Zones of Origin for Great Lakes Cyclones in North America, 1899–1996

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ABSTRACT

The zones of origin for all cyclones that traversed the Great Lakes region from 1899 to 1996 are analyzed using a digital daily record of central pressure and location for individual cyclones. Plots of latitude of formation show that Great Lakes cyclones form (or reform) east of the Rocky Mountains at all latitudes between 25° and 65°N. In winter, about the same number of cyclones originate to the northwest as to the southwest of the Great Lakes region. In spring, the southwest zone is dominant. The number of summertime cyclones is greatly reduced, with the west zone of origin most active, while the fall plot displays a transition between the summer and winter distributions. The proportion of strong Great Lakes cyclones that originate in the southwest zone is greater than for all cyclones; however, the seasonal shifts in the latitudinal distributions of origin in the two datasets are similar.

An analysis of differences in frequencies by zone of origin for Great Lakes cyclones during months characterized by positive and negative Pacific–North American (PNA) index patterns reveals a statistically significant relationship between the midtropospheric flow pattern and cyclogenesis. The results indicate that the number of cyclones per month for the positive (PNA index > 0.5) and negative (PNA index < -0.5) categories are approximately equal and that the combined frequencies for positive and negative PNA pattern categories for the northwest, west, and southwest zones of origin are similar. The study supports the intuitive assertion that more Great Lakes cyclones originate from the northwest during months characterized by positive PNA index values than the negative pattern while more cyclones from the west and southwest are associated with the negative PNA index pattern than the positive one.

Approximately 20% of the cyclones that traversed the Great Lakes from 1899 to 1996 originated in the region. The most noteworthy and puzzling finding of the study is that cyclogenesis over the lakes as a proportion of cyclone presence in the region is highest in the summer months. This result corresponds with the finding that cyclones traversing the Great Lakes region in May–July accelerate as they approach the region and increase their rates of deepening over the lakes.

1. Introduction

Weather in the Great Lakes region of North America is generally characterized by an alternating series of low and high pressure systems moving eastward in a prevailing westerly circulation. These cyclones, with their attendant winds, clouds, precipitation, and temperature phenomena, account for much of the inclement weather within this continental interior region. The storms not only govern much of the variability of day-to-day weather, but their frequency, paths, and area of formation also affect the seasonal and annual variation in precipitation and temperature (Reitan 1979; Agee 1991; Rodionov 1994). In the Great Lakes region, the strongest of these cyclones have been responsible for significant loss of human life and property (Eichenlaub 1979). Historically, the severity of storms on the Great Lakes was measured in terms of the number of ships or lives taken (Lewis 1987). With the dramatic increase in use and value of lakeshore property over the past decades, the economic cost of the shoreline erosion caused by these storms, especially when lake levels are high, has become increasingly important (Changnon 1987).

Prompted by the need to better forecast the frequency

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and movement of cyclones into the region, Garriott (1903) documented the surface pressure and air temperatures of 238 strong cyclones that traversed the Great Lakes between 1876 and 1900. He identified the U.S. Southwest, Midwest, Northwest, and the Gulf of Mexico as the primary source regions for these storms. The first comprehensive study of cyclone tracks in the United States delineated nine paths commonly followed by low pressure centers crossing the country from 1892 to 1912 (Bowie and Weightman 1914). The authors cataloged the position of low pressure centers at 24-h intervals using 5° latitude by 5° longitude grids. Five of the cyclone tracks (Alberta, North Pacific, northern Rockies, Colorado, and central) traverse the Great Lakes region and represent 77% of the 2597 cyclones enumerated, with the Alberta type alone accounting for 38% of the total.

Numerous subsequent studies (Table 1) have presented tracks of cyclones passing over the Great Lakes region of North America, stratifying the cyclone data by central pressure, month, season, and/or year. For most of these studies, the storm tracks were calculated by counting the cyclones that passed through each cell of a grid defined by lines of longitude and latitude. Isopleth maps were then created from the cell totals, often weighted by grid cell area, to identify regions of high frequency. The resulting elongated zones were considered preferred cyclone tracks. To avoid area inequality and directional bias associated with using grid systems to catalog cyclone paths, Changnon et al. (1995) and Angel (1996) enumerated cyclones within a fixed radius of selected points. Despite the use of different methodologies, grid intervals, and periods of record, the results of the storm track studies in Table 1 are similar (e.g., Klein 1957; Reitan 1974). For January, the contour maps show two cyclone pathways into the Great Lakes region, a primary path beginning in Alberta and a secondary track starting in Colorado, while a third pathway parallels the east coast of North America. Maps for April usually depict the same two pathways through the Great Lakes region, with the southern one dominant. The primary cyclone track into the region on July maps follows the United States–Canada border, and on October isopleth maps, the cyclone tracks appear similar to those for January.

The objective of this study is to analyze the paths of cyclones moving into the Great Lakes region using a complete dataset spanning from 1899 to 1996. The 98-yr digital dataset provides the capability of resolving characteristics of individual cyclones. Previous studies of Great Lakes cyclone tracks (Table 1) either were based on datasets containing counts of cyclones that moved through grid cells during a sequence of years, restricting subsequent research to analyses of temporal and spatial variations in cyclone frequencies, or were based on datasets containing relatively short or noncomprehensive time series of individual cyclones.

In this study, seasonal changes in the location of genesis of Great Lakes cyclones are analyzed. Here, cyclogenesis refers to the development of a cyclone as opposed to its strengthening, and is denoted by the first appearance of a closed low pressure center. A second focus of the research is the relationship between midtropospheric flow patterns as indicated by the Pacific–North American (PNA) index and preferred zones of cyclone origin. The influence of the Great Lakes on the speed and intensity of passing cyclones, as well as secular trends in frequency and central pressure of Great Lakes cyclones and their relationships to the PNA index have been characterized elsewhere by Angel and Isard (1997, 1998).

2. Data

Three datasets were combined into the 98-yr record of cyclones within the Great Lakes region (defined by 40°–50°N latitude and 93°–75°W longitude, Fig. 1) used in this study. Two were obtained in digital form from the National Climatic Data Center (NCDC). Klein's (1957) data were abstracted from daily maps of pressure centers for North America appearing on the Northern Hemisphere Historical Weather Maps (U.S. Weather Bureau 1944) covering the period from 1899 to 1938. In addition, the National Oceanic and Atmospheric Association's (NOAA) working tape of cyclone tracks for 1965 to the present was utilized. Both datasets contain 1200 UTC (0700 EST) observations of central pressure in whole millibars and cyclone center location to the nearest whole degree of latitude and longitude. Central pressure and location at 1200 UTC for each cyclone that passed through the Great Lakes region were extracted from monthly cyclone maps in the *Monthly Weather Review* for the 1939–58 period, and from the NOAA publication *Storm Data* (1959–65) to complete the time series. For all three datasets, a cyclone was defined as a closed low pressure center with at least one 4-mb contour that persisted for $\geq$24 h.

Because the number of National Weather Service stations reporting surface air pressure in the region increased from 38 in 1901 to 262 in 1980 (Angel and Isard 1998), potential problems relating to the homogeneity of the combined dataset were examined. It was anticipated that the overall increase in spatial resolution of observations might have resulted in an increase through the century in the number of cyclones reported and a lowering of central pressure observations (Nicholls 1995). Consequently, the cyclone time series was stratified into five periods with respect to the change in the number of stations [see Fig. 4 in Angel and Isard (1998)]: 1) moderate increase until 1925, 2) dramatic increase from 1926 to 1950, 3) moderate increase from 1951 to 1965, 4) dramatic increase from 1966 to 1975, and 5) a gradual decrease thereafter. Differences among the distributions are not statistically significant. Although mean cyclone frequency for the periods ranged from 53.6 to 70.5 yr^{-1}, the mean of lowest central pres-

TABLE 1. Studies of cyclone tracks that include paths through the Great Lakes region.

Author(s) and date	Grid interval	Spatial coverage/period of record	Resolution of maps	General comment
Finley 1884	2.5° × 2.5°	North America and Europe 1864–83	Monthly	Relative frequency within grid cells calculated for 154 cyclones from a variety of data sources.
Bigelow 1897	—	United States 1877–97	Monthly	Individual storm tracks plotted for each month and representative paths drawn freehand.
Garriott 1903	—	Great Lakes Region 1876–1900	Individual cyclones	Mapped pressure and temperature over 32- to 48-h periods for 238 individual storms.
Bowie and Weightman 1914	5° × 5°	United States 1892–1912	Cyclone type and monthly	Frequency of low pressure centers within grid cells. Used cyclone locations for 24-h intervals.
Kullmer 1933	5° × 2.5°	United States 1883–1930	Monthly	Frequency of cyclone tracks within grid cells.
Hurley 1954	—	U.S. Midwest (50°–30°N, 85°–100°W) 1920–29	Summer, winter, and annual	Classified direction of movement (octants) of low pressure centers for 12-h intervals.
Hosler and Gamage 1956	5° × 5°	United States 1905–54	Monthly	Frequency of occurrence of cyclone tracks within grid cells.
Klein 1957	5° × 5°	Northern Hemisphere 1899–1939	Monthly	Frequency of low pressure centers within grid cells. Used cyclone location at 1230 GMT.
Reitan 1974	≈8° × 8°	North America 1951–70	Jan, Apr, Jun, Jul, and Oct	Frequency of cyclone tracks within grid cells.
Colucci 1976	1° × 1°	Eastern United States (48°–25°N, 65°–90°W) 1946–73	Winter	Frequency of cyclone tracks within grid cells.
Brennan and Smith 1978	2° × 2°	U.S. Midwest (52°–32°N, 78°–98°W) 1950–74	Seasonal	Frequency of cyclone tracks within grid cells
Harman et al. 1980	—	Lakes Superior, Huron, and Michigan 1955–76	Nov	Point of origin east of Rocky Mountains with respect to 42°N used to classify tracks.
Zishka and Smith 1980	2° × 2°	North America 1950–70	Jan and Jul	Frequency of cyclone tracks within grid cells.
Whittaker and Horn 1984	5° × 5°	Northern Hemisphere 1958–77	Jan, Apr, Jul, and Oct	Frequency of cyclone tracks within grid cells.
Lewis 1987	—	Great Lakes Region 1957–85	Individual cyclones	Shows a surface map and track for 100 severe storms over the Great Lakes.
Changnon et al. 1995	5° × 5°	North America 1950–93	Seasonal and annual	Frequency of cyclone tracks within equal area circles.
Angel 1996	1° × 1°	Great Lakes Region, and Superior, Michigan-Huron-St. Clair, and Erie-Ontario subregions 1899–1990	Seasonal	Frequency of strong cyclones (central pressure $<$ 992 mb) within equal area circles. Included cyclones from Klein (1957).

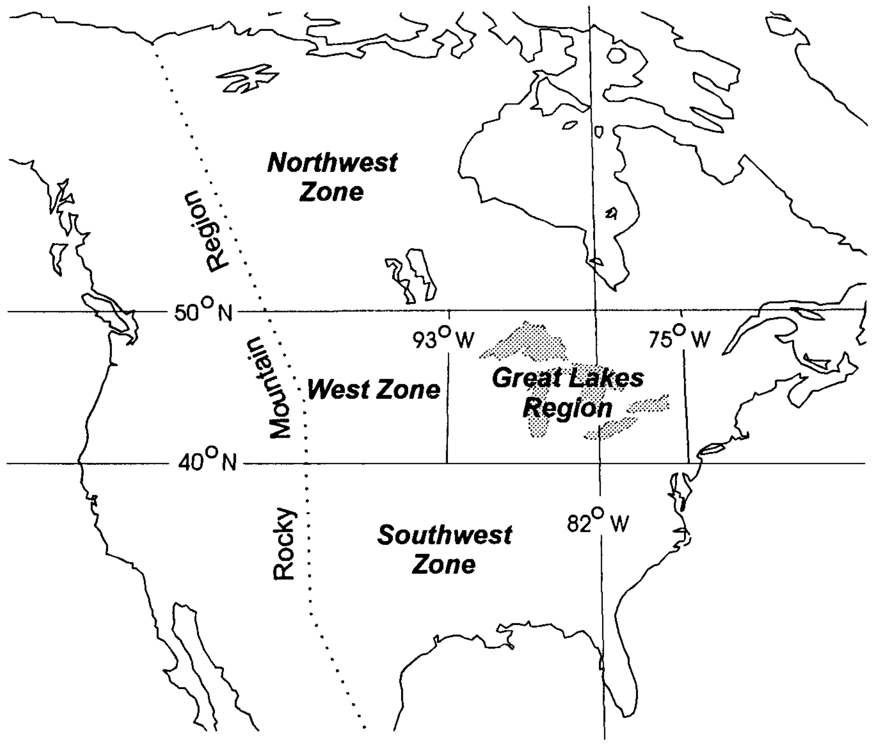

FIG. 1. Map of North America showing Great Lakes region and zones of cyclone origin used in this study. The dotted line approximates the eastern boundary of the Rocky Mountain region.

sure observations within the region ranged only from 1001.3 to 1002.1 mb. Neither cyclone frequency nor pressure appear to vary systematically with the spatial resolution of the observations (Fig. 2).

The effect of dataset coarseness (24-h time resolution) on the location and frequency of cyclogenesis was evaluated using the 6-h resolution data in NOAA's working tape of cyclone tracks from January 1996 through December 1984. Figure 3 shows cyclogenesis in the Great Lakes region stratified by time of observation and month for this 19-yr period. The number of cyclones that were first noted at the 0000, 6000, 1200, and 1800 UTC varied greatly for many of the months and no systematic variation in the time of cyclogenesis across months or seasons is apparent. Total cyclogenesis for each month using the 24- and 6-h resolution datasets are also presented in Fig. 3. A comparison of the two plots shows that cyclogenesis in the region was greater using the 24-h rather than 6-h resolution dataset for most months. This indicates that more cyclones formed upstream over land and subsequently tracked into the region before being recorded in the 24-h resolution dataset than formed over the Great Lakes and tracked downstream over land prior to observation. The 24- and 6-h resolution datasets disclose that 22% and 19% of the cyclones present over the Great Lakes during the 19-yr period originated within the region, respectively. It was anticipated that the temporal coarseness of the dataset would result in greater errors in cyclogenesis counts for the cold (November–April) than the warm (May–October) months because of differences in the speeds of Great Lakes cyclones during the two seasons (cyclone speeds averaged 48 km day^{-1} and 42 km day^{-1} for the two seasons, respectively). Although 60% of the 44 Great Lakes cyclogenesis events that were in the 24- but not the 6-h resolution dataset occurred in October, December, and February combined, the effect of temporal resolution on cyclogenesis was small for November, January, March, and April.

The distribution of lowest central surface pressure observation is used to identify a subset of strong Great Lakes cyclones. It should be noted that there are situations, such as when a cyclone is embedded in a large-scale region of low pressure, where central pressure is not a good indication of cyclone intensity (e.g., Sinclair 1994). However, central pressure has been used as an indication of cyclone intensity in a large number of climatological studies, including Hurley (1954), Brennan and Smith (1978), Harman et al. (1980), Zishka and Smith (1980), Angel (1996), and Angel and Isard (1997, 1998). Angel (1996) showed that the relationship between lowest central pressure and the pressure gradient for the 112 Great Lakes cyclones reported in *Storm Data* between 1959 and 1990 was statistically significant. Although measurements of cyclonic geostrophic relative vorticity can provide a more rigorous, physically based estimate of cyclone intensity (Sinclair 1994), the record of global analyses of atmospheric fields [NCEP–NCAR

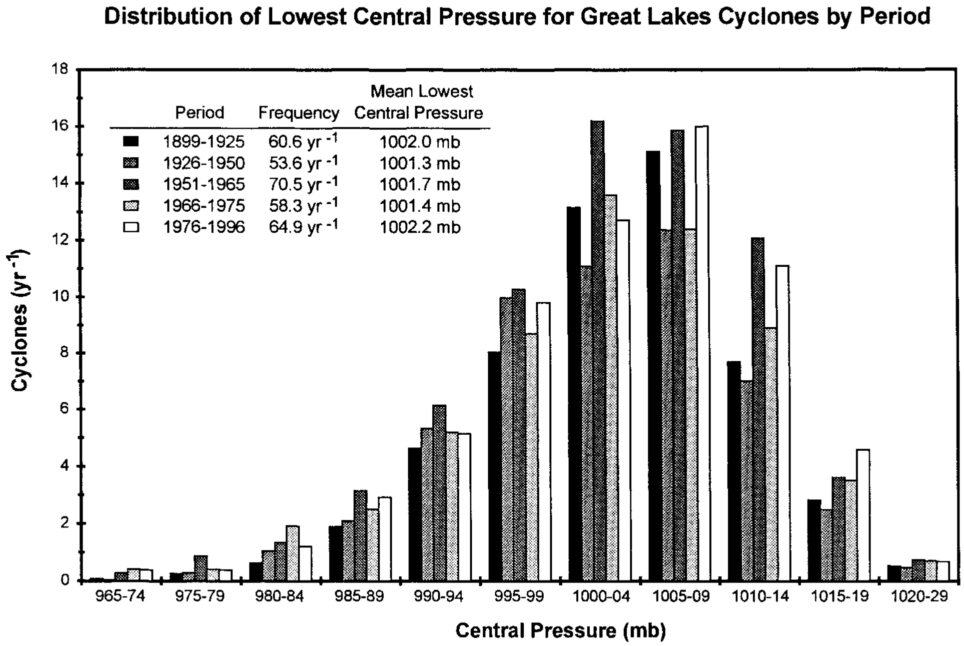

FIG. 2. Distribution of lowest central pressure for five periods of record. All cyclones that originated in or tracked through the Great Lakes region are included. Central pressure values are missing for 122 (7%), 37 (3%), 1, 0, and 0 of the cyclones in the 1899–1925, 1926–50, 1951–65, 1966–75, and 1976–96 periods, respectively. Analysis of variance was used to evaluate the homogeneity of the combined dataset. Differences among the five distributions are not statistically significant ($\alpha = 0.05$).

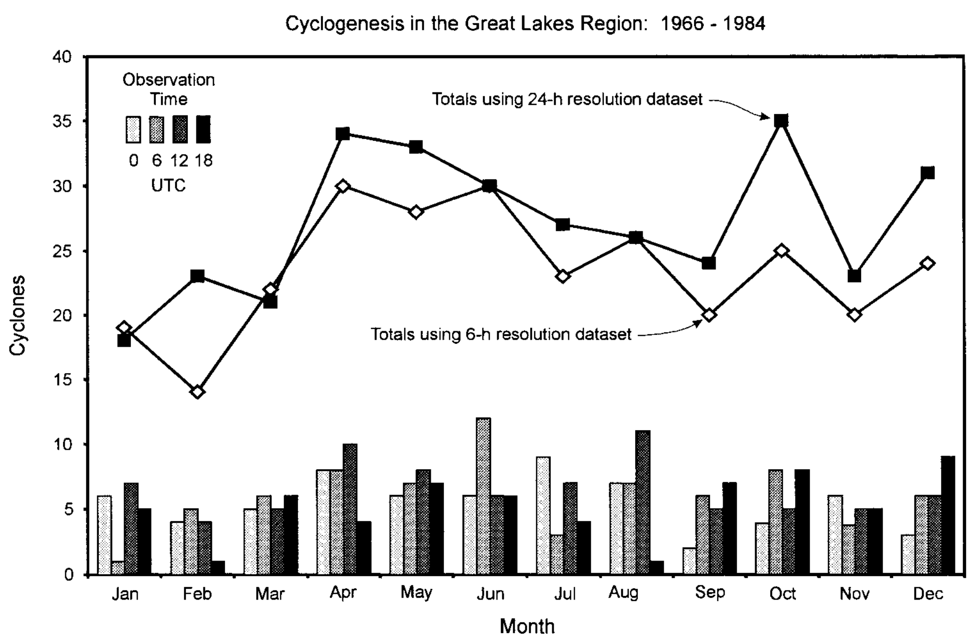

FIG. 3. Cyclogenesis in the Great Lakes region stratified by time of observation and month for 1966–84 (vertical bars). Total cyclogenesis for each month over the 19-yr record using the 24- (solid squares) and 6-h resolution dataset (hollow triangles). The 24- and 6-h datasets contain 325 and 281 cyclones that originated over the Great Lakes region during the 19-yr period, respectively.

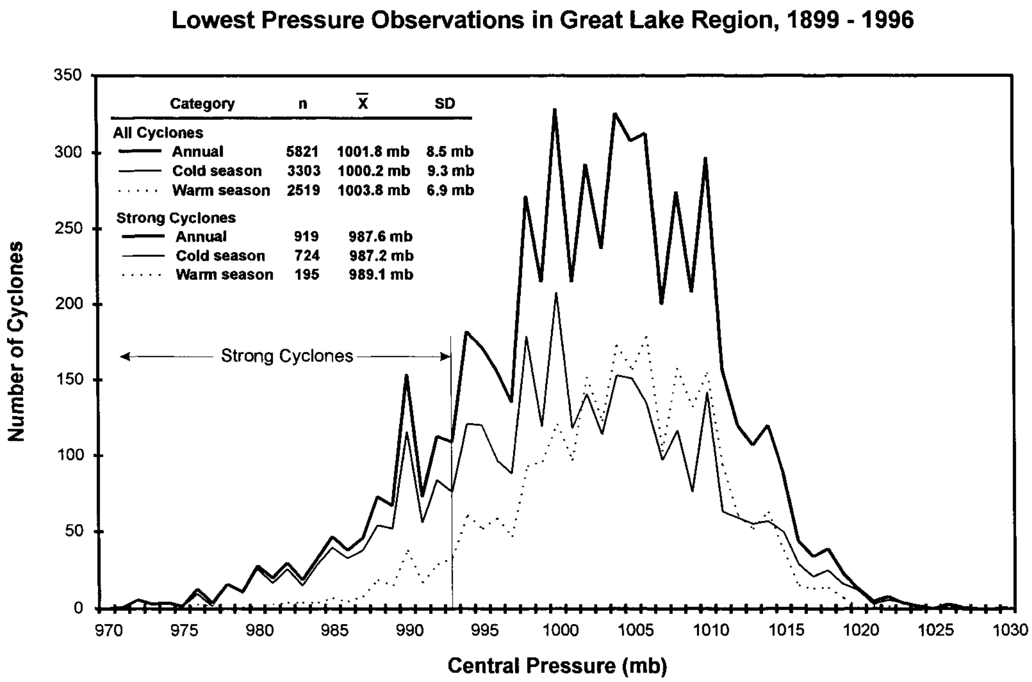

FIG. 4. Distribution of lowest central surface pressure observations over the Great Lakes for all cyclones and strong cyclones that traversed the region between 1899 and 1996. Data are stratified into annual, cold season, and warm season categories. Strong cyclones are defined as those cyclones having a minimum surface pressure observation less than 1 standard deviation below the mean for the annual series.

global reanalysis project; Kalnay et al. (1996)] needed to calculate cyclonic geostrophic relative vorticity do not include the first half of the twentieth century.

Figure 4 displays the distribution of lowest central surface pressure observations for all cyclones within the Great Lakes region during the entire 98-yr record as well as distributions for cold season (November–April) and warm season (May–October) cyclones. The mean value of these observations for the annual series is 1001.8 mb with a standard deviation of 8.5 mb. Using reports of shoreline damage by Great Lakes cyclones cataloged in *Storm Data* between 1959 and 1990, Angel (1996) defined strong cyclones as those with minimum pressure values of $\leq$992 mb. For this study, strong Great Lakes cyclones will be defined as those having a minimum surface pressure observation <1 standard deviation below the mean for the annual cyclone series (i.e., $\leq$993 mb), a value only 1 mb higher than that used by Angel (1996) and Angel and Isard (1998). Seventy-nine percent of these strong cyclones traversed the Great Lakes region during the cold season.

Seventy-three percent of the 5821 cyclones in the 98-yr record appeared on weather maps as closed low pressure centers located west of the 82°W meridian of longitude prior to entering the Great Lakes region. Twenty percent of the cyclones in the dataset were first observed over the Great Lakes with the remaining 7% of Great Lakes cyclones entering the region from other directions, primarily the southeast. The analysis of the zones of origin of Great Lakes cyclones below focuses on the 4315 low pressure centers that were carried by the westerlies into the region from 1899 to 1996. Because of the lower numbers of cyclones that moved westward into the region ($\approx$4 cyclones/yr), these cyclones are excluded from subsequent analyses.

Gridded data for the 700-mb level provided by the National Centers for Environmental Prediction for 1958–91 (NCAR 1990) were used to calculate monthly values of the PNA index. This index provides a measure of the amplitude and longitudinal position of the ridges and troughs in the midtropospheric flow above North America and has been associated with regional temperature and precipitation regimes (Leathers et al. 1991; Rodionov 1994) and cyclone frequency and intensity in the Great Lakes region (Angel and Isard 1998). PNA index values were calculated based on a linear combination of the departures from the mean geopotential height (Z^*) at three locations following Yarnal and Diaz (1986):

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

Large positive PNA index values are associated with long waves in the midtropospheric flow above North America that are more amplified than normal and characterized by a ridge along the west coast and troughs over both the east–central North Pacific and eastern portion of the continent. In contrast, extreme negative val-

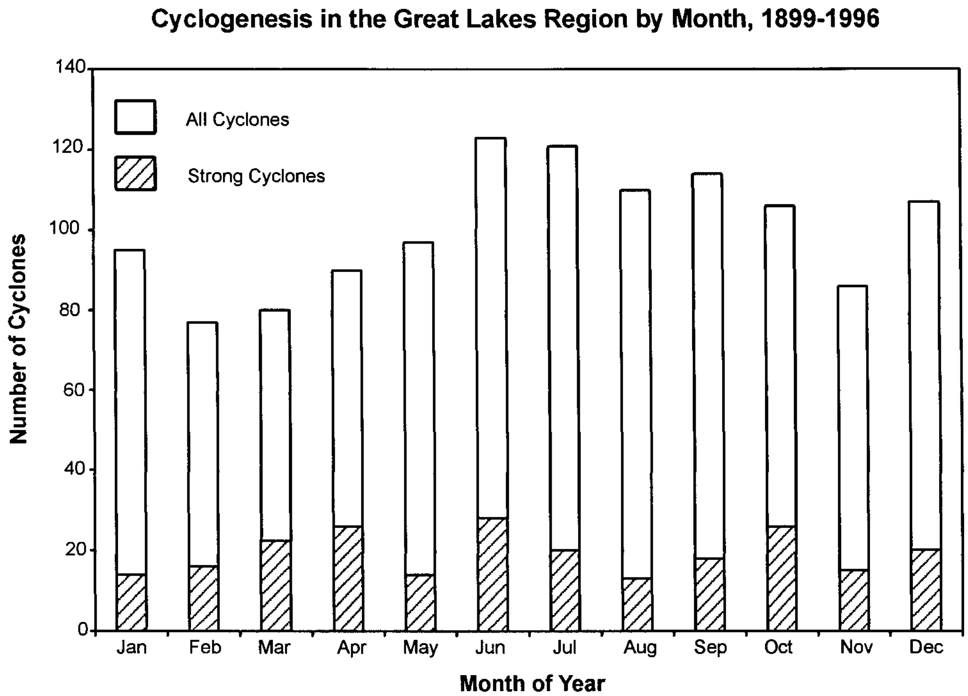

FIG. 5. The number of cyclones in all and strong categories that formed over the Great Lakes and subsequently tracked out of the region between 1899 and 1996, stratified by month. Cyclogenesis was defined by the first appearance of a closed low pressure center in the dataset.

ues represent a reverse flow pattern with an amplified trough along the west coast of North America and a ridge over both the east–central North Pacific and eastern North America. Near-zero values indicate that the PNA teleconnection is not active over North America. As noted in Angel and Isard (1998), there is no clear consensus for defining thresholds for separating the inactive, positive, and negative PNA flow patterns. In this study, we followed Vega et al. (1995) and used PNA index threshold values of ± 0.5 to delineate the three states of the PNA. The statistical significance of differences among frequencies of Great Lakes cyclones for months characterized by positive and negative PNA patterns stratified by zone of origin and season are evaluated using the distribution-free Wilcoxen rank-sums test at the 95% confidence level ($\alpha = 0.05$).

3. Cyclogenesis in the Great Lakes region

Cyclogenesis, as indicated by the first observation of a closed low pressure center, occurred within the Great Lakes region on 1527 occasions between 1899 and 1996. Approximately 79% of these cyclones subsequently tracked out of the region and 258 (17%) had at least one central pressure observation $\leq$993 mb (i.e., strong cyclone) while in the region. There is a slight seasonal variation in the number of cyclones that formed over the lakes and subsequently left the region during the 98-yr period of record (Fig. 5). Maximum frequencies occurred during the warm season ($>$1.2 cyclones month^{-1} for June and July) with a minimum in the late winter ($<$0.8 cyclones month^{-1} for February and March), although few cyclones formed over the lakes in November either. An examination of these data as a proportion of the total number of cyclones that were present in the region between 1899 and 1996 indicates that the Great Lakes region is a relatively active cyclogenesis area in the warm season (Fig. 6). From November to May, between 10% and 20% of the cyclones in the "all" and "strong" categories that were present over the lakes formed in the region. These proportions increased for June–October, reaching a maximum of 31% and 61% for all and strong cyclone categories in July.

4. Latitudinal zone of origin

The positions of formation for Great Lakes cyclones that moved into the region between 1899 and 1996 are shown in Fig. 7. The latitude of the first cyclone observation east of the Rocky Mountains and west of 82°W longitude are stratified by zone and season. The December–February plot (Fig. 7a) shows pronounced dual maxima centered at 37° and 50°–51°N. Approximately 28% and 36% of the 1228 winter cyclones entered the region from the southwest (latitude $<$ 40°N) and northwest (latitude $>$ 50°N), respectively. The southern cyclogenesis area near 37°N is clearly dominant from March to May (Fig. 7b) with 56% of the 1313 cyclones forming between 35° and 45°N latitude. The number of Great Lakes cyclones in June–August (Fig. 7c) is greatly

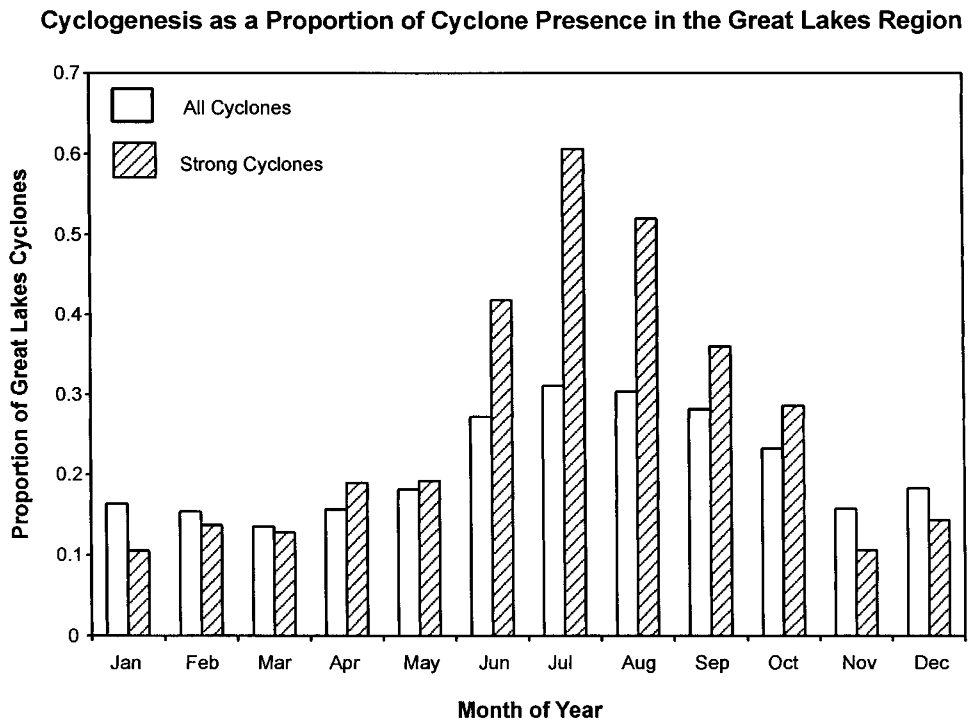

FIG. 6. Cyclones that formed over the Great Lakes and subsequently left the region as a proportion of the total number of cyclones present in the Great Lakes region between 1899 and 1996, stratified by month. Cyclogenesis was defined by the first appearance of a closed low pressure center in the dataset.

reduced (774) with the majority (58%) tracking into the region from the west. The plot for September–November shows the transition from the summer to winter latitudinal distributions with ≈30% of the 1000 cyclones in both the southwest and northwest categories (Fig. 7d). The number of Great Lakes cyclones that originated to the southwest and northwest of the region are approximately equal (29% and 28%, respectively) when the seasons are combined.

The latitudinal distributions of the position of formation for strong Great Lakes cyclones for the seasons of the year are similar to that for all cyclones. A notable exception is that they are skewed in favor of cyclones of southwest origin. The number of strong cyclones in the dataset that originated to the southwest and northwest of the region were 39% and 26%, respectively. The December–February plot (Fig. 8a) shows dual maxima centered at 37° and 51°N latitude, with the southern one clearly larger. Approximately 39% and 32% of the 316 strong winter cyclones entered the region from the southwest (latitude $<$ 40°N) and northwest (latitude $>$ 50°N), respectively. For March–May (Fig. 8b), 60% of the 300 strong cyclones formed between 35° and 45°N latitude and 20% originated northwest of the region. The majority (61%) of the 62 strong summer cyclones (Fig. 8c) tracked into the region from the west. Again, the plot for September–November shows the transition from the summer to winter latitudinal distributions with 37% and 27% of the 208 strong cyclones in the southwest and northwest categories (Fig. 8d).

5. Relationship between midtropospheric flow pattern and zone of origin

The mean number of cyclones that moved over the Great Lakes from west of the 82°W meridian of longitude stratified by season (and year) and zone of origin were calculated for months characterized by positive ($>$0.5) and negative ($<-$0.5) PNA patterns during the 1958–91 period (Table 2). For the annual, winter, and fall categories, the frequency of cyclones from the northwest zone of origin are significantly greater during months with positive than negative PNA patterns. In contrast, the number of cyclones are significantly larger for the negative than positive PNA modes for the annual and fall series when the cyclones originated to the west of the Great Lakes region and for the annual and winter series when the zone of origin was southwest.

The mean frequency of strong Great Lakes cyclones by zone of origin for months characterized by positive and negative PNA patterns are shown in Table 3. The number of strong cyclones are significantly larger for the negative than positive PNA pattern categories for the annual series, when the cyclones originated to the southwest of the Great Lakes region. Differences for the west zone of origin in annual, winter, and spring seasons

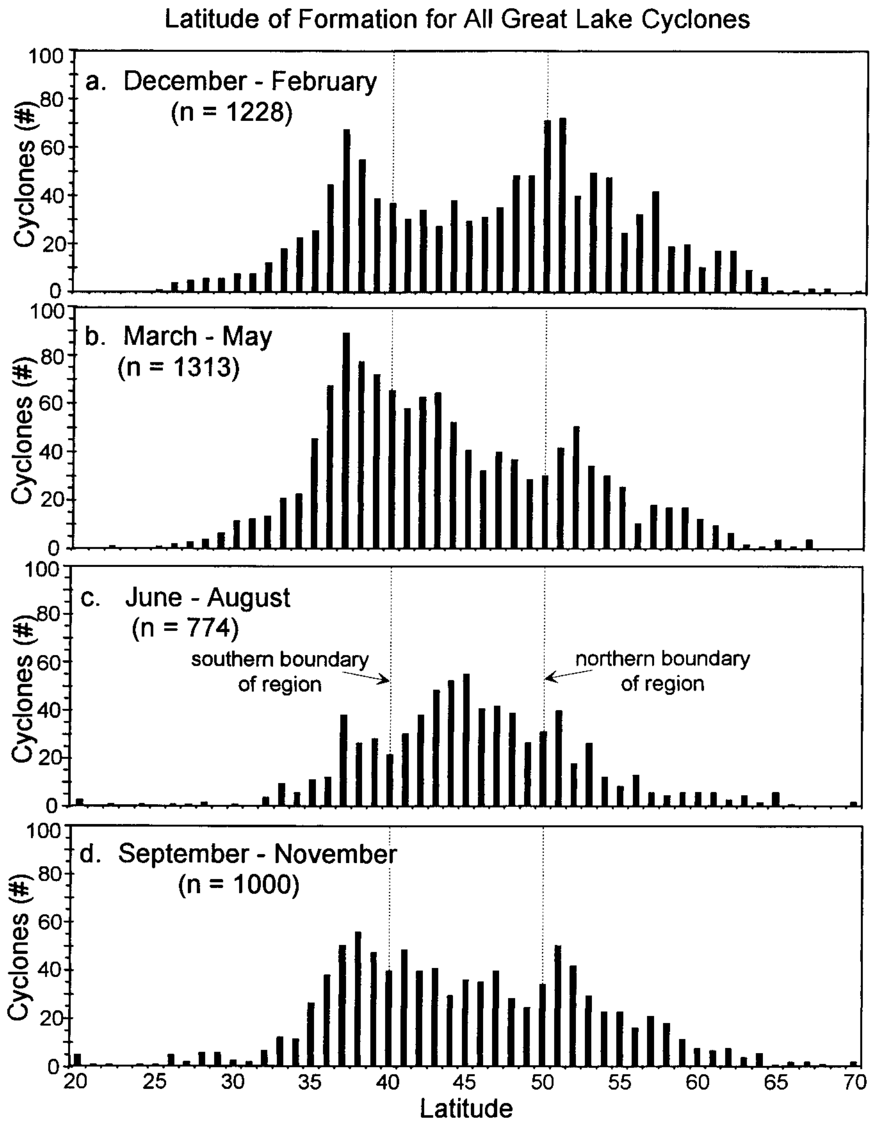

FIG. 7. The latitude of formation for Great Lakes cyclones that moved into the region from 1899–1996. Data include the first observation for each cyclone that occurred east of the Rocky Mountains and west of 82°E longitude and are stratified by season.

are also statistically significant; very few strong cyclones entered the Great Lakes region from the west during months with positive PNA patterns (only 10 in the 34 yr analyzed).

6. Summary

Numerous studies have linked extreme weather events and seasonal variations in precipitation and temperature in the Great Lakes region with cyclones from particular zones of origin. Examples include severe winter storms (Changnon 1969), November cold waves (Wendland 1987), high winter precipitation (Rodionov 1994), and snowfall (Leathers and Ellis 1996).

This study analyzed the zone of origin for all cyclones that traversed the Great Lakes region over a 98-yr period. In general, the results of the analysis of the daily observations of central pressure and location for individual cyclones concur with those from previous studies of cyclone frequency and tracks listed in Table 1. The plots of latitude of formation (Fig. 7) show that eastwardly moving cyclones form (or reform) east of the Rocky Mountains at all latitudes between about 25° and 65°N. The winter plot shows maxima in the latitudinal distribution of zones of cyclone origin both northwest and southwest of the Great Lakes region. In spring, the frequency of cyclones from the northwest is less than in winter and the southwest zone is dominant. The number of summertime cyclones is greatly reduced with the west zone of origin most active, while the fall plot dis-

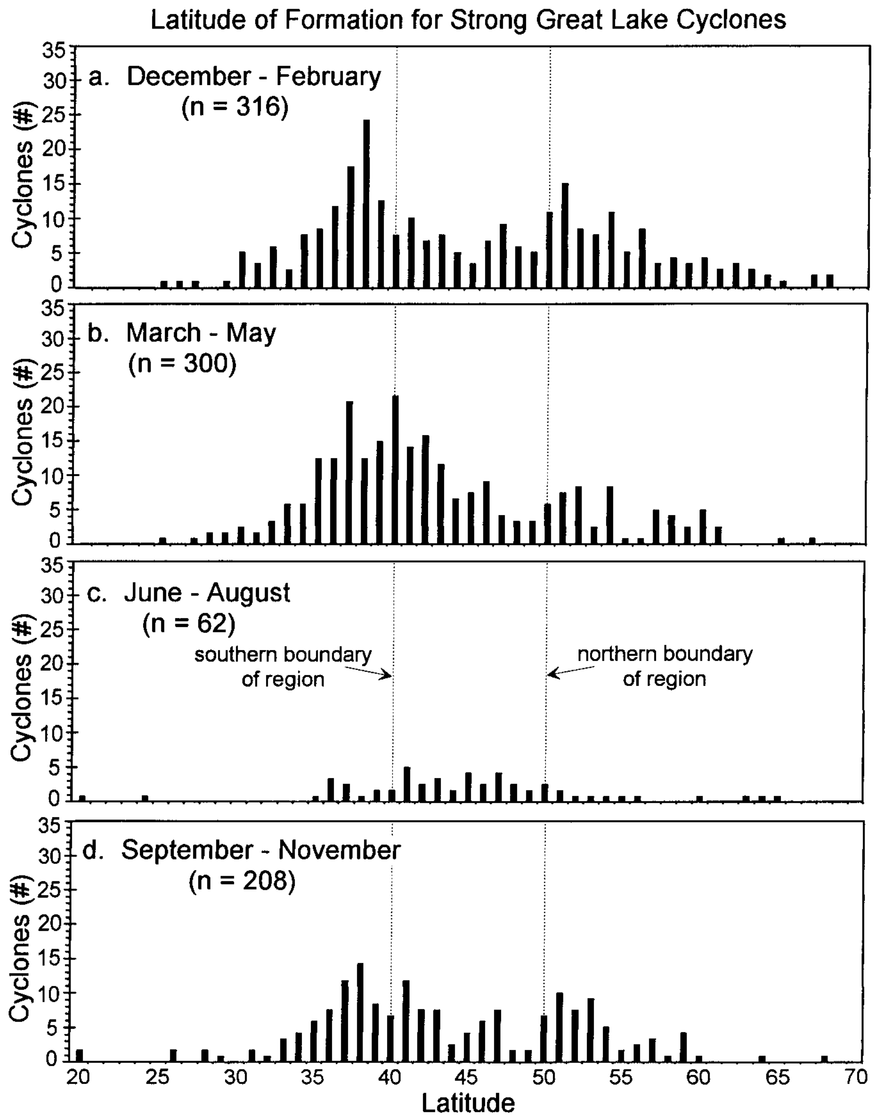

FIG. 8. The latitude of formation for strong Great Lakes cyclones that moved into the region from 1899 to 1996. Data include the first observation for each cyclone that occurred east of the Rocky Mountains and west of 82°E longitude and are stratified by season.

TABLE 2. Great Lakes cyclone frequency (cyclones month^{-1}) by zone of origin and season for months with positive and negative PNA patterns. For each zone of origin and season (or annual category), the differences between monthly frequencies for months with positive (>0.5) and negative (<−0.5) PNA patterns were tested for statistical significance using the standard two-tailed t-test. Number of months in each category (n) shown in the bottom row. Differences between values with asterisks in each zone and season (or annual) categories are statistically significant at $\alpha = 0.05$.

Zone of origin	Annual		Winter		Spring		Fall	
	>0.5	<−0.5	>0.5	<−0.5	>0.5	<−0.5	>0.5	<−0.5
Northwest	1.52*	0.95*	2.26*	1.33*	0.89	0.81	1.68*	0.90*
West	1.03*	1.38*	0.95	1.18	1.19	1.47	0.65*	1.37*
Southwest	0.94*	1.31*	0.83*	1.45*	1.61	1.94	0.91	1.22
n	139	141	42	40	36	36	34	41

TABLE 3. Frequency (cyclones month^{-1}) by zone of origin and season for months with positive and negative PNA patterns for strong Great Lakes cyclones. For each zone of origin and season (or annual category), the differences between monthly frequencies for months with positive (>0.5) and negative (<−0.5) PNA patterns were tested for statistical significance using the standard two-tailed *t*-test. Number of months in each category (*n*) shown in the bottom row. Differences between values with asterisks in each zone and season (or annual) categories are statistically significant at $\alpha = 0.05$.

Zone of origin	Annual		Winter		Spring		Fall	
	>0.5	<−0.5	>0.5	<−0.5	>0.5	<−0.5	>0.5	<−0.5
Northwest	0.19	0.12	0.40	0.25	0.03	0.08	0.26	0.10
West	0.07*	0.31*	0.07*	0.33*	0.11*	0.44*	0.09	0.32
Southwest	0.22*	0.35*	0.21	0.43	0.42	0.61	0.18	0.27
n	139	141	42	40	36	36	34	41

plays a transition between the summer and winter distributions. The seasonal shifts in the latitudinal distributions of origin of strong Great Lakes cyclones (Fig. 8) is similar to that for all cyclones, but indicates that a greater percentage of strong cyclones that traverse the lakes track from the southwest than the northwest.

The analysis of differences in frequencies by zone of origin for Great Lakes cyclones during months characterized by positive and negative PNA index patterns reveals an interesting relationship between the midtropospheric flow pattern and cyclogenesis (Table 2). In the annual series, the number of months and the number of cyclones per month for the positive and negative categories were approximately equal (139 and 141 months; 3.49 and 3.64 cyclones month^{-1}, respectively). Likewise, the combined frequencies for positive and negative pattern categories for the northwest, west, and southwest zones of origin were similar (2.47, 2.41, and 2.25, respectively). As anticipated, more Great Lakes cyclones from the northwest occurred during the positive PNA pattern while more cyclones from the west and southwest were associated with the negative PNA pattern. This relationship is apparent in the strong Great Lakes cyclone dataset as well (Table 3), although the number of strong cyclones from the northwest zone is small (Fig. 8) and the difference in this category is not statistically significant.

One interesting finding of this study, not highlighted in previous literature, is that approximately 20% of the cyclones present over the Great Lakes between 1899 and 1996 originated within the region. Although this may suggest that the lakes, in aggregate, contribute to cyclogenesis, Fig. 5 shows that the seasonal variation in Great Lakes cyclogenesis is small (between 0.8 and 1.2 cyclones month^{-1}). The data do not indicate a maxima of Great Lakes cyclogenesis for the late fall and early winter months, when the potential for cyclogenesis is usually considered greatest (e.g., Angel and Isard 1997; Weiss and Sousounis 1999). Cyclogenesis over the lakes, as a proportion of cyclone presence in the region, is highest in the summer months (Fig. 6). Angel and Isard (1998) reported that cyclones traversing the Great Lakes region between 1965 and 1990 accelerated as they approached the region and increased their rates of deepening over the lakes in the stable season (May–July). Theory and numerous observational and modeling studies have shown that cyclone intensification is enhanced over the Great Lakes in early winter when heat and moisture provided by the water bodies destabilize the overlying air (e.g., Cox 1917; Petterssen and Calabrese 1959; Danard and Rao 1972; Danard and McMillan 1974; Boudra 1981; Sousounis and Fritsch 1994; Weiss and Sousounis 1999). In contrast, no satisfying explanation for the development and intensification of cyclones over the Great Lakes during the summer stable season has been suggested (Angel and Isard 1998). Some may question these results for this reason; however, they are based on our definition of cyclogenesis and the NCDC cyclone dataset. Clearly, further investigation is warranted from independent data sources such as the NCEP–NCAR reanalysis project and with objective schemes to detect relative minima in geopotential heights and geostrophic relative vorticity. Additional case studies with observed surface and upper-air data and analyses also would be informative.

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REFERENCES

Agee, E. M., 1991: Trends in cyclone and anticyclone frequency and comparison with periods of warming and cooling over the Northern Hemisphere. *J. Climate*, **4,** 263–266.

Angel, J. R., 1996: Cyclone climatology of the Great Lakes. Illinois State Water Survey, Misc. Publ. 172, 122 pp.

——, and S. A. Isard, 1997: An observational study of the influence of the Great Lakes on the speed and intensity of passing cyclones. *Mon. Wea. Rev.,* **125,** 2228–2237.

——, and ——, 1998: The frequency and intensity of Great Lakes cyclones. *J. Climate,* **11,** 61–71.

Bigelow, F. H., 1897: *Storms, Storm Tracks, and Weather Forecasting.* Weather Bureau, U.S. Department of Agriculture, 87 pp.

Boudra, D. B., 1981: A study of the early winter effects of the Great Lakes. I: Comparison of very finescale numerical simulations with observed data. *Mon. Wea. Rev.,* **109,** 2507–2526.

Bowie, E. H., and R. H. Weightman, 1914: Types of storms of the United States and their average movements. *Mon. Wea. Rev.,* Suppl. 1, 3–37.
Brennan, F. E., and P. J. Smith, 1978: The climatology of cyclones and anticyclones in the upper Mississippi and Ohio River Valleys and Great Lakes region, 1950–1974. *Proc. Indiana Acad. Sci.,* **87,** 391–402.
Changnon, D., J. J. Noel, and L. H. Maze, 1995: Determining cyclone frequencies using equal-area circles. *Mon. Wea. Rev.,* **123,** 2285–2294.
Changnon, S. A., Jr., 1969: *Climatology of Severe Winter Storms in Illinois.* Illinois State Water Survey, Bulletin 70, 177 pp.
——, 1987: Climate fluctuations and record-high levels of Lake Michigan. *Bull. Amer. Meteor. Soc.,* **68,** 1394–1402.
Colucci, S. J., 1976: Winter cyclone frequencies over the eastern United States and adjacent western Atlantic, 1964–73. *Bull. Amer. Meteor. Soc.,* **57,** 548–553.
Cox, H. J., 1917: Influence of the Great Lakes upon movement of high and low pressure areas. *Proc. Second Pan American Scientific Congress*, Vol. 2, 432–459.
Danard, M. B., and G. V. Rao, 1972: Numerical study of the effects of the Great Lakes on a winter cyclone. *Mon. Wea. Rev.,* **100,** 374–382.
——, and A. C. McMillan, 1974: Further numerical studies of the effects of the Great Lakes on winter cyclones. *Mon. Wea. Rev.,* **102,** 166–175.
Eichenlaub, V. L., 1979: *Weather and Climate of the Great Lakes Region.* University of Notre Dame Press, 335 pp.
Finley, J. P., 1884: *Charts of Relative Storm Frequency for a Portion of the Northern Hemisphere.* Signal Office, U.S. War Department, 9 pp.
Garriott, E. B., 1903: *Storms of the Great Lakes.* U.S. Department of Agriculture, Weather Bureau, 486 pp.
Harman, J. R., R. Rosen, and W. Corcoran, 1980: Winter cyclones and circulation patterns on the western Great Lakes. *Phys. Geogr.,* **1,** 28–41.
Hosler, C. L., and L. A. Gamage, 1956: Cyclone frequencies in the United States for the period 1905 to 1954. *Mon. Wea. Rev.,* **84,** 388–390.
Hurley, J. C., 1954: Statistics on the movement and deepening of cyclones in the middle west. *Mon. Wea. Rev.,* **82,** 116–122.
Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.
Klein, W. H., 1957: Principal tracks and mean frequencies of cyclones and anticyclones in the Northern Hemisphere. U.S. Weather Bureau Research Paper 40, 60 pp.
Kullmer, C. J., 1933: The latitude shift of the storm track in the 11-year solar period: Storm frequency maps of the United States, 1883–1930. *Smithsonian Miscellaneous Collections,* **89,** 1–34.
Leathers, D. J., and A. W. Ellis, 1996: Synoptic mechanisms associated with snowfall increases to the lee of lakes Erie and Ontario. *Int. J. Climatol.,* **16,** 1117–1135.
——, B. Yarnal, and M. A. Palecki, 1991: The Pacific–North American teleconnection pattern and United States climate. Part I: Regional temperature and precipitation associations. *J. Climate,* **4,** 517–528.
Lewis, P. J., 1987: Severe storms over the Great Lakes: A catalogue summary for the period 1957–85. Canadian Climate Center Rep. 87–13, Atmospheric Environment Service, Downsview, ON, Canada, 342 pp. [Available from Climatological Services Division, Atmospheric Environment Service, 4905 Dufferin St., Downsview, ON M3H 5T4, Canada.]
NCAR, 1990: *National Meteorological Center Grid Point Data Set, Version II.* Department of Atmospheric Sciences, University of Washington and the Data Support Section, National Center for Atmospheric Research, CD-ROM. [Available from National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307.]
Nicholls, N., 1995: Long-term climate monitoring and extreme events. *Climatic Change,* **31,** 231–245.
Petterssen, S., and P. A. Calabrese, 1959: On some weather influences due to warming of the air by the Great Lakes in winter. *J. Meteor.,* **16,** 646–652.
Reitan, C. H., 1974: Frequencies of cyclones and cyclogenesis for North America, 1951–1970. *Mon. Wea. Rev.,* **102,** 861–868.
——, 1979: Trends in the frequencies of cyclone activity over North America. *Mon. Wea. Rev.,* **107,** 1684–1688.
Rodionov, S. N., 1994: Association between winter precipitation and water-level fluctuations in the Great Lakes and atmospheric circulation patterns. *J. Climate,* **7,** 1693–1706.
Sinclair, M. R., 1994: An objective cyclone climatology for the Southern Hemisphere. *Mon. Wea. Rev.,* **122,** 2239–2256.
Sousounis, P. J., and J. M. Fritsch, 1994. Lake-aggregate mesoscale disturbances. Part II: A case study of the effects on regional and synoptic-scale weather systems. *Bull. Amer. Meteor. Soc.,* **75,** 1793–1811.
U.S. Weather Bureau, 1944: Daily Synoptic Series, Historical Weather Maps, Northern Hemisphere Sea Level, January 1899 to June 1939. Cooperative project of U.S. Army, Air Force, and U.S. Weather Bureau.
Vega, A. J., K. G. Henderson, and R. V. Rohli, 1995: Comparison of monthly and intramontly indices for the Pacific/North American teleconnection pattern. *J. Climate,* **8,** 2097–2103.
Weiss, C. C., and P. J. Sousounis, 1999: A climatology of collective lake disturbances. *Mon. Wea. Rev.,* **127,** 565–574.
Wendland, W. M., 1987: Prominent November coldwaves in the north central United States since 1901. *Bull. Amer. Meteor. Soc.,* **68,** 616–619.
Whittaker, L. M., and L. H. Horn, 1984: Northern Hemisphere extratropical cyclone activity for four midseason months. *J. Climatol.,* **4,** 297–310.
Yarnal, B. M., and H. F. Diaz, 1986: Relationships between extremes of the Southern Oscillation and the winter climate of the Anglo–American Pacific coast. *J. Climatol.,* **6,** 197–219.
Zishka, K. M., and P. J. Smith, 1980: The climatology of cyclones and anticyclones over North America and surrounding ocean environs for January and July, 1950–77. *Mon. Wea. Rev.,* **108,** 387–401.