The Frequency and Intensity of Great Lake Cyclones

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ABSTRACT

Cyclones are an important feature of the Great Lakes region that can have important impacts on shipping, lake temperature profiles, ice cover, and shoreline property damages. The objective of this research is to analyze the frequency and intensity of cyclones that traversed the Great Lakes region, the changes of these characteristics since 1900, the interrelationship of cyclone frequency and intensity, and their relationships to circulation patterns and regional temperature and precipitation.

Significant increases in the number of strong (≤992 mb) cyclones over the twentieth century were found for the annual, cold season, November, and December time periods. In contrast, the frequency of all cyclones in the annual and warm season time series and the central pressure of all cyclones in the annual, cold, and warm season time series displayed significant decreases from 1900 to 1939.

Relationships between cyclone frequency and intensity and between cyclone and anticyclone frequency and intensity suggest that there is a partial compensation within the region. As the number of cyclones increases, their intensity decreases. As the number of cyclones increases, so does the number of anticyclones. And, finally, as the cyclones become stronger, so do the anticyclones. Comparisons with the Pacific–North American teleconnection index indicate that lower (higher) cyclone frequency is associated with more zonal (meridional) flow. Comparisons of cyclone characteristics with temperature and precipitation in the Great Lakes region shows that cyclone frequency is inversely related to temperature and directly related to precipitation in most month and season categories. In contrast, the relationships between cyclone intensity and climate variables are inconsistent.

1. Introduction

The winds and precipitation associated with cyclones that traverse the Great Lakes have important impacts on the physical environment and human habitation in the region. Historically, the stronger of these cyclones have caused extensive damage to shipping. The ‘‘great storm of 1913,’’ the most devastating cyclone on the Great Lakes for which there are reliable records, sank a dozen ships and killed more than 250 people (Barcus 1960). In part, it was the loss of life in the region caused by severe cyclones during 1868 and 1869 that prompted the United States Congress to form a national weather service at the urging of University of Wisconsin Professor Increase Lapham (Hughes 1970).

Cyclones that pass over the Great Lakes have a number of other vital, albeit less striking, environmental and socioeconomic impacts. Their strong winds mix lake water and consequently decrease the vertical stratification of water temperature and enhance the downward fluxes of oxygen and pollutants (McCormick 1990). These processes in turn influence the populations and distributions of fish and other aquatic life in the Great Lakes. The high wind speeds associated with winter cyclones break up extensive areas of ice cover, opening shipping lanes but decreasing the abundance of the microbiota that thrive beneath the ice and the organisms that feed on them (Assel 1991). The ice cover can also afford shorelines protection from high-energy waves. The trend in use and value of lakeshore property is increasing rapidly and thus raising the economic cost of shore erosion caused by strong cyclones in the region. The winds and waves associated with strong cyclones are especially damaging to shoreline property when water levels in the lakes are high (Changnon 1987). For example, the Chicago Park District alone spent $35 million to restore beaches damaged by storms during 1985 and 1986 when the water in Lake Michigan was at a record high level.

Despite the importance of Great Lakes cyclones, only three studies have directly documented their features. Garriott (1903) described 238 cyclones that traversed the Great Lakes during the 25-yr period between 1876

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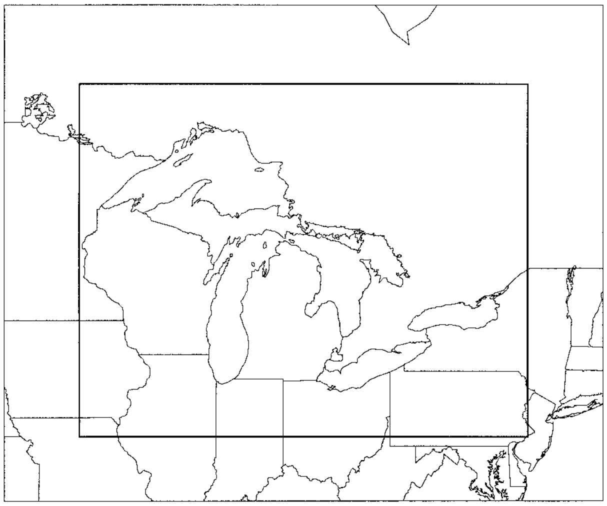

FIG. 1. Box surrounding the Great Lakes that was used to determine those cyclones that passed through the region.

and 1900. The study was motivated by the need to forecast the movement of strong cyclones into the region. Four geographic sources were identified for cyclones that entered the Great Lakes region: southwestern midwestern, and northwestern United States as well as the Gulf of Mexico. The study also revealed that during the last quarter of the nineteenth century, the frequency of cyclones over the Great Lakes was greatest in November and generally lowest during summer months.

Lewis (1987) catalogued 100 storms that passed over the Great Lakes during the period between 1957 and 1985. A surface analysis, storm track, and other important meteorological parameters were included for each storm. In the study, a storm was defined as an atmospheric disturbance characterized by wind speeds greater than 88 km h^{-1}. Angel (1996) found that 92 of the 100 storms were cyclones and that 83% of the cyclones occurred between November and March.

Harman et al. (1980) analyzed the cyclones that traversed Lakes Superior, Michigan, and Huron during the months of October–February between 1955 and 1976. The authors found that cyclone frequency was greatest in December and January. November cyclones exhibited the lowest mean surface air pressure. Southern and northern Great Plains source regions for the cyclones passing over the western Great Lakes were separated by the 42° parallel of latitude. The cyclones of southern origin were stronger for each of the five months studied than those of northern origin. The greater strength of the cyclones from the southern source region was attributed to the presence of more pronounced troughs in the airflow within the midtroposphere and to the greater amounts of atmospheric moisture at low levels within these cyclones than those from the northern Great Plains.

The objective of this research is to construct a climatology of cyclones that traversed the Great Lakes between 1900 and 1990. The temporal trends in the frequency of strong cyclones, those that have a significant impact on human life and the economy in the region, are an important focus of the study. The climatological analysis is divided into three parts. In the first section, the frequency and intensity of all cyclones (a 64-yr, discontinuous record) and the frequency of strong cyclones (a 90-yr, continuous record) that passed over the Great Lakes are investigated. The data are stratified by month and year to analyze the variability and time trends of cyclone frequency and intensity. Second, the relationship between cyclone frequency and intensity is explored. Here, the analysis focuses on a 39-yr time series that includes all the cyclones as well as the anticyclones that traversed the Great Lakes. The third section of the climatology relates the time trends in frequency and intensity of strong cyclones to midtropospheric circulation patterns and regional air temperature and precipitation regimes.

2. Constructing a historical dataset of strong cyclones for the Great Lakes region

Cyclones are closed atmospheric circulations and centers of low pressure. These storm systems are characterized by wavelengths that can range from 1000 to 2500 km (Huschke 1959). In North America, midlatitude cyclones generally move from west to east and are widely recognized as causing the day-to-day variability in weather. While usually 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.

Maps of cyclone tracks across North America were published 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, a cyclonic center is defined as a closed low-pressure region persisting for at least 24 h. These maps are the basis for many previous works on cyclone frequencies and tracks (e.g., Hosler and Gamage 1956; Hayden 1981; Reitan 1974; Zishka and Smith 1980; Whittaker and Horn 1984) and are used in this study as well.

Although cyclones frequently pass over the Great Lakes, not all of these cyclones pose a threat to human life and the economy of the region. It is generally assumed that strong cyclones are more harmful than weaker cyclones. Reports of damage to the United States shoreline of the Great Lakes by cyclones have been catalogued in the National Oceanic and Atmospheric Association (NOAA) publication *Storm Data* since 1959. This dataset includes property damage caused by 112 cyclones from the period between 1959 and 1990 (Angel 1996). The lowest central pressure while in the Great Lakes region (defined by 40°–50°N latitude and 93°–75°W longitude, Fig. 1) was extracted from the

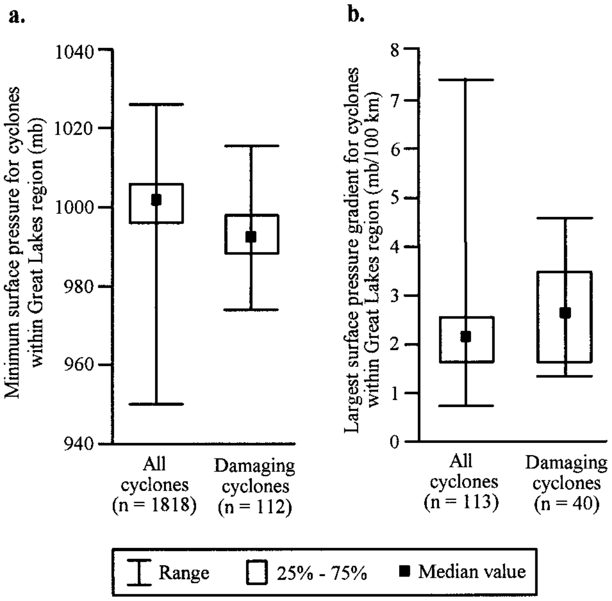

FIG. 2. Box plots of the (a) minimum surface pressure and (b) largest surface pressure gradients for cyclones passing over the Great Lakes region and those cyclones associated with NOAA *Storm Data* reports.

monthly cyclone track maps in *Monthly Weather Review* for each of the cyclones responsible for damage recorded in *Storm Data.* The distribution of the minimum pressure values for all cyclones passing over the Great Lakes during the 31-yr period and distribution of minimum pressure values associated with cyclones that appear in *Storm Data* damage reports are presented in Fig. 2a for comparison. Surprisingly, the median pressure value for damaging cyclones (992 mb) is only 8 mb lower than that for all cyclones. A number of the cyclones with very low central pressure did not appear in the damage reports.

Measurements of the pressure gradient across a subset of the 112 cyclones associated with *Storm Data* were extracted from the corresponding surface weather maps. The change in surface air pressure over the distance spanned by an east–west transect that extended across the area bounded by the outermost closed isobar and through the cyclone center was used to estimate the pressure gradient. Measurements in the north–south direction were not included in the pressure gradient estimate because most cyclones had fronts extending to the south that distorted 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 is presented in Fig. 2b. The largest pressure gradient measurement (i.e., maximum intensity) for each cyclone while it was in the region was used in the analysis. Again, the median values of the distributions are similar and a number of cyclones with large pressure gradients did not appear in the damage reports. Certainly the level of the lake water and the direction of cyclone movement relative to the position, shape, and orientation of the lakes impact storm damage and are likely to be important reasons why some very strong cyclones on the Great Lakes are not included in *Storm Data.*

The median pressure gradient of the subset of cyclones that were recorded in *Storm Data* was 2.7 mb (100 km)$^{-1}$ for the 5-yr period. A linear regression of the pressure gradient and the minimum surface pressure indicates that a pressure gradient of 2.7 mb (100 km)$^{-1}$ yields a central pressure value of 991 mb, which is approximately the median central pressure (992 mb) of cyclones associated with damage reports. Because central pressure is easier to retrieve from the cyclone track maps than is the pressure gradient, and because central pressure can be retrieved from the National Climatic Data Center's (NCDC) computerized records of cyclones, whereas the pressure gradient associated with the cyclone center cannot, the minimum surface pressure (value of the innermost isobar) is used in this study as a measure of cyclone intensity. Cyclones with at least one center surface pressure value $\leq$992 mb within the Great Lakes region are considered to be ''strong'' cyclones while all others are classified as weak cyclones.

Three datasets based on the monthly cyclone track maps are used in this climatology of Great Lake cyclones. The first, covering the period from 1900 to 1938, was compiled by Klein (1957) and obtained in digital form from NCDC. This daily dataset provides surface air pressure for anticyclone and cyclone centers in North America, the location of the high and low pressure centers to the nearest whole degree of latitude and longitude, and information on their movement and change in pressure. These data were recorded for 1200 UTC (0700 EST) and include 3847 cyclones and 2536 anticyclones that traversed the Great Lakes region. The distribution of cyclones with respect to the minimum surface pressure while in the region is shown in Fig. 3a. The second dataset, covering the period from 1966 to 1990, was obtained from an NCDC ''working tape'' of cyclone tracks digitized from the *Mariners Weather Log.* Location, movement, and surface air pressure for cyclone centers in North America are provided for 6-h intervals (0000, 0600, 1200, and 1800 UTC). The distribution of the 1818 cyclones that traversed the Great Lakes region with respect to their minimum pressure (Fig. 3b) is similar to that for the earlier cyclones. The mean values of the distributions are 998.1 and 998.5 mb for the 1900–38 and 1966–90 datasets, respectively. Both distributions are slightly asymmetrical and display a general trend in the number of cyclones with increasing pressure that ascends gradually to the 1005- or 1006-mb categories and decreases more steeply thereafter. Cyclones in the cold season (November–April) tended to be stronger than those in the warm season (May–October).

A daily time series containing 1200 UTC observations of central pressure and location of each of the 341

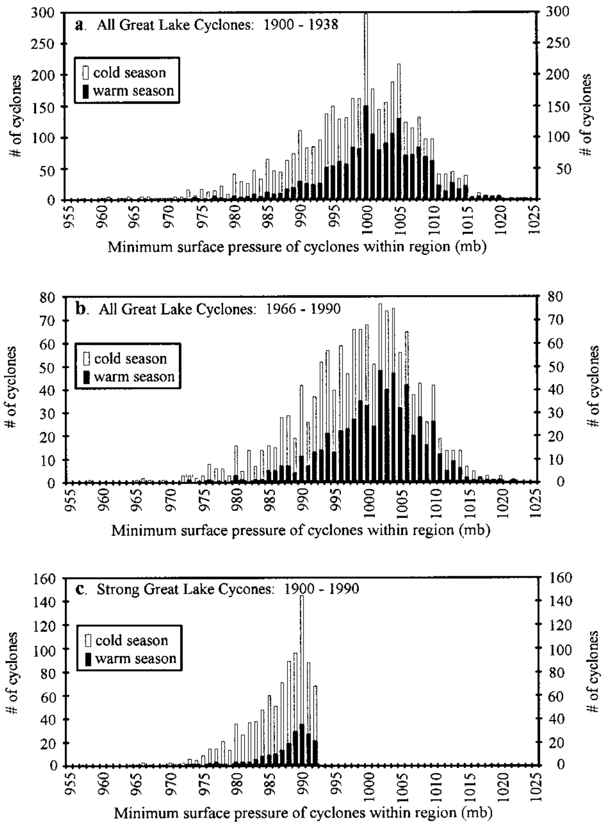

FIG. 3. Distribution of the minimum surface pressure of cyclones with the Great Lakes region for (a) all cyclones for 1900–38, (b) all cyclones for 1966–90, and (c) strong cyclones from 1900–90.

strong cyclones [(≤992 mb) that passed through the region (Fig. 1)] was extracted by Angel (1996) from monthly cyclone track maps in the *Monthly Weather Review* to fill the gap from 1939 to 1965. The three sources were combined to build a historical dataset of observations at 1200 UTC (the one common observation time) of cyclones with at least one central pressure measurement ≤992 mb that traversed the Great Lakes region during the period from 1900 to 1990. Combining records from the three sources resulted in a time series containing 1000 strong cyclones (~11 yr^{-1}). Figure 3c shows the distribution of the number of strong cyclones that traversed the Great Lakes region with respect to the minimum surface pressure. Approximately 80% of the strong cyclones occurred during the months of November–April. There are a number of potential problems associated with combining different datasets, especially questions related to their homogeneity (Nicholls 1995). The number of stations reporting surface air pressure to The National Weather Service within the Great Lake states increased dramatically from 38 to 262 between 1901 and 1980 (Fig. 4). There was likely a corresponding improvement in the analyses of cyclones due to the increase in spatial resolution of observations. This could have resulted in cyclones with lower central pressure and an increase through time in the number of strong cyclones. However, as will be shown below, the central pressure of Great Lake cyclones increased over the historical record. The standard deviations of the annual frequency of strong cyclones, a statistical measure of dataset homogeneity, are similar for the Klein (3.7), Angel (3.5), and NCDC working tape (3.5) datasets.

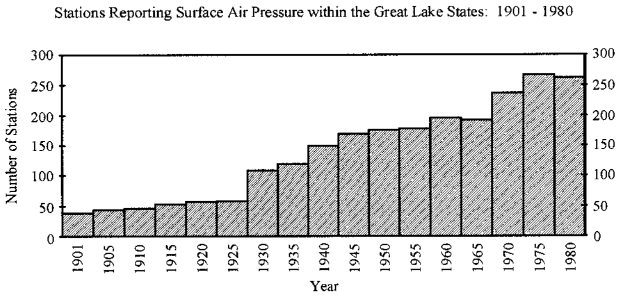

FIG. 4. Distribution of the stations reporting surface air pressure within the Great Lake states (MN, WI, IL, IN, MI, OH, PA, and NY). The numbers are based on the index of original surface weather records for each state (National Climatic Data Center 1983).

3. Variations in frequency and intensity of Great Lake cyclones between 1900 and 1990

The Great Lake cyclones were stratified by month, the cold (November–April) and warm (May–October) seasons, and year. The two datasets containing all Great Lake cyclones (1900–38 and 1966–90) were combined for this analysis. Cyclone frequency was determined by counting the number of cyclones passing through the region during a time period and are shown in Figs. 5a,b for all cyclones and strong cyclones, respectively. The distribution of cyclones throughout the year is essentially similar for the two datasets. The frequency of strong cyclones in the Great Lakes region increases in November and remains high through April (Fig. 5b). Among these cold season months, the frequency of strong cyclones is highest in January and March and lowest in February and April. A comparison of Figs. 5a,b also indicates that most of the cyclones that traverse the lakes in summer are weak. The minimum pressure for each cyclone while it was in the region, stratified by month, are displayed in Figs. 5c and 4d. Overall, cyclones in December were stronger than those that traversed the region during the other months (Fig. 5c). January cyclones are strongest considering only those with at least one central pressure value ≤992 mb within the Great Lakes region (Fig. 5d). However, differences in the intensity of strong cyclones among categories are difficult to interpret because a minimum surface pressure ≤992 mb was the criteria used for including cyclones in the dataset. For example, an increase in the average surface pressure of strong cyclones averaged for a month could be associated with a decrease in the average surface pressure of all Great Lakes cyclones

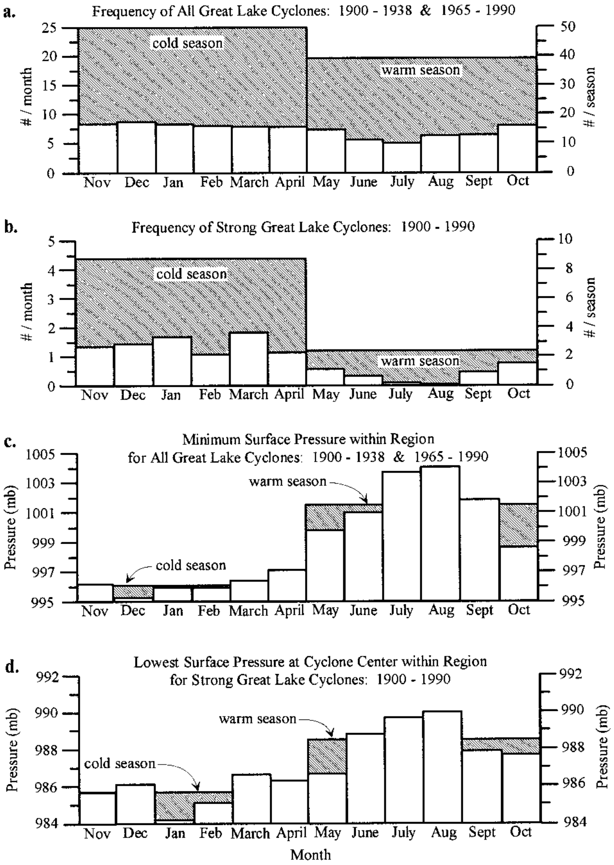

FIG. 5. Monthly distribution of the frequency of (a) all cyclones and (b) strong cyclones as well as the lowest surface pressure of (c) all cyclones and (d) strong cyclones.

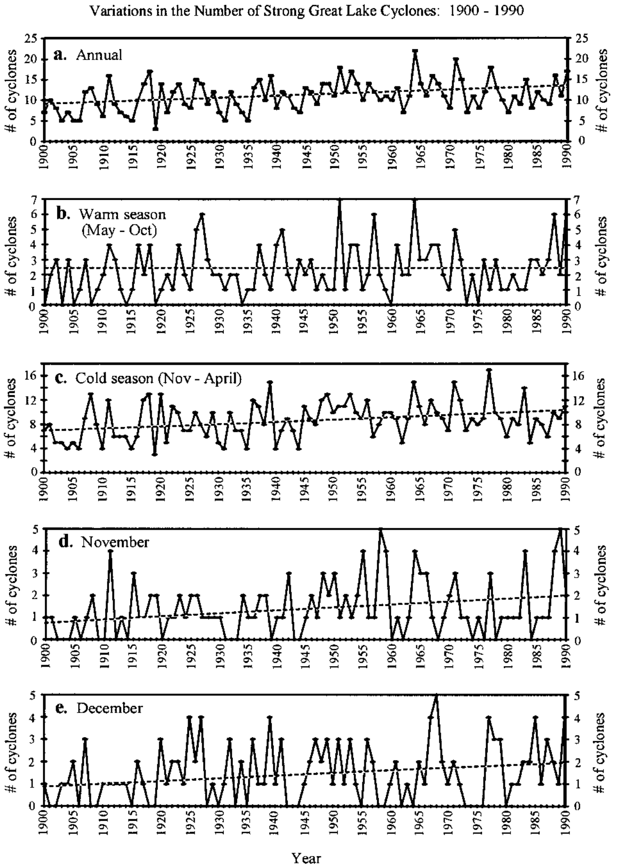

FIG. 6. The number of strong Great Lakes cyclones over time for 1900–90 for months and seasons with statistically significant trends.

during that month simply because more cyclones were just intense enough (e.g., minimum surface pressure between 990 and 992 mb) to be included in the strong cyclone dataset.

The findings displayed in Fig. 5 differ from the results of Harman et al. (1980), which show that cyclones passing over the western Great Lakes between 1955 and 1976 were significantly stronger in November than during December and January. Figures 5b,c suggest that there is a transition in the frequency and strength of Great Lake cyclones between March and May and again between September and November. It appears more appropriate to define a cold season (November–April) and a warm season (May–October) to study the frequency and intensity of Great Lake cyclones than to use the unstable (September–February) and stable (April–September) seasons suggested by Eichenlab (1979) in his discussion of the influence of the Great Lakes on the weather and climate of the region or the more traditional four seasons (December–February, March–May, June–August, and September–November).

The 1900–90 data were examined for time trends in the frequency and central pressure of strong Great Lake cyclones. The frequency of these cyclones ranges from only 3 in 1919 to 22 in 1964. The number of strong Great Lakes cyclones during the annual, cold season, November, and December time periods (Figs. 6a,c,d,e, respectively) increased over the 90-yr record (statistically significant at $\alpha = 0.05$). Approximately 21% of the total number of Great Lake cyclones occur in November and December. The number of strong cyclones per year more than doubled from 0.9 to 2.0 for November and from 0.9 to 1.9 for December. Cyclone frequency also increased over the period for all other months except January and August and the warm season (Fig. 6b), although these relationships are not statistically significant. The increases in the number of strong Great Lake cyclones over the 90 yr for the cold season and annual periods are 3.2 yr^{-1} and 4.2 yr^{-1}, respectively.

The frequency and pressure data for all Great Lake cyclones from 1900 to 1938 and from 1966 to 1990 were also examined for time trends. The plots of the frequency of cyclones in the annual and warm season time series (Fig. 7a) and the central pressure in the annual, cold season, and warm season time series (Fig. 7b) each display a statistically significant decrease over the first 39 years of the twentieth century. The increasing trend in cyclone intensity was remarkably consis-

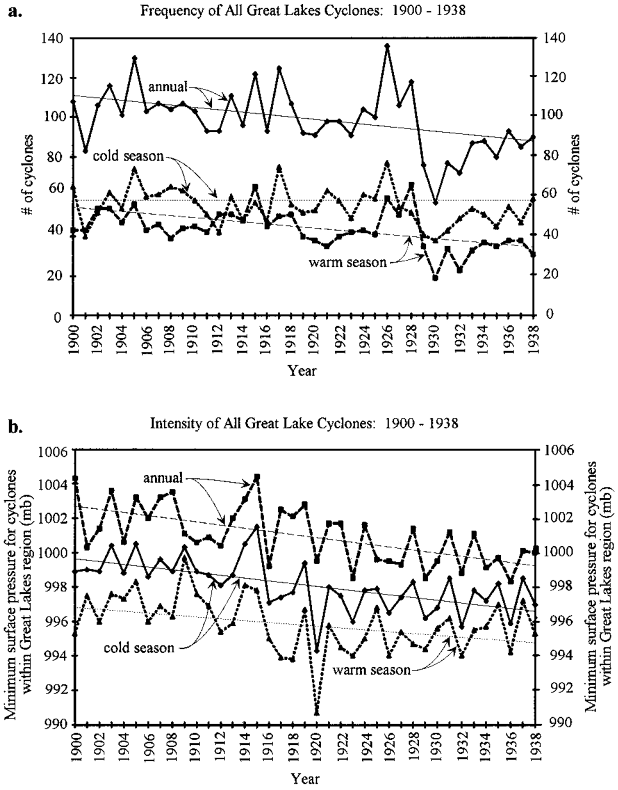

FIG. 7. (a) Frequency of all Great Lakes cyclones for the annual, warm, and cold seasons for 1900–38. (b) Intensity, as measured by the lowest surface pressure, of all Great Lakes cyclones for the same three seasons for 1900–38. These data are from the extensive dataset of Klein (1957).

tent throughout the period even though the number of reporting stations within the Great Lake states (Fig. 4) almost doubled (58 to 109) between 1925 and 1930. The increase in the frequency of strong cyclones during this period (Fig. 6a) is consistent with the increase in the average intensity of all cyclones (Fig. 7b). This indicates that the decrease in the frequency of all cyclones for the 1900–38 period (Fig. 7a) can be attributed to a dramatic decrease in the number of weak cyclones that traversed the lakes. In contrast, there are no significant time trends in the frequency and intensity of all Great Lake cyclones between 1966 and 1990 for the annual, cold season, and warm season periods (Figs. 8a,b). Again, the effect of the 40% (75) increase between 1965 and 1975 in the number of recording stations within the Great Lake states (Fig. 4) is not apparent. A visual inspection of Fig. 6a also indicates that there are no trends in the frequency of strong cyclones for the corresponding time period. A comparison of Figs. 7a,b with 8a,b reveals that there is a pronounced decrease in frequency of Great Lake cyclones from 99 yr^{-1} for the 1900–38 period to 73 yr^{-1} for the 1966–90 period but that the intensity of cyclones average for the two periods is similar (998.1 and 998.5 mb, respectively).

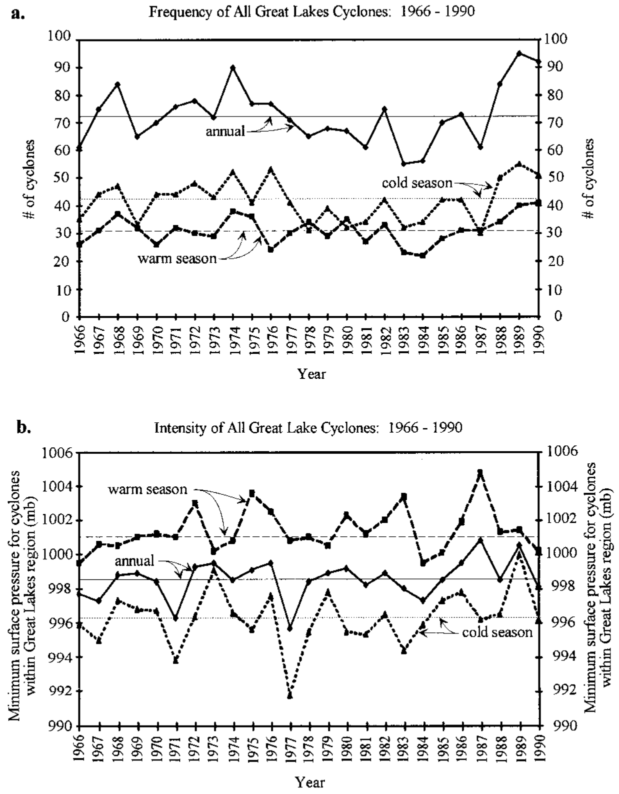

FIG. 8. (a) Frequency of all Great Lakes cyclones for the annual, warm, and cold seasons for 1966–90. (b) Intensity, as measured by the lowest surface pressure, of all Great Lakes cyclones for the same three seasons for 1966–90.

Previous research on Great Lake cyclones did not address changes in their characteristics over time. However, a number of studies have shown that the frequency and intensity of cyclones within other regions of the United States and for the North American continent have varied over the twentieth century. Brennan and Smith (1978) analyzed cyclones and anticyclones in the upper Mississippi and Ohio river valleys and the Great Lakes region between 1950 and 1974. Their plots of cyclones and anticyclones display a general decline from a peak in 1959 through 1974. Reitan (1979) examined cyclone frequencies over North America for four midseason months (January, April, July, and October) between 1949 and 1976 and found decreases in the number of cyclones over time. Zishka and Smith (1980) studied cyclones and anticyclones over North America for January and July between 1950 and 1977. Their results show statistically significant declines in the number and the mean central pressures of cyclones and anticyclones for January and July. Agee (1991) analyzed trends in cyclone and anticyclone frequency over North America using the Zishka and Smith (1980) dataset and statistics on surface cyclone frequencies in the United States for 1905–40 from Hosler and Gamage (1956). His analysis shows an increase in cyclone activity from 1900 to 1940, followed by a decrease in both cyclone and anticyclone frequency 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.

Although the overall trend in the number of strong cyclones that traversed the Great Lakes region between 1900 and 1990 increased significantly, a close inspection of Fig. 6a reveals that the pattern is remarkably similar to those reported in the larger-scale studies. There appears to be an increase in strong Great Lake cyclones throughout the first half of the twentieth century, followed by a decrease between 1950 and 1985, and finally an increase during the last 5 yr in the cyclone time series. However, the trends in the frequency and intensity of all cyclones that crossed the Great Lakes region are very different from those reported in the larger-scale studies. First, Agee (1991) found that cyclones increased in frequency over the United States from 1905 to 1940, whereas Fig. 7a shows that they decreased in frequency over the Great Lakes between 1900 and 1939. Second, the results of previous studies indicate that cyclone frequency in North America decreased between the early 1950s and mid-1980s, whereas there was no significant change in cyclone frequency over the Great Lakes for the 1966–90 period (Fig. 8a). Finally, Zishka and Smith (1980) found an increasing trend in cyclone intensity for the period from 1950 to 1977. This trend is not apparent in the first half of the 1966–85 dataset of all Great Lake cyclones (Fig. 8b). These discrepancies indicate that regional-scale changes in the frequency and intensity of Great Lakes cyclones do not correspond to the larger-scale trends in characteristics of North America cyclones.

4. Relationship between cyclone frequency and intensity over the Great Lakes

The time series plots provide evidence of a relationship between the frequency and intensity of cyclones in the Great Lakes region. The increase in the frequency of strong cyclones for the 1900–90 period (Fig. 6a) was accompanied by a decrease in the frequency of all cyclones between the 1900–38 (Fig. 7a) and 1966–90 (Fig. 8a) datasets. Similarly, as the frequency of cyclones decreased over the 1900–38 period (Fig. 7a), the average of the minimum surface pressure values for cyclones within the region also decreased (Fig. 7b), indicating that the intensity of Great Lake cyclones increased. The correlations between cyclone frequency and the minimum pressure values are positive and statistically significant ($\alpha = 0.05$) for the annual period (0.41) and warm season (0.45) in the 1900–38 dataset and the annual (0.33), warm season (0.37), and cold season (0.34) for the 1966–90 record of Great Lake cyclones. These results are consistent with the findings of Zishka and Smith (1980) that show a decrease in the number of North American cyclones in January and July for 1950–77 accompanied by an increase in their average intensity.

Reitan (1979) did not make a direct comparison between the frequency and intensity of North American cyclones, but he did speculate on a mechanism that could link the two characteristics. He suggests that a shift to fewer but stronger cyclones over North America should accompany an equatorward movement of the region of maximum cyclone activity. However, his analysis indicates that the decrease in cyclone frequency between 1949 and 1976 was accompanied by a general poleward shift in the locus of cyclone activity.

The increase in frequency of strong cyclones along with the decline in frequency of all cyclones from 1900 to 1938 and between that period and the 1966–90 record 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 $1 \times CO_2$ and $2 \times CO_2$ levels and compared characteristics of cyclones that resulted from the two scenarios. 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 winter cyclones in the Northern Hemisphere between the $1 \times CO_2$ and $2 \times CO_2$ runs resulted from a reduction in the equator-to-pole temperature gradient, while the increase in the frequency of stronger winter cyclones (based on lows with departures of 200 m or more from the 1000-mb geopotential height field) could be attributed to an increase in water vapor, and thus latent heat release, with global warming.

Analysis of the 1900–38 dataset reveals a statistically significant positive correlation of 0.42 between the annual numbers of cyclones and anticyclones that passed over the Great Lakes region. The negative correlation (-0.69) between the annual averages of minimum cyclone and maximum anticyclone surface pressures within the region is also significant. These results indicate that both frequency and intensity are components of the compensation between cyclones and anticyclones that maintains the pressure field in the Great Lakes region over the long term. However, the relatively low correlations also suggest that much of the compensation between cyclones and anticyclones likely occurs at larger spatial scales.

5. Relationships between midtropospheric flow patterns and cyclone frequency and intensity over the Great Lakes

In the Pacific–North America region, a common configuration of the midtropospheric flow is a wave characterized by a ridge along the west coast of North America accompanied by troughs over both the east-central North Pacific and eastern North America. A number of studies have shown that variations in the amplitude and longitudinal position of the ridge and troughs in this quasi-stationary wave have important associations with regional temperature and precipitation regimes in North America on timescales of months to seasons (e.g., Leathers et al. 1991; Rodionov 1994). To quantify the temporal variations of the midtropospheric airflow pattern, Wallace and Gutzler (1981) identified four centers of anomalies in the 700-mb height field in the sector and developed an index based on a linear combination of the departures from the mean geopotential height (Z*) at these locations. This Pacific–North American (PNA) index was subsequently modified by Yarnal and Diaz (1986) to emphasize the midtropospheric flow pattern over the middle latitudes of North America and is calculated in this study using

$$\mathrm{PNA} = \frac{1}{3}[-Z^*(50°\mathrm{N}, 170°\mathrm{W}) + Z^*(50°\mathrm{N}, 110°\mathrm{W}) - Z^*(30°\mathrm{N}, 90°\mathrm{W})]. \qquad (1)$$

Near-zero PNA values indicate a flow pattern that is close to the mean, positive values of the index indicate a more meridional flow pattern, and negative PNA values indicate a pattern that is more zonal than the mean flow. An extremely negative PNA index value represents a reverse PNA pattern, characterized by a trough along the west coast of North America and a ridge over both the east-central North Pacific and eastern North America. Reverse PNA patterns are infrequent and no clear consensus was found in the literature for defining this midtropospheric pattern using the PNA index. For example, Vega et al. (1995) used a PNA index threshold value of −0.5 to define the reverse PNA pattern and Rogers and Raphael (1992) used the four lowest PNA negative values in each month. An examination of monthly mean 700-mb height maps revealed that the reverse PNA pattern was pronounced for <10% of months between 1966 and 1990, usually when the PNA index was less than −1.0. Because the objective was to analyze relationships between midtropospheric flow patterns and cyclone frequency and intensity in the Great Lakes region, data from months with a PNA index of less than −1.0 were removed to simplify the interpretation of the results. Monthly values of the PNA index were calculated from the 700-mb gridded data of the National Meteorological Center (recently renamed the National Centers for Environmental Prediction; NCAR 1990).

The relationships between the PNA index and the frequency and intensity of all Great Lake cyclones (1966–90) and the frequency of strong cyclones (1947–90) are shown in Table 1. The correlations between the PNA index and the frequency of all cyclones during the cold season are negative and are statistically significant ($\alpha = 0.05$) for 3 of the 6 months. The negative correlation indicates that cyclone frequency in the Great Lakes region is greater during the cold season when the pattern of midtropospheric flow above North America is zonal than when it is meridional. Although the relationships between the PNA index and cyclone intensity are not statistically significant, the correlations between PNA index and frequency of strong cyclones indicate that these cyclones occur more often in November, December, and January during periods of meridional rather than zonal flow. In general, the relationships between the PNA index and the frequency and intensity of Great Lake cyclones during the warm season months are weak. These results support the conclusions of Harman et al. (1980) that severe cyclones over the western Great Lakes are most frequent when the ridge–trough pattern over North America is amplified and persistent. They are also consistent with the findings of Noel and Changnon (1995) that periods of high cyclone frequency over North America are associated with a more zonal flow at 700-mb level while the frequency of cyclones is lower when the flow is more meridional.

TABLE 1. Correlations between PNA index and the frequency and intensity of all cyclones (1966–90) and between the PNA index and the frequency of strong cyclones (1966–90) within the Great Lakes region. An asterisk indicates that a relationship is statistically significant at $\alpha = 0.05$.

		All cyclones 1966–90		Strong cyclones 1947–90
Season	Month	Frequency	Intensity	Frequency
Cold season	November	−0.54*	−0.16	−0.37*
	December	−0.16	0.37	−0.47*
	January	−0.45*	0.20	−0.50*
	February	−0.23	−0.16	0.04
	March	−0.66*	0.07	−0.23
	April	−0.25	0.19	−0.25
Warm season	May	−0.12	0.22	−0.21
	June	0.05	0.27	−0.20
	July	−0.01	−0.10	−0.08
	August	0.08	−0.43*	0.22
	September	−0.36	−0.43*	−0.25
	October	0.21	−0.14	0.15

6. Relationships between cyclone frequency and intensity and temperature and precipitation regimes in the Great Lakes region

Daily values of air temperature and precipitation averaged for the region were obtained from the Great Lakes Environmental Research Laboratory (GLERL). These data were spatially averaged from individual stations within the region by a Thiessen weighting technique developed by Croley and Hartmann (1985). The daily temperatures and precipitation amounts were subsequently averaged and summed respectively over monthly, seasonal, and annual time periods for each year between 1900 and 1990.

Table 2 shows the correlation coefficients for the relationships between the frequency and intensity of all cyclones (1900–38 and 1966–90 datasets combined) and temperature and precipitation within the Great

TABLE 2. Relationships between the frequency and intensity of cyclones and average temperature and precipitation within the Great Lakes region. Correlation coefficients shown for the combined all cyclone (1900–38 and 1966–90) and strong cyclone (1900–90) datasets stratified by month and grouped into cold and warm seasons. An asterisk indicates that a relationship is statistically significant at $\alpha = 0.05$.

	All cyclones 1900–38 and 1966–90				Strong cyclones 1900–90	
Time period	Frequency vs temperature	Frequency vs precipitation	Intensity vs temperature	Intensity vs precipitation	Frequency vs temperature	Frequency vs precipitation
November	−0.17	0.20	−0.05	0.14	0.00	0.29*
December	−0.17	0.07	−0.09	−0.07	0.23*	0.17
January	0.07	0.07	−0.07	−0.07	0.17	0.30*
February	0.05	0.29*	−0.03	−0.05	0.18	0.33*
March	−0.07	0.10	0.22	−0.17	0.02	0.39*
April	−0.15	0.18	0.10	−0.23	−0.08	0.36*
Cold season	−0.20	0.03	0.36*	0.27	0.00	0.05
May	−0.10	0.37*	0.17	−0.37*	−0.13	0.15
June	−0.39*	0.31*	0.16	−0.11	−0.14	0.13
July	−0.30*	0.36*	0.16	−0.16	0.03	0.11
August	−0.34*	0.28*	0.24	0.12	−0.25*	0.06
September	−0.09	0.06	−0.01	0.03	0.00	0.24*
October	−0.32*	0.32*	0.21	−0.14	−0.32*	0.44*
Warm season	−0.32*	0.12	0.05	0.16*	−0.22*	0.17
Annual	−0.31*	−0.01	0.05	0.29*	−0.02	0.06

Lakes region. Cyclone frequency is inversely related to temperature and directly related to precipitation within the Great Lakes region for most of the categories. The relationships are statistically significant for the June, July, August, October, warm season, and annual time periods. In contrast, the signs of the correlations between cyclone intensity and the climate variables are inconsistent and not statistically significant for most of the categories. Table 2 also indicates that air temperature decreases during the warm season as the frequency of strong cyclones increases (and vice versa), although the signs of the correlations for the individual months are inconsistent and are statistically significant for only three of the months. As is the case for all cyclones, the frequency of strong cyclones is directly related to precipitation within the region, with statistically significant correlations for the months from September through April with the exception of December.

Agee (1991) analyzed the trends in the frequency of cyclones and anticyclones for the Northern Hemisphere during periods of warming and cooling in the twentieth century. Using the National Aeronautics and Space Administration temperature dataset for the Northern Hemisphere (Hansen and Lebedeff 1988), and cyclone and anticyclone frequency statistics from Zishka and Smith (1980), Parker et al. (1989), and Hosler and Gamage (1956), he identified a positive relationship between frequency and temperature. The frequency of cyclones and anticyclones increased within the Northern Hemisphere during the warming trend between 1900 and 1940 and decreased during the cooling period between 1940 and 1978. Agee suggests that warmer than normal temperatures in North America tend to occur during periods of zonal flow when numerous, yet relatively weak, disturbances traverse the continent, while colder than normal conditions are characterized by stronger, less numerous disturbances migrating eastward. The statistically significant inverse relationship between cyclone frequency and temperature within the Great Lakes region for the annual series (Table 2) provides an example where the relationship between cyclone frequency and temperature at a regional scale differs from that at a continental scale. The strong negative correlations for the warm season months suggest that cloud cover may play an important role in the association of temperature and cyclone frequency within the Great Lakes region.

Rodionov (1994) examined the relationship between cyclone frequency and precipitation within the Great Lakes basin for the 10 wettest and 10 driest Januarys. The change from dry to wet regimes was accompanied by an increase of cyclones from the Colorado region and a slight decrease in Alberta cyclones. The combined result was a positive relationship between cyclone frequency and precipitation, which is consistent with our findings shown in Table 2. An analysis of relationships among cyclone frequency and intensity, their source regions, and temperature and precipitation regimes using the datasets presented herein are the focus of an ongoing study on the tracks of Great Lake cyclones.

7. Summary

Cyclones are an important feature of the Great Lakes region with important impacts on lake temperature structure, ice cover, shipping, and shoreline property damages. Despite the importance of cyclones to the region, few studies have examined their features. The objective of this research is to construct a climatology of cyclones that traversed the Great Lakes between 1900 and 1990.

The climatological analysis is divided into three sections. In the first section, the frequency and intensity of all cyclones (a 64-yr, discontinuous record) and the frequency of strong cyclones (a 90-yr, continuous record) that passed over the Great Lakes are investigated. The number of strong Great Lakes cyclones during the annual, cold season, November, and December time periods increased significantly over the 90-yr record. Strong cyclones are those whose central pressure was ≤992 mb within the Great Lakes region. The number of strong cyclones per year more than doubled for both November and December. The frequency of all cyclones in the annual and warm season time series and the central pressure of all cyclones in the annual, cold, and warm season time series displayed significant decreases from 1900 to 1938. These findings are different from previous studies of larger-scale trends in cyclones over North America and the Northern Hemisphere.

In the second section, the relationship between cyclone frequency and intensity is explored. Using all cyclones from the 1900–38 period, the correlation between cyclone frequency and central pressure is positive. As the number of cyclones per year increases, their average pressure increases (i.e., their intensity decreases). An examination of the cyclone and anticyclone frequencies for the same period indicate a positive relationship between the two. An inverse relationship exists between the central pressure of cyclones and anticyclones. As the cyclones become stronger (lower pressure), so do the anticyclones (higher pressure). While the statistical relationships are not strong, they indicate that there is some compensation between cyclone frequency and pressure as well as between cyclone and anticyclone activity that maintains the pressure field in the Great Lakes region over the long term.

In the final section, the cyclone frequency and intensity of Great Lake cyclones are related to midtropospheric circulation patterns and regional air temperature and precipitation regimes. A comparison of the PNA index with the frequency and intensity of all cyclones for the period 1966–90 shows a significant inverse relationship with the frequency for the months of November, January, and March. For strong cyclones (≤992 mb), there are significant negative relationships in November, December, and January. These results indicate that lower cyclone frequency is associated with more zonal flow, and higher cyclone frequency is associated with more meridional flow. Comparisons of cyclone characteristics with temperature and precipitation in the Great Lakes region shows that cyclone frequency is inversely related to temperature and directly related to precipitation for most categories of months and seasons. In contrast, the relationships between cyclone intensity and climate variables are inconsistent.

This is the first study to document an increase in the frequency of strong cyclones over the Great Lakes during the twentieth century. The increase was statisitically significant for the annual, November, and December time series. The results of this study also suggest that the assumption often stated explicitly or implicitly in studies of the impacts of future climate change in the Great Lakes region that characteristics of cyclones have not or will not change over time is invalid. The relationships between cyclone characteristics and temperature and precipitation presented herein should be useful in climate change studies and for applications with the NWS long-range forecasts.

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