An Observational Study of the Influence of the Great Lakes on the Speed and Intensity of Passing Cyclones

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ABSTRACT

Case studies have shown that the Great Lakes can intensify and alter the speed of passing cyclones in winter by contributing latent and sensible heat to the storms. However, the influence of the Great Lakes on cyclones has not been systematically examined using an extensive dataset. In this research, a National Climate Data Center dataset for the period 1965–90 was used to examine the rate of movement and change in mean sea level pressure of 583 cyclones as they passed over the Great Lakes.

The Great Lakes had a strong effect on the passing cyclones during the ice-free/unstable season from September through November. As cyclones approached the lakes during this season, they accelerated. Once in the Great Lakes region, their rate of intensification increased (the change in pressure tendency at the center of the cyclone was negative). The acceleration into the region was less for cyclones during the ice-cover/unstable season, and rates of intensification for these cyclones did not change within the region. Cyclones that traversed the Great Lakes region during the stable season from May through July exhibited essentially the same behavior as those in the ice-free/unstable season.

The authors' results for the unstable seasons (ice free and ice cover) are consistent with previous modeling case studies of the influence of the Great Lakes on passing cyclones. Because the lakes are generally cooler than the overriding air during spring and summer, a satisfactory explanation for the influence of the Great Lakes on cyclones during the stable season is not apparent.

1. Introduction

Large inland water bodies such as the Great Lakes can strongly influence the weather and motion 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 primarily due to differential heating between water and land. Because the surface waters of large lakes warm and cool more slowly than the 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 energy that intensifies vertical motions within overlying air masses (Eichenlaub 1979). The unstable season in the Great Lakes region varies among the lakes due to size, depth, and latitude. Generally, it extends from September to March and can be divided into two periods. During the first portion of the unstable season, the lakes are entirely unfrozen and provide both sensible and latent heat to overlying air masses. However, a significant area of surface water in the Great Lakes freezes during a normal winter (Assel et al. 1983), and ice cover generally reduces the upward flow of energy from lakes to the atmosphere. The remainder of the year, when the temperature of the surface water in the lakes is typically 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 air masses 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., Braham and Kelly 1982; Reinking et al. 1993), few studies have examined the larger-scale effects of the Great Lakes on weather systems. Cox (1917) was the first to note that the Great Lakes amplify low pressure centers that pass over them

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during the unstable season. An analytical treatment of the effect of the Great Lakes on the overlying air during typical winter conditions by Petterssen and Calabrese (1959) showed that the warm lake water can provide enough heat to cause horizontal convergence in the lower atmosphere and lead to the development of cyclonic circulation. They calculated the mean sea level pressure field corresponding to observed rotational motion and compared it with the actual pressure fields for two case studies of cyclones. They concluded that the warming of the passing cyclones by the Great Lakes accounted for a 6-mb drop in the mean sea level pressure field.

Danard and Rao (1972) simulated the intense cyclone of 24–26 February 1965 with a mesoscale (190-km grid spacing with eight layers) primitive equation model, both with and without the Great Lakes. 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 mean sea level pressure field calculated by Petterssen and Calabrese (1959). For the situation where cold dry air is advected over relatively warm water, their model showed that the Great Lakes could contribute to cyclone intensification in three important ways. First, the warm Great Lakes emit radiant energy to the air passing above them. Second, the lakes provide sensible heat to the air mass. Finally, the Great Lakes provide latent heat to the air that contributes to intensification of 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). Simulations from their model suggested that the influence of the Great Lakes on passing cyclones is not as great as indicated by earlier studies. For the 24–26 February 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 mean sea level pressure field.

Boudra (1981) used a primitive equations model of higher resolution (40–45-km grid spacing with 15 levels) to examine the effect of the Great Lakes on the atmosphere in early winter. In a case study of the 9–10 December 1977 cyclone, model simulations compared favorably with observations and exhibited less error than the operational forecast of the National Centers for Environmental Prediction's (formerly known as the National Meteorological Center) Limited-Area Fine-Mesh (LFM2) Model (which did not include the Great Lakes). The simulations showed that a drop of 4.5 mb in the mean sea level pressure field could be attributed to the influence of the Great Lakes on the passing storm.

Fritsch et al. (1989) compared surface observations with forecasts from models that ignored the Great Lakes to show how the lakes could alter the strength, speed, and path of relatively weak cyclones as they pass through the region. In a case study of the period 14–15 November 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, operational forecasts using the LFM model indicated that the same cyclone would track south of the Great Lakes region and at a more uniform speed.

Sousounis and Fritsch (1994) used a high-resolution (30-km grid spacing with 36 levels) numerical model to examine the aggregate effect of the Great Lakes on passing cyclones. A comparison of simulations from model runs with and without lake parameterization for the 14–15 November 1992 cyclone case study confirmed the results of Fritsch et al. (1989). The cyclone accelerated rapidly into the Great Lakes region, then slowed for 12 h while deepening 5 mb over the lakes, and subsequently moved east. In a corresponding model run without lake parameterization, the cyclone ''followed a steady path'' and exhibited a 2-mb decrease in mean sea level pressure. The authors noted that the intensification of the passing cyclones by the addition of sensible and latent heat from the Great Lakes during the unstable season can have important effects on weather downstream and can potentially influence East Coast cyclogenesis.

The purpose of this study was to evaluate the hypothesis that the Great Lakes exert a systematic influence on passing cyclones using an extensive observational dataset. Six propositions concerning the effect of the Great Lakes on passing cyclones were examined:

1) cyclones accelerate immediately prior to entering the Great Lakes region,
2) they intensify immediately prior to entering the region,
3) cyclones linger within the Great Lakes region,
4) they intensify within the region,
5) cyclones accelerate as they depart the Great Lakes region, and
6) they weaken as they depart the region.

Most of these propositions were suggested by the modeling studies, reviewed above, of the influence of the Great Lakes on individual cyclones during the unstable season. To examine whether or not the Great Lakes affect passing cyclones throughout the year, this set of propositions was evaluated for cyclones that traversed the Great Lakes during both the unstable and stable seasons. The former was further divided into ice-free/unstable and ice-cover/unstable seasons. Data on percent ice cover for each of the Great Lakes and Lake St. Clair from 1960 to 1979 indicate that ice generally covers a portion of the lakes between mid-December and late April (Assel et al. 1983). However, even in the coldest winter during this 20-yr period, the ice cover on Lakes Michigan, Huron, and Ontario was not complete. The normal values of percent ice cover for the six lakes combined were approximately 17% during early Janu-

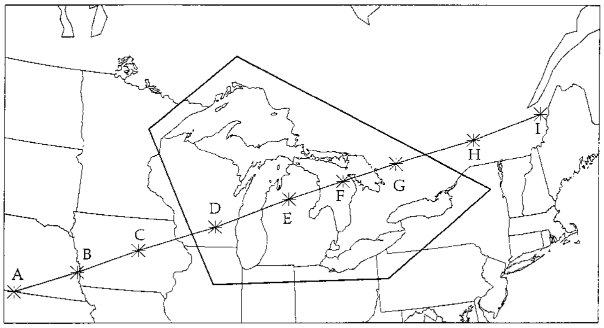

FIG. 1. The Great Lakes region as defined in this study (polygon) and a schematic of an individual cyclone track. Changes in cyclone speed and pressure tendency before entering the region were calculated from values at points *A* and *B.* Changes in cyclone speed and pressure tendency within the region were computed as the difference between values at point *B* and the average values of observations within the region (e.g., *D, E, F,* and *G*). Changes in cyclone speed and pressure tendency upon exiting the region were made by comparing the average values of observations within the region with values at point *I.* The overall changes in cyclone speed and pressure were made by subtracting the values at point *B* from those at *I.*

ary, reached a high of 64% during late February, and decreased to 11% in early April. Therefore, the ice-cover/unstable period was defined as January–March. The period from September to November was designated as the ice-free/unstable season, while the stable season was defined as May–July. April, August, and December were considered transition months because the categories to which they belong differ among the lakes due primarily to differences in latitude, size, and depth.

2. Data and methodology

The data used to examine the influence of the Great Lakes on passing cyclones was obtained from a National Climate Data Center ''working tape'' of cyclone tracks digitized from the *Mariners Weather Log* and covers the period from May 1965 to the end of 1990. The dataset provides location and mean sea level pressure for the center of each cyclone at 6-h time intervals.

For this analysis, the Great Lakes region was demarcated with a simple polygon to include all of the surface water while minimizing the amount of land surface within the basin (Fig. 1). Only cyclones that traversed some portion of this region were used. The focus of this study was the influence of the Great Lakes region as a whole on passing cyclones. The regional scale was chosen rather than that associated with individual lakes for two reasons. First, the typical diameter of cyclones (measured within the area of closed isobars) 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, model simulations by Sousounis and Fritsch (1994) indicate that the influence of the Great Lakes on passing cyclones may extend over an area with a radius as large as 1000 km.

The influence of the Great Lakes was evaluated by comparing differences between observations of the location and air pressure adjusted to mean sea level for the centers of cyclones (hereafter referred to as central pressure) as they generally moved from the interior of the continent across the Great Lakes toward the east coast of North America. The speed of cyclone movement for each observation was computed as the distance traversed by the low pressure center over the previous observation interval (6 h) and is given in meters per second. Similarly, pressure tendency was computed as the change in the central pressure of the cyclone during the previous observation interval and is given in millibars per day. The central pressure for most of the cyclones in the dataset decreased through time (deepened) as they moved from the continental interior across the Great Lakes (e.g., see last columns in Tables 1–3). Therefore, changes in the pressure tendency between observations were used to evaluate the influence of the Great Lakes on cyclone strength. Using this measure, a statistically significant decrease between the pressure tendency observations for cyclones prior to entering the region and the mean of observations within the region would suggest that the lakes intensify passing cyclones.

Six measures were constructed to evaluate the effect of the Great Lakes on passing cyclones that correspond to the components (propositions) of the hypothesis specified above (Fig. 1). The first and second measures relate to the acceleration and intensification of cyclones immediately prior to entry into the region. They were computed for each cyclone as the change in the speed of movement (a) and pressure tendency (b) between the second from the last observation before entry and the last observation before entry into the region. These observations were chosen because the results of Sousounis and Fritsch (1994) indicate that the 14–15 November 1992 cyclone began to accelerate 3–6 h prior to entry into the Great Lakes region. The third and fourth measures describe the change in speed and strength of cyclones over the Great Lakes. They were computed for each cyclone as the change in the speed (c) and pressure tendency (d) between the last observation before entry and the mean of the corresponding values inside the Great Lakes region. The fifth and sixth measures relate to the acceleration and reduction in strength of cyclones after leaving the region. They were computed for each cyclone as the change in speed (e) and pressure tendency (f) between the mean value within the region and the corresponding value for the second observation after exiting the Great Lakes region. The cyclone center for the first observation after leaving the region was often near the Great Lakes. Because the average distance between the cyclone centers for the first and second observations after leaving the region was 320 km, it is likely that the cyclones were largely beyond the influence of the Great Lakes by the second observation. The statistical significance of each of these measures of the

TABLE 1. Results of the analysis of the six measures of the influence of the Great Lakes on the speed and intensity of passing cyclones for the ice-cover/unstable season of January–March. Values of overall change in cyclone speed and mean sea level pressure are also shown. An asterisk indicates a statistically significant difference at the 95% confidence level.

	Measures								
Categories	No. of cyclones	Δspeed before[a] (m s^{-1})	ΔPT before[b] (mb day^{-1})	Δspeed within[c] (m s^{-1})	ΔPT within[d] (mb day^{-1})	Δspeed exit[e] (m s^{-1})	ΔPT exit[f] (mb day^{-1})	Δspeed overall[g] (m s^{-1})	ΔP overall[h] (mb)
Cyclone intensity									
Strong cyclones (central pressure ≤ 992 mb)	73	1.3	−1.6*	−0.4	1.3	−0.4	5.9*	0.5	−6.0
Weak cyclones (central pressure > 992 mb)	155	1.5*	0.2	0.6	−0.7	0.0	−3.3	2.1*	−1.3*
Source region									
Alberta cyclones	127	1.2*	0.0	−0.4	−0.3	−0.4	−0.2	0.4	−1.9*
Colorado cyclones	101	1.8*	−0.9	1.1	0.3	0.2	−0.5	3.1*	−3.8*
Month of year									
January	95	1.8*	−0.2	0.5	−0.1	−0.5	−0.3	1.8	−3.1*
February	58	1.9*	−0.5	−0.6	−0.1	1.0	−1.5	2.3	−3.6*
March	75	0.7	−0.5	0.7	0.1	−0.5	0.4	0.9	−1.7
Overall mean	228	1.5*	−0.4	0.3	0.0	−0.1	−0.3	1.6*	−2.8*

[a] Change in cyclone speed (m s^{-1}) before entering the region.
[b] Change in pressure tendency (mb day^{-1}) at the center of cyclones before entering the region.
[c] Change in cyclone speed (m s^{-1}) within the region.
[d] Change in pressure tendency (mb day^{-1}) within the region.
[e] Change in cyclone speed (m s^{-1}) upon exiting the region.
[f] Change in pressure tendency (mb day^{-1}) upon exiting the region.
[g] Change in cyclone speed (m s^{-1}) between the second observations after leaving and before entering the Great Lakes region.
[h] Change in central pressure (mb) between the second observations after leaving and before entering the Great Lakes region.

effect of the Great Lakes on passing cyclones was evaluated using the one-tailed paired t test at the 95% confidence level ($\alpha = 0.05$).

To evaluate the hypothesis that the Great Lakes have a systematic influence on passing cyclones, the dataset was classified in three ways. The first division of the data was by cyclone strength. An examination of all cyclones that were reported as having destroyed property along the shores of the Great Lakes between 1959 and 1990 shows that these storms had lower surface pressures than most other cyclones that traversed the Great Lakes region during the same years (Angel 1995). The median central pressure of the destructive cyclones while over the lakes was 992 mb. This value was used to divide the dataset into two intensity categories, strong cyclones (lowest central pressure in region less than or equal to 992 mb) and weak cyclones (>992 mb). Of the cyclones that traversed the Great Lakes during the ice-cover/unstable seasons between 1965 and 1990, 73 were classified as strong and 155 were designated as weak. Fewer cyclones passed over the lakes during the stable seasons within the study period; only 10 of these cyclones were considered strong (≤992 mb) and 148 cyclones were regarded as weak. During the ice-free/unstable seasons between 1965 and 1990, 42 and 155 strong and weak cyclones, respectively, traversed the lakes.

The second classification was by cyclone source region. Previous studies of cyclone tracks in North America (e.g., Zishka and Smith 1980; Whittaker and Horn 1984), and for the Great Lakes region in particular (Harman et al. 1980), show that the province of Alberta, Canada and the Colorado–southwestern region of the United States are the two primary source areas for cyclones that pass over the Great Lakes. In this study, cyclones that originated poleward of 43°N are referred to as Alberta cyclones, while those that developed equatorward of 43°N were designated Colorado cyclones. This classification yielded 127 Alberta and 101 Colorado cyclones for the ice-cover/unstable season between 1965 and 1990. For the stable season during the study period, 85 were classified as Alberta and 101 were designated as Colorado cyclones. For the ice-free/unstable season, 96 and 101 were considered Alberta and Colorado cyclones, respectively.

The third division of the cyclone data was by month. Between 1965 and 1990 during the ice-cover/unstable season, 95, 58, and 75 cyclones traversed the Great Lakes region in the months of January–March, respectively. In May, June, and July (stable season), 62, 59, and 37 cyclones, respectively, traversed the lakes between 1965 and 1990. During the ice-free/unstable season, 51, 61, and 85 cyclones passed through the region in the months of September–November, respectively. The total number of cyclones in the transition months of April, August, and December were 68, 41, and 93, respectively. As mentioned earlier, these cyclones were not included in the analysis.

3. Results for the ice-cover/unstable season (January–March)

a. Acceleration of cyclones prior to entry into the Great Lakes region during the ice-cover/unstable season

Statistically significant ($\alpha = 0.05$) increases in cyclone speed were found for weak (1.5 m s^{-1}), Alberta (1.2 m s^{-1}), Colorado (1.8 m s^{-1}), January (1.8 m s^{-1}), and February (1.9 m s^{-1}) cyclones as they approached the Great Lakes during the ice-cover/unstable season (Table 1). Although not statistically significant, an increase in the rate of movement was also exhibited by strong and March cyclones. The overall mean increase in the speed of cyclones as they approached the Great Lakes region in the ice-cover/unstable season (1.5 m s^{-1}) was statistically significant.

b. Intensification of cyclones prior to entry into the Great Lakes region during the ice-cover/unstable season

Statistically significant changes in pressure tendency were found only for strong cyclones (-1.6 mb day^{-1}) as they approached the Great Lakes during the ice-cover/unstable season (Table 1). The strength of cyclones in the Colorado, January, February, and March categories also increased, but the decreases in the pressure tendency for these categories were not statistically significant. The pressure tendency for weak cyclones increased slightly and it was zero for the Alberta category. Although the overall mean change in the pressure tendency of cyclones as they approached the Great Lakes region in the ice-cover/unstable season was a decrease, it was not statistically significant.

c. Lingering of cyclones within the Great Lakes region during the ice-cover/unstable season

There were no statistically significant changes in cyclone speed within the region for the ice-cover/unstable season (Table 1). The speed of the cyclones in the strong, Alberta, and February categories decreased, while cyclones in the weak, Colorado, January, and March categories increased their speed once they entered the Great Lakes region. The overall mean change in the speed of cyclones within the region during the ice-cover/unstable season was an increase. On average, cyclones remained over the Great Lakes for 2.9 observations (sd = 1.5), approximately 17 h, and differences between categories were not significant.

d. Intensification of cyclones within the Great Lakes region during the ice-cover/unstable season

Changes in pressure tendency for cyclones within the region during the ice-cover/unstable season were also not statistically significant (Table 1). Weak, Alberta, January, and February cyclones exhibited negative changes, while strong, Colorado, and March cyclones showed changes that were positive. The overall mean change in the pressure tendency within the region for all cyclones during the ice-cover/unstable season was zero.

e. Acceleration of cyclones upon departing the Great Lakes region during the ice-cover/unstable season

Changes in cyclone speed upon exiting the Great Lakes region (Table 1) were not statistically significant. Colorado and February cyclones increased their speed while strong, Alberta, January, and March cyclones slowed. The overall mean decrease in cyclone speed upon departing the Great Lakes region for all cyclones in the ice-cover/unstable season was not statistically significant.

f. Weakening of cyclones upon departing the Great Lakes region during the ice-cover/unstable season

The rate of cyclone deepening increased for all categories, except strong and March cyclones, upon leaving the Great Lakes region during the ice-cover/unstable season (Table 1). Only the positive change in the pressure tendency for strong cyclones (5.9 mb day^{-1}) was statistically significant. The overall mean change in the pressure tendency for cyclones exiting the region during the ice-cover/unstable season was a decrease, and it was not statistically significant.

4. Results for the stable season (May–July)

a. Acceleration of cyclones prior to entry into the Great Lakes region during the stable season

Statistically significant increases in cyclone speed were found for weak (2.4 m s^{-1}), Alberta (2.1 m s^{-1}), Colorado (2.5 m s^{-1}), June (2.3 m s^{-1}), and July (4.5 m s^{-1}) cyclones as they approached the Great Lakes during the stable season (Table 2). Although not statistically significant, an increase in the rate of movement was also exhibited by strong cyclones and those that approached the region during May. The mean increase in the speed of cyclones as they approached the Great Lakes region in the stable season was statistically significant at 2.3 m s^{-1}.

b. Intensification of cyclones prior to entry into the Great Lakes region during the stable season

There were no statistically significant changes in pressure tendency for cyclones as they approached the Great Lakes during the stable season (Table 2). The changes for cyclones in the strong, Colorado, and June categories were negative; the changes for weak, Alberta, and July cyclones were positive; and there was no change for

TABLE 2. Results of the analysis of the six measures of the influence of the Great Lakes on the speed and intensity of passing cyclones for the stable season of May–July. Values of overall change in cyclone speed and mean sea level pressure are also shown. An asterisk indicates at statistically significant difference at the 95% confidence level.

	Measures								
Categories	No. of cyclones	Δspeed before[a] (m s^{-1})	ΔPT before[b] (mb day^{-1})	Δspeed within[c] (m s^{-1})	ΔPT within[d] (mb day^{-1})	Δspeed exit[e] (m s^{-1})	ΔPT exit[f] (mb day^{-1})	Δspeed overall[g] (m s^{-1})	ΔP overall[h] (mb)
Cyclone intensity									
Strong cyclones (central pressure ≤ 992 mb)	10	0.5	−1.6	0.9	4.2	1.1	8.2*	2.5	−3.1
Weak cyclones (central pressure > 992 mb)	148	2.4*	0.1	1.6	−1.0*	−1.1	−0.7	2.8*	−1.0*
Source region									
Alberta cyclones	85	2.1*	0.6	1.6	−1.1*	−0.8	−0.2	2.8*	−1.5*
Colorado cyclones	73	2.5*	−0.7	1.5	−0.1	−1.2	0.0	2.8*	−0.8
Month of year									
May	62	0.9	0.0	1.3	0.1	−1.2	−0.2	1.0	0.5
June	59	2.3*	−0.1	2.1	−1.3*	−1.1	0.5	3.3*	−1.9
July	37	4.5*	0.1	1.0	−0.9	−0.5	−1.0	4.9*	−2.7*
Overall mean	158	2.3*	0.0	1.5	−0.6*	−1.0	−0.2	2.8*	−1.1*

[a] Change in cyclone speed (m s^{-1}) before entering the region.
[b] Change in pressure tendency (mb day^{-1}) at the center of cyclones before entering the region.
[c] Change in cyclone speed (m s^{-1}) within the region.
[d] Change in pressure tendency (mb day^{-1}) within the region.
[e] Change in cyclone speed (m s^{-1}) upon exiting the region.
[f] Change in pressure tendency (mb day^{-1}) upon exiting the region.
[g] Change in cyclone speed (m s^{-1}) between the second observations after leaving and before entering the Great Lakes region.
[h] Change in central pressure (mb) between the second observations after leaving and before entering the Great Lakes region.

May cyclones. The overal mean change in the pressure tendency of cyclones as they approached the Great Lakes region in the stable season was zero.

c. Lingering of cyclones within the Great Lakes region during the stable season

For the stable season, the speed of the cyclones in all categories increased within the Great Lakes region (Table 2); however, these changes were not statistically significant. On average, cyclones remained over the Great Lakes for 3.3 observations (sd = 2.0), approximately 20 h, and differences between categories were not significant.

d. Intensification of cyclones within the Great Lakes region during the stable season

Changes in pressure tendency for cyclones after entering the region in the stable season (Table 2) were statistically significant for weak (−1.0 mb day^{-1}), Alberta (−1.1 mb day^{-1}), and June (−1.3 mb day^{-1}) categories. The rate of deepening also increased for Colorado and July cyclones and decreased for strong and May cyclones, although the values were not statistically significant. The overall mean change in the pressure tendency within the region for cyclones during the stable season (−0.6 mb day^{-1}) was statistically significant.

e. Acceleration of cyclones upon departing the Great Lakes region during the stable season

There were no statistically significant changes in cyclone speed upon exiting the Great Lakes region during the stable season (Table 2). Cyclone speed decreased for all categories except strong cyclones.

f. Weakening of cyclones upon departing the Great Lakes region during the stable season

The rate of cyclone deepening for cyclones upon leaving the Great Lakes region during the stable season (Table 2) increased for weak, Alberta, May, and July categories, while cyclones in the June category displayed a positive change in the pressure tendency. None of these changes were statistically significant. However, the positive change in the pressure tendency for strong cyclones (8.2 mb day^{-1}) was statistically significant. The overall mean decrease in the pressure tendency for cyclones exiting the region during the stable season was not statistically significant.

5. Results for the ice-free/unstable season (September–November)

a. Acceleration of cyclones prior to entry into the Great Lakes region during the ice-free/unstable season

Statistically significant ($\alpha = 0.05$) increases in speed were found for cyclones in all the categories as they

TABLE 3. Results of the analysis of the six measures of the influence of the Great Lakes on the speed and intensity of passing cyclones for the ice-free/unstable season of September–November. Values of overall change in cyclone speed and mean sea level pressure are also shown. An asterisk indicates a statistically significant difference at the 95% confidence level.

	Measures								
Categories	No. of cyclones	Δspeed before[a] (m s^{-1})	ΔPT before[b] (mb day^{-1})	Δspeed within[c] (m s^{-1})	ΔPT within[d] (mb day^{-1})	Δspeed exit[e] (m s^{-1})	ΔPT exit[f] (mb day^{-1})	Δspeed overall[g] (m s^{-1})	ΔP overall[h] (mb)
Cyclone intensity									
Strong cyclones (central pressure ≤ 992 mb)	42	2.0*	−1.6	−2.2*	−0.8	−0.7	9.8*	−0.8	−9.0*
Weak cyclones (central pressure > 992 mb)	155	2.5*	−0.3	0.7	−1.2*	0.3	−1.8	3.5*	−2.9*
Source region									
Alberta cyclones	96	2.4*	0.1	−0.8*	−1.6*	−0.3	−1.0	1.3	−2.8*
Colorado cyclones	101	2.3*	−1.3*	1.0	−1.5	0.4	2.3*	3.7*	−5.6*
Month of year									
September	51	3.2*	−0.7	1.0	−1.5	0.9	−1.2	5.1*	−3.3*
October	61	1.8*	−0.9	−0.6	−1.2	0.1	0.7	1.2	−4.3*
November	85	2.2*	−0.4	0.1	−1.0	−0.3	1.7	1.9*	−4.7*
Overall mean	197	2.3*	−0.6	0.1	−1.2*	0.1	0.7	2.5*	−4.2*

[a] Change in cyclone speed (m s^{-1}) before entering the region.
[b] Change in pressure tendency (mb day^{-1}) at the center of cyclones before entering the region.
[c] Change in cyclone speed (m s^{-1}) within the region.
[d] Change in pressure tendency (mb day^{-1}) within the region.
[e] Change in cyclone speed (m s^{-1}) upon exiting the region.
[f] Change in pressure tendency (mb day^{-1}) upon exiting the region.
[g] Change in cyclone speed (m s^{-1}) between the second observations after leaving and before entering the Great Lakes region.
[h] Change in central pressure (mb) between the second observations after leaving and before entering the Great Lakes region.

approached the Great Lakes during the ice-free/unstable season (Table 3). The increase in the rate of movement was 2.0, 2.5, 2.4, 2.3, 3.2, 1.8, and 2.2 m s^{-1} for strong, weak, Alberta, Colorado, September, October, and November cyclones, respectively. The overall mean increase in the speed of cyclones as they approached the Great Lakes region in the ice-free/unstable season was also statistically significant at 2.3 m s^{-1}.

b. *Intensification of cyclones prior to entry into the Great Lakes region during the ice-free/unstable season*

Changes in pressure tendency were not statistically significant for any category of cyclones except Colorado cyclones (−1.3 mb day^{-1}) as they approached the Great Lakes during the ice-free/unstable season (Table 3). The pressure tendency of cyclones in the strong, weak, September, October, and November categories decreased, while the pressure tendency of Alberta cyclones increased slightly. The overall mean change in the pressure tendency of cyclones as they approached the Great Lakes region in the ice-free/unstable season was a decrease; however, it was not statistically significant.

c. *Lingering of cyclones within the Great Lakes region during the ice-free/unstable season*

The speed of strong (−2.2 m s^{-1}) and Alberta cyclones (−0.8 m s^{-1}) decreased significantly over the Great Lakes for the ice-free/unstable season (Table 3). The speed of the cyclones in the October category also slowed while weak, Colorado, September, and November cyclones increased their speed once they entered the Great Lakes region, although none of the changes were statistically significant. The overal mean change in the speed of cyclones within the region during the ice-free/unstable season was an increase, but not statistically significant. On average, cyclones remained over the Great Lakes for 3.0 observations (sd = 1.6), equal to 18 h, and differences between categories were not significant.

d. *Intensification of cyclones within the Great Lakes region during the ice-free/unstable season*

The pressure tendency for cyclones in all categories decreased once they entered the Great Lakes region during the ice-free/unstable season (Table 3). The changes in pressure tendency were statistically significant for weak (−1.2 mb day^{-1}) and Alberta (−1.6 mb day^{-1}) categories. The overall mean change in the pressure tendency within the region for all cyclones during the ice-free/unstable season (−1.2 mb day^{-1}) was statistically significant.

e. *Acceleration of cyclones upon departing the Great Lakes region during the ice-free/unstable season*

Changes in cyclone speed upon exiting the Great Lakes region (Table 3) were not statistically significant.

Weak, Colorado, September, and October cyclones increased their speed while strong, Alberta, and November cyclones slowed. The overall mean increase in cyclone speed upon departing the Great Lakes region in the ice-free/unstable season was not statistically significant.

f. Weakening of cyclones upon departing the Great Lakes region during the ice-free/unstable season

The increase in the pressure tendency upon leaving the Great Lakes region during the ice-free/unstable season (Table 3) was statistically significant for the strong (9.8 mb day^{-1}) and Colorado (2.3 mb day^{-1}) cyclone categories. Changes in the other categories, including the overall mean, were not statistically significant. The pressure tendency for cyclones in the weak, Alberta, and September categories decreased, while those in the other categories increased. The overall mean change in the pressure tendency for cyclones exiting the region during the ice-free/unstable season was an increase.

6. Discussion

This observational study of cyclones that traversed the Great Lakes between 1965 and 1990 identifies several important features regarding the influence of the lakes on these storm systems. This is the first study to document the influence of the Great Lakes on passing cyclones during the stable season (May–July) and to distinguish between ice-free/unstable and ice-cover/unstable seasons (January–March) systematically.

As cyclones approached the Great Lakes during the ice-free/unstable season (September–November), they accelerated. Once in the Great Lakes region, their rate of intensification increased (the change in pressure tendency at the center of the cyclone was negative). On average, the rate of movement of cyclones that traversed the lakes during the ice-free/unstable season increased. The difference in speed between the second observations after leaving and the observation immediately before entering the Great Lakes region was 2.5 m s^{-1} (Table 3). Overall, cyclones deepened as they traversed the Great Lakes region; their central pressure changed −4.2 mb on average between the observations on either side of the Great Lakes region (Table 3). The results concerning the accelerations of cyclones into the region and the intensification of cyclones within the region are consistent with those from earlier modeling case studies of the influence of the Great Lakes on passing cyclones during the unstable season.

As cyclones approached the Great Lakes during both the stable and ice-cover/unstable seasons, they also accelerated. Surprisingly, this increase in speed during the stable season was equal to that for cyclones during the ice-free/unstable season. Cyclones also increased their rates of intensification within the Great Lakes region during the stable season although only about half as much as those in the ice-free/unstable season. In contrast, cyclones that traversed the region during the ice-cover/unstable season did not increase their rates of intensification over the lakes. For these seasons, the ice-cover/unstable (1.6 m s^{-1}) and stable (2.8 m s^{-1}), the rates of movement of cyclones that traversed the region also increased (Tables 1 and 2). Cyclones also deepened as they traversed the Great Lakes region during these seasons; the central pressure of ice-cover/unstable and stable season cyclones changed −2.8 mb and −1.1 mb, respectively, between the second observations after leaving and the observation immediately prior to entering the region (Tables 1 and 2).

The results of the analysis of the influence of the Great Lakes on cyclones during the stable season were unexpected. Most surprisingly, instead of weakening as they pass from the warm land over the cool surface of the Great Lakes, the surface pressure at the center of these cyclones deepened. A review of the literature on Great Lakes cyclones 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 are 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 usually only 1°–2°C warmer than that of nearby land surfaces (Eichenlaub 1979), although the differences may be much larger in particular cases (e.g., Lyons and Olsson 1973). Convergence along 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 in the lowest layer of the storm. The consequences of horizontal variations in frictional drag can impact cyclogenesis (e.g., Petterssen and Smebye 1971; Bosart 1975; Bosart and Lin 1984; Carlson 1991), although the influence of changes in surface roughness on Great Lake cyclones has not been explored.

The results also suggest that the effect of ice cover on the sensible and latent heat fluxes from the relatively warm water to the cold atmosphere has an important impact on cyclones during the unstable season. Ice cover reduces the influence of the lakes on passing cyclones, although its extent varies greatly among years and within the ice-cover/unstable season (when averaged for 2-week periods in the months of January–March, normal ice-cover values varied from 17% to 65% while the extreme values ranged from 3% to 96% between 1960 and 1979). Unlike cyclones during the early unstable season, those in January–March did not increase their rate of intensification over the Great Lakes. Likewise, the acceleration of cyclones into the region during the ice-cover/unstable season was approximately 35% less than during the ice-free/unstable season.

Fritsch et 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. The weak cyclones (lowest central pressure in regions greater than 992 mb) in this study accelerated into the region more than the strong cyclones (≤992 mb) during each of the three seasons. It should be noted that there were only 10 strong cyclones during the stable season over the 26 years in this study. During the ice-free/unstable and stable seasons, weak cyclones increased their rates of intensification over the Great Lakes while strong cyclones did not. The differences between observations of cyclone speed and pressure after leaving and before entering the region indicate that weak cyclones generally accelerated across the Great Lakes region, while the increase in the speed of strong cyclones was not significant. The intensity of the weak cyclones also increased as they traversed the region, whereas, except for the ice-free/unstable season, this was not the case for strong cyclones.

The Great Lakes appear to influence Colorado cyclones differently than Alberta cyclones. Cyclones from both source regions between 1965 and 1990 accelerated into the region during each season. The tracks for both categories of cyclones were primarily west to east. The mean increase in latitude within the region of the centers of cyclones from the Colorado source region was 1.9° while the mean change in latitude for Alberta cyclones was zero. Alberta cyclones increased their rate of intensification over the Great Lakes (except during the ice-covered/unstable season) while Colorado cyclones did not. During the ice-free/unstable season, Alberta cyclones also lingered over the lakes. In contrast, Colorado cyclones during the ice-free/unstable season increased their rate of intensification immediately prior to entering the Great Lakes region, and their pressure tendency was positive as they left the region. Finally, the changes in cyclone speed and pressure between observations before entering and after leaving the region for the unstable season categories indicate that Colorado cyclones increased their speed and decreased their central pressure as they traversed the region to a greater extent than did the Alberta cyclones.

While this study provides statistical evidence of differences in the movement and pressure tendencies of cyclones that are, in many ways, consistent with an influence by the Great Lakes, this dataset cannot provide physical explanations for the results. It is possible that the differences found here may be due to other dynamic influences in the region; however, these other influences would have to be present year-round and affect both the speed and pressure of the passing cyclones. Ideally, it would be desirable to identify a control group of cyclones that had developed under similar circumstances but did not pass over the Great Lakes.

Unfortunately, this is difficult because the Great Lakes are at the convergence of two important cyclone tracks (Alberta and Colorado). Any control group collected within a polygon to the west (southwest) of the Great Lakes would be composed mainly of Alberta (Colorado) cyclones as they were starting to develop in the northern (southern) plains. A polygon to the south would miss most of the Alberta and Colorado cyclones, and a polygon to the east would extend over the Atlantic Ocean. Any physical explanations of the results of this study will have to come from continued modeling efforts with lake/no-lake scenarios.

7. Summary

A dataset containing 583 cyclones for the period 1965–90 was used to examine the rates of movement and the changes in mean sea level pressure at the center of cyclones as they passed over the Great Lakes. The results of the analyses strongly support the hypothesis that the Great Lakes have a significant influence on passing cyclones during the unstable seasons. During September–November, when the lakes are ice-free, cyclones accelerated as they approached the region and increased their rate of intensification over the lakes. Ice cover appears to reduce the influence of the Great Lakes on passing cyclones. During January–March, when ice cover is generally present (but not complete) on the lakes, the acceleration of cyclones into the region was reduced and the cyclones did not increase their rates of deepening over the lakes. Overall, these findings are consistent with results of previous modeling studies that have focused on the influence of the Great Lakes on individual cyclones during the unstable seasons.

In general, cyclones that traverse the Great Lakes region during the stable season (May–July) exhibited the same behavior as those in the ice-free/unstable season. They accelerated as they approached the region and increased their rates of deepening over the lakes. However, because the lakes are usually cooler than the overriding air during the stable season, a satisfactory explanation for this phenomenon is not apparent. Case studies using high-resolution numerical models, such as that employed by Sousounis and Fritsch (1994), are needed to identify the physical processes that cause cyclones to intensify over the Great Lakes during the stable season and to evaluate the control of ice cover over the intensification of passing cyclones during winter.

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