyclone speeds of the last observation before entry into the Great Lakes region with the lowest cyclone speeds inside the Great Lakes region. The results show that the decreases in cyclone speeds are statistically significant for most of the cyclone categories and changes range from 1.3 to 2.9 m/s (2.6 to 5.7 knots).

The fourth proposition tested is that the cyclones accelerate after departing the Great Lakes region. Statistically significant increases in departing cyclone speed are found for both strong and weak cyclone categories, for both Alberta and Colorado (all) cyclones categories, and for all cyclones that pass over the lakes during the months of September, January, and February. The increases in cyclone speed are comparable to the decreases in cyclone speed that occur upon entry into the region.

While these features have been noted in the case study of one cyclone (Fritsch et al., 1989) and in modeling studies of one or two cyclones (e.g., Sousounis and Fritsch, 1994), this is the first time that these features have been documented using a large sample (1965-1990) of historical data. The characteristics of the cyclone deepening rate after they depart the Great Lakes region and the speed and deepening rate of cyclones during the stable season have here-to-for not been examined.

The fifth proposition evaluated is that the increased cyclone deepening rate that occurred within the Great Lakes region is not maintained by the cyclones after departing from the region. The analysis showed that the cyclone deepening rate for all cyclones that occurs in fall and winter over the Great Lakes region returns to previous, lower deepening rates after they exit the region.

The sixth and seventh propositions assessed relate to the influence of the Great Lakes on passing cyclones during the stable season (March through June). The influence of the lakes on cyclone speed is minimal and only statistically significant for Colorado cyclones and for all cyclones in April.

The seventh proposition yields unexpected results. Instead of weakening cyclones during the stable season, the Great Lakes region appears to strengthen cyclones in nearly all cases. Statistically significant increases in cyclone deepening rates are found for both strong and weak cyclones, and for both Alberta and Colorado cyclones during the stable season. With the exception of September, the deepening rates increase significantly for each month in the stable season. These results are unexpected; however, Roebber (1989) found the same feature, cyclone deepening did not occur exclusively in the cold season, for oceanic cyclones that passed from land to ocean along the east coast of the United States.

A review of the literature on Great Lakes storms and those along the east coast of the United States yields a few plausible explanations for the influence of the lakes on passing cyclones during the stable season that warrant mentioning here. Lansing (1965) suggested that the Great Lakes is a source of energy for driving thunderstorms at night during the stable season when the lakes are warmer than the surrounding land. However, it is not clear whether or not the energy transferred from the lakes to the atmosphere at night is enough to enhance large-scale cyclones. Even during the last few hours of summer nights, the temperature of the surface water is only 1 to 2°C warmer than that of nearby land surfaces (Eichenlaub 1979) although the water-land surface temperature contrast may be much larger in particular cases (e.g., Lyons and Olsson 1973). Convergence along the lake-breeze fronts that move inland from the lakes during the stable season can intensify existing squall lines and thunderstorms (Simpson 1994). However, again it is not likely that this phenomenon is strong enough to intensify large-scale cyclones that traverse the Great Lakes. Finally, as a cyclone passes from land to water surfaces, the reduction in surface roughness and thus frictional drag decreases the dissipation of the kinetic energy of the lowest layer of the storm. The consequences of horizontal variations in frictional drag can enhance cyclogenesis (e.g., Petterssen and Smebye 1971, Bosart and Lin 1984, Carlson 1991), although the influences of changes in surface roughness on Great Lake cyclones has not been explored.

Fritsch el al. (1989) and Sousounis and Fritsch (1994) proposed that the Great Lakes have a greater influence on relatively weak cyclones than on the stronger cyclones that traverse the region. Weak cyclones appear to accelerate into and out of the region more than the strong cyclones during the unstable season, and have larger changes in their deepening rate in both the stable and unstable season. However, the strong cyclones (lowest central pressure in region ≤992mb) that passed over the Great Lakes during the unstable seasons between 1965 and 1990 slowed in the region more and their deepening rate decreased more upon departing the region than the weak cyclones (>992 mb). During the stable season, the strong cyclones also slowed in the region more than the weak cyclones.

The Great Lakes appear to influence Colorado cyclones differently than Alberta cyclones. During the unstable seasons between 1965 and 1990, Colorado cyclones accelerated into and out of the region to a greater extent than Alberta cyclones. The speed of Colorado cyclones slowed over the Great Lakes during the stable seasons as well. However, it should be noted that Colorado cyclones did not slow over the lakes during the unstable seasons as did the Alberta cyclones. In terms of changes in the deepening rates, the Great Lakes appear to have more of an influence on the Alberta cyclones, with these cyclones deepening at a greater rate than the Colorado cyclones. Finally, the results of this study suggest that the influence of the Great Lakes on the intensity and speed of passing cyclones does not change in a systematic manner as the unstable and stable seasons progress.

The results of this analysis strongly support the hypothesis that the Great Lakes have a major influence on passing cyclones during the unstable season. Although passing cyclones also intensify at a greater rate over the Great Lakes during the stable season, a satisfactory explanation for this phenomenon could not be found in the literature. Case studies and the diagnosis of a number of cyclones using models such as Sousounis and Fritsch (1994) are needed to find out what physical processes are causing cyclone deepening rates to increase over the Great Lakes during the stable season.

9. SUMMARY AND CONCLUSIONS

Purpose of Research

Cyclones are an important feature of the Great Lakes region. An examination of the literature suggests that cyclone frequency and intensity over the region have important impacts on precipitation, ice cover, thermal structure, and the water quality and aquatic life in the Great Lakes. Cyclone activity also affects the shipping industry on the lakes and causes property damage along their shores. The Great Lakes have an impact on passing cyclones, especially during winter when the air is cold and the lake waters are relatively warm. Case studies have shown that the energy that a passing cyclone gains from the Great Lakes in winter can alter a cyclone's speed and increase its intensity. For these many reasons, it is important to understand the climatology of cyclones on the Great Lakes. Changes over time of cyclone characteristics, such as frequency, intensity, and source regions, are of great interest as well. It is necessary to understand the climatology of cyclones and changes in cyclone characteristics during the last century to gauge potential economic impacts of changes in cyclone frequency and intensity that could result from future changes in the climate in the Great Lakes region. Despite the importance of Great Lakes cyclones, only three studies have directly documented their features (Garriott 1903, Harman et al. 1980, and Lewis 1987).

In the present study, a historical dataset of the cyclones that passed over the Great Lakes was constructed for the period 1900 to 1990. This dataset was used to address the following five research topics: a) the trends and fluctuations in the characteristics of cyclones, b) the balance between cyclone frequency and cyclone intensity, c) the sensitivity of cyclone characteristics to climate variables, particularly temperature and precipitation regimes, d) the preferred tracks of cyclones passing over the region and changes in these tracks over time, and e) the influence of the Great Lakes on passing cyclones.

Constructing a Historical Cyclone Dataset for the Great Lakes Region

The first objective of this investigation was to establish a meaningful and consistent dataset of cyclones over the Great Lakes for the 20th century. It was decided to include only strong cyclones capable of producing economic damage. The criteria for identifying economically important cyclones were explored using previous studies and available datasets. Because there was no agreement in cyclone criteria between these studies and datasets, reports of damage due to cyclones were examined to identify the appropriate criteria. As a result of this analysis a median central pressure of 992 mb associated with damaging storm events found in NOAA *Storm Data* was selected as the criterion for including a storm in the historical cyclone dataset. Central pressure is also the meaningful storm parameter that is most easily recovered from all the available historical cyclone records.

The NOAA *Storm Data* was used to examine historical damages from 1959 to 1990 on the U.S. shores of the Great Lakes. This is the first time such an analysis has been achieved for the Great Lakes and the results are published in Angel (1995). While most years experienced little damage, the years 1967, 1970, 1972, 1973, and 1975 had damages exceeding $10 million and the years 1984 and 1985 had damages exceeding $60 million. An examination of lake levels indicates that higher than average lake levels can be a contributing factor in damages caused by cyclones. The geographic distribution of damage reports indicates that the eastern and western shores of Lake Erie experience the most reports. The number of damage reports per month has maxima in both November and April. A relative minimum between late fall and spring is due to the protective ice formation along the shores.

Three datasets were combined to construct the long-term record of cyclones in the Great Lakes region. Cyclone track data compiled and analyzed by Klein (1957) were obtained in digital form from the National Climatic Data Center (NCDC) and covers the period from 1899 to 1939. This dataset provides the central pressure, location of high and low pressure centers, and information on movement and change in pressure on a daily basis. The reporting time was 0700 Eastern Standard Time (EST) and only cyclones with a central pressure ≤ 992 mb in the Great Lakes region were included in the historical dataset. A "working tape" of cyclone track data digitized from the NOAA *Mariners Weather Log* was obtained from NCDC for the period from May 1965 to December 1990. This dataset provided observations of cyclone locations at 6 hr intervals. Only the 12Z (0700 EST) observations for cyclones with a central pressure ≤992 mb in the Great Lakes region were incorporated into the historical dataset. However, the higher resolution data for both strong and all cyclones were used in supplemental analyses. A daily time series of central pressure and location of the cyclone center, for cyclones with a central pressure ≤992 mb in the Great Lakes region, was extracted from monthly weather maps summarizing cyclone tracks in the back *of Monthly Weather Review*. These data were digitized to fill the gap from 1940 to 1965 between the other two datasets. The cyclone tracks in the *Monthly Weather Review* were also based on the location of the cyclone at 0700 EST.

The resulting combined dataset provides homogeneous information (daily observations of location, central pressure, speed, and movement) on strong cyclones passing through the Great Lakes region for the period 1900 to 1990. It is an appropriate dataset on which to base a climatological analysis of large-scale storms over the Great Lakes.

Changes in Characteristics of Great Lake Storms during the Twentieth Century

A climatology of cyclones over the Great Lakes during the 20th century was constructed with emphasis on trends and fluctuations in the characteristics of the strong cyclones. The characteristics examined included frequency, intensity (as indicated by central pressure), and the speed and direction of cyclone movement. The characteristics were examined by month, the four traditional seasons (winter-December through February, spring - March through May, summer - June through August, and fall - September through November), and for the entire year.

The direction of cyclones movement was calculated as the vector average of the cyclones along their entire path. The speed was calculated by averaging the speed of the cyclones along their entire path. The frequency of cyclones was measured by counting the number of cyclones passing through the region for each time period (months, seasons, and years). The pressure associated with each cyclone was its lowest central pressure within the region. These characteristics were then aggregated into 5-year periods for easier analysis.

Results of the analyses of changes in speed and direction of cyclone movement with time are not conclusive because few of the results are statistically significant and the results are not consistent across the Great Lakes region. Statistically significant changes in cyclone direction are found for the entire region in fall, and October in particular, showing a shift toward a more zonal path (west to east) over time. Increases in speed of cyclone movement over time are statistically significant in January and February for the Great Lakes region. This study shows that the central pressure of cyclones decreased (i.e., increased in intensity) over the 90-year period for fall for the Great Lakes region. The decrease in pressure, combined with increases in frequency, suggest that fall cyclones in the Great Lakes region have become stronger and more frequent during the 20th century.

The results of this analysis show statistically significant increases in cyclone frequency between 1900 and 1990 for November, December, fall, and annual time periods in the Great Lakes region. The overall effect is an increase in the annual cyclone frequency by 44%, driven, primarily by a doubling in the frequency of strong cyclones in November and December. Possible mechanisms associated with this increase and implications for analysis of the impacts of climate change were explored in later chapters and summarized below.

Relationship between Cyclone Frequency and Intensity over the Great Lakes

Zishka and Smith (1980) suggested that a balance between cyclone frequency and intensity might exist in the Great Lakes region such that as cyclones become more frequent they also become less intense. It is also possible that a change in anticyclone activity may partially balance a change in cyclone activity. To address these questions, the relationship between cyclone frequency and intensity (as measured by central pressure) was examined. All cyclones from the 1965 to 1990 NCDC *Mariners Weather Log* dataset, regardless of strength were used. For the analysis of the relationship between cyclone and anticyclone activity, the earlier dataset from Klein (1957) was used.

For winter, summer and the entire year, a positive, statistically significant relationship exists between cyclone frequency and their central pressure. A positive relationship exists between the number of cyclones and anticyclones, while an inverse relationship exists for cyclone and anticyclone central pressure. The inverse relationship means that when the central pressure of cyclones averaged for annual periods decreases, the central pressure of anticyclones averaged for the same periods increases (i.e., an increase in strength in both cases). These results suggest that during years when cyclones are less frequent in the Great Lakes, the storms have lower pressure (i.e., stronger). During years when cyclones are more frequent, the storms have higher pressure (i.e., weaker). Finally, the frequency and intensity of anticyclone activity changes to compensate for the changes in cyclone activity.

Relationships between Climate Variables and the Characteristics of Cyclones in the Great Lakes Region

ANOVA and correlation analyses of the historical record reveal a statistically significant positive relationship between cyclone frequency and precipitation and no relationship between cyclone frequency and temperature. A weak negative relationship exists between cyclone pressure and temperature and no relationship between cyclone pressure and precipitation. An analysis of periods of extreme temperature and precipitation provides further evidence of a positive relationship between cyclone frequency and precipitation. No relationships are found between cyclone characteristics and the 700-mb heights and the Southern Oscillation Index. However, an inverse relationship is found with the Pacific-North America (PNA) teleconnection pattern.

The results of the analysis of cyclone characteristics, their interrelationships, and their changes through time in Chapters 4,5, and 6 allow some speculation concerning physical explanations that might be associated with the increases in strong cyclone frequency over time for November and December. Whittaker and Horn (1981) suggested that the poleward transport of sensible and latent energy in the mid-latitudes is achieved by a balance between standing waves and cyclone frequency. The statistically significant negative relationship between frequency of strong cyclones and the PNA teleconnection index in November and December support this mechanism. The higher frequency of strong cyclones is associated with a low amplitude standing wave (i.e., more zonal flow), indicating that more transport is being achieved by the cyclones and less by the standing wave.

A second explanation for the increase in the frequency of strong cyclones during the 20th century is suggested by the positive relationship between cyclone frequency and cyclone pressure (found in this study and also noted by Zishka and Smith (1980)). As the frequency of all cyclones decreases, the cyclone intensity increases (i.e., the pressure decreases). The increase in intensity causes more of the cyclones to be classified in the strong cyclone category (central pressure ≤992 mb). The results of Lambert (1995), based on GCM simulations, showed this very pattern of reduced cyclone frequency in general and increased frequency of "strong" cyclones (defined in that study as departures of-200 m or more from the 1000 mb geopotential height field) in the Northern Hemisphere. Lambert attributed the decrease in frequency of all cyclones to reduced baroclinicity caused by preferential warming at higher latitudes in the case of doubled CO_2 amounts. The increase in strong cyclones was attributed to increased water vapor, which leads to an increase in available latent energy. Lambert's results were based on a doubling of CO_2, a condition that did not occur between 1900 and 1990, when CO_2 amounts increased from only 300 to 350 ppm (Boden et al. 1990). Evaluations of increases in water vapor, necessary for more intense cyclones, over North America for the period 1900 to 1990 are not available due to the lack of data before 1948.

If the relationships between precipitation regimes and cyclone activity that exist in the historical record remain essentially unchanged, then future climate changes involving increases in precipitation in the Great Lakes region will probably be associated with increases in cyclone frequency. Until regional precipitation is better modeled by GCMs, this relationship with cyclone frequency can not be fully utilized. The strong link between cyclone frequency and the 3-category precipitation scheme currently used by the National Weather Service (NWS) indicates the possibility of forecasting strong cyclone activity with their new long-range outlooks.

Cyclone Tracks for the Cyclones Passing Over the Great Lakes

The results of this analysis of only those strong cyclones with central pressure ≤ 992 mb and passing over the Great Lakes show that the dominant incoming tracks are from the Colorado-Utah region and from Alberta, Canada. After passing over the Great Lakes region, the predominant track passes through the Canadian provinces of Ontario and Quebec. Dividing the Great Lakes region into three subregions (Superior, Michigan-Huron-St.Clair, and Erie-Ontario), the tracks in the three subregions are similar for winter. For spring and fall, the Michigan-Huron-St.Clair and Erie-Ontario region show the Colorado track but not the Alberta track.

For the entire Great Lakes region, the cyclones are evenly divided between the two major source regions of Colorado and Alberta. However, the western Great Lakes (Lake Superior) is dominated by the Alberta track, while the middle and eastern regions of the Great Lakes are, dominated by the Colorado track.

Regarding changes in cyclone activity between 1901-1945 and 1946-1990 time periods, three features are outstanding: a) an area of decrease in frequency of strong cyclones along the eastern coast of Canada and Maine, b) an increase in frequency of strong cyclones across the upper Midwest and into the Hudson Bay region, and c) a decrease in frequency of strong cyclones in the west central portion of the U.S. This suggests a shift away from the earlier source regions for Great Lakes cyclones of Alberta and Colorado over the last 45 years. In addition, the cyclones that passed over the Great Lakes region during the later half of the record generally tracked further north over eastern Canada than they did in the 1901-1945 period.

The Effects of the Great Lakes on Passing Cyclones

Because surface water temperatures of the Great Lakes lag behind air temperatures, the lakes are cooler (warmer) than the air passing over them in summer (winter). The period when water temperatures are warmer than air temperatures is defined the unstable season. It usually extends from September to February or until the lake freezes over. During this unstable season, the Great Lakes can influence passing cyclones by transferring latent and sensible heat to them.

Previous studies on the influence of the Great Lakes on cyclones were based on a total of only five cyclones. In this study, using data from 712 cyclones from the period 1965 to 1990 at 6-hour intervals, the Great Lakes were found to impact passing cyclones in many ways. The first notable effect is the acceleration of cyclones into the Great Lakes region. This acceleration was investigated by comparing cyclone speeds before entry and within the Great Lakes region. Statistically significant accelerations are found for weak cyclones (>992 mb), for cyclones along both the Alberta and Colorado tracks, and during the months of September and November.

Cyclones intensify over the Great Lakes during the unstable season. The change in strength was examined by comparing cyclone deepening rates prior to and within the Great Lakes region. The differences in the cyclone deepening rates reveals statistically significant increases in cyclone strength for strong, weak, Alberta, and Colorado cyclones. The cyclone deepening rate of cyclones (all strength and source region categories) increased by a statistically significant amount as they entered the Great Lakes region for every month during the unstable season.

The speed of movement of cyclones decreases once they enter the Great Lakes region. This decrease in speed was examined by comparing cyclone speeds prior to and within the Great Lakes region. The results show that the speed of cyclone movement over the Great Lakes slowed significantly for strong and weak cyclones, Alberta cyclones, and for all cyclones in October, November, January, and February.

Cyclones reaccelerated after departing the Great Lakes region. This change in speed was examined by comparing the speed of movement of cyclones inside the Great Lakes region with their speed after departing the region. Statistically significant increases in cyclone speed were found for both strong and weak cyclones, for both Alberta and Colorado cyclones, and during the months of September, January, and February. The increases in cyclone speed are comparable to the decreases in cyclone speed that occur upon entry into the region.

Cyclones maintain their enhanced intensity downstream of the Great Lakes region, although they do not continue to deepen (intensify further) at the higher rate found over the lakes. This change in cyclone strength was examined by comparing cyclone deepening rates inside the Great Lakes region with deepening rates of cyclones after they departed the region. In nearly all cases, the cyclone deepening rate returned to levels similar to that before entry into the region.

The Great Lakes also influence passing cyclones during the stable season (March through June). Changes in the rate of movement of cyclones were examined by comparing cyclone speed before entry and within the Great Lakes region. The influence of the Great Lakes on cyclone speed is weak and only significant for Colorado cyclones and cyclones in April. However, instead of weakening cyclones during the stable season as expected, the Great Lakes appear to strengthen cyclones during spring and early summer. Changes in intensity were examined by comparing cyclone deepening rates before entry and within the Great Lakes region. Statistically significant increases in the cyclone deepening rate were found for strong and weak cyclones, for Alberta and Colorado cyclones, and all months. These results show that, contrary to previous research, the Great Lakes do intensify passing cyclones during the stable season. Further research is needed to identify possible physical processes that cause cyclone intensification over the Great Lakes during spring and early summer.

While some of these features have been noted in the case or modeling studies of one or two cyclones, this is the first time that the systematic influence of the Great Lakes on passing cyclones has been documented statistically using long-term historical data. These results underscore the importance of including the Great Lakes, and other water bodies of similar size, in numerical models of the atmosphere. Accurate representations of the energy fluxes between these lake surfaces and the atmosphere and the surface roughness of water bodies, will likely improve the predictions in forecast and general circulation models.

Concluding Remarks

This research has provided several important findings. An extensive search of the climatological literature suggests that this is the first study to document a statistically significant increase in the frequency of strong cyclones over the Great Lakes in November and December during the 20th century. This is a time of year when Great Lakes cyclones cause important-economic damage (40% of the NOAA *Storm Damage* reports associated with cyclones occurred in those two months). Studies of the impacts of future climate change generally assume that the cyclone frequency will not change over time. The results of this research suggest that this assumption is invalid. The increase in the frequency of strong cyclones is believed to be the result of a general increase in intensity of all cyclones, which yielded more cyclones in the strong cyclone category.

An analysis of changes in cyclone characteristics, temperature, and precipitation yields a positive relationship between cyclone frequency and precipitation. This relationship should be useful in climate change studies and for applications with the NWS long-range forecasts. This research also provides climatological evidence (as opposed to case studies or models) of the important influence of the Great Lakes on passing cyclones. During the unstable season, cyclones accelerate into the region, slow and deepen over the lakes, and then return to their prior speed and rate of deepening after they exit the region. The influence of the Great Lakes on passing cyclones is important not only during the unstable season, but also in late spring and early summer.

Further Research

The lack of good observational data on shoreline damages and the shoreline physical processes hampers the ability to relate economic and physical damage to storm features that cause the losses. Accurate and consistent economic and physical measures of damage are needed with comprehensive coverage for each storm. The need for research in this area can only become more acute as the natural and economic value of the shores of the Great Lakes become fully realized.

A physically-based explanation for the changes in cyclone characteristics over time and the influence of the Great Lakes during the "stable" season is also needed. This will require more cases studies of cyclones using sophisticated numerical models. Research is also needed to develop techniques for forecasting strong cyclone characteristics months or seasons ahead in conjunction with the new NWS long-range forecasts.

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