LAKE-EFFECT LIGHTNING CLIMATOLOGY OF THE GREAT LAKES

Ted Letcher
Scott Steiger
State University of New York
Oswego, New York

Abstract

Lake-effect storms form over the Great Lakes region every year during the fall and winter months, when cold air crosses over the relatively warm lakes. Occasionally, these storms are capable of producing lightning. Lake-effect thunderstorms are important to study because they produce lightning in shallow convective clouds compared to the traditional summertime thunderstorms. Also, lake-effect thunderstorms can be associated with thundersnow. A climatology of lake-effect thunderstorms was constructed for each Great Lake in order to find any seasonal patterns. In order to determine the number of lake-effect thunderstorm events that occurred during the 12-year period from 1995-2007, radar and sounding data were analyzed for lake-effect parameters identified in previous research, and then compared to lightning flash density plots using National Lightning Detection Network (NLDN) data across the Great Lakes region. A total of 31 separate lake-effect thunderstorm events were found over the upper Great Lakes, adding to the 70 events previously found over the lower Great Lakes. The lower Great Lakes produced the highest number of thundersnow events. The majority of lake-effect thunderstorms that occurred across the upper Great Lakes was early-season rain or mixed precipitation events. Several inhibiting factors for lake-effect thunderstorms were noted to be responsible for the relative dearth of lake-effect lightning across the upper Great Lakes (Superior, Huron, Michigan). The predominant factors included lake surface temperature, shape and geographic location. It was also found during the study that enhancement from upstream lakes is tied to lake-effect thunderstorm development. The most evident lake-effect thunderstorm enhancement occurred from Lake Huron to Lake Erie in what has been defined by this paper to be a Lake Huron-to-Erie Connection (LHEC). The results of this study will aid forecasters to better predict lake-effect thunderstorms as well as provide an opportunity for more in-depth research on lightning in shallow convective clouds.

Corresponding Author: Ted Letcher
State University of New York at Oswego
104 Country View Ct Ashton, MD 20861
email: tletcher12@gmail.com

1. Introduction

Lake-effect thunderstorms occasionally occur near the shores of the Great Lakes during the fall and the winter months of each year. Lake-effect lightning differs from lightning produced by other thunderstorms in that it forms in a shallow convective cloud compared to normal summertime thunderstorms. Lake-effect lightning is also of concern because often it is observed in conjunction with snow when the public does not expect it.

Lake-effect thunderstorms can be better understood by constructing a detailed climatology of these events. The primary goals of this study were: (1) to extend the climatology done by Steiger et al. (2009) on the lower Great Lakes (Erie and Ontario) to include lake-effect thunderstorms across all five of the Great Lakes, (2) create individual climatologies for each Great Lake, and (3) determine the precipitation type of each event associated with each lake. The results were then used to make inferences and pose new questions about the nature of lake-effect thunderstorms, as well as to aid forecasters in the prediction of this unique phenomenon.

2. Previous work

Previous research concerning lake-effect storms producing lightning indicates that the majority of lake-effect thunderstorms occur downwind of the lower Great Lakes. Niziol et al. (1995) defined type-I lake-effect snow storms as narrow bands of intense precipitation forming parallel to the long axis of a lake. These bands typically form under conditions in which there is a large fetch and weak vertical wind shear. It is thought that most lake-effect lightning occurs with type-I lake-effect storms (Moore and Orville 1990). A satellite study by Kristovich and Steve (1995) concluded that the majority of type-I lake-effect storms occur over and downwind of Lakes Erie and Ontario.

A previous climatological study by Steiger et al. (2009) focused on the 12-year period of 1995-2007 and found that 70 separate lake-effect thunderstorm events occurred over the lower Great Lakes during that period. This study also concluded that the majority of these events occurred during the early part of the lake-effect season (October through December).

Criteria thought to be crucial to lake-effect lightning production include relatively deep convection and a mixed phase convective cloud. Typical lake-effect convection is very shallow (1-2km) when compared to that of a summertime thunderstorm. It is thought that a deeper (3-4 km) convective cloud allows for greater charge separation (Steiger et al. 2009). A mixed phase cloud is important to the lightning production within a lake-effect cloud. The collisions between graupel and ice crystals with super-cooled water droplets present are thought to be critical in separating charge within a cloud (Reynolds et al. 1957).

Lending credence to the theory that a mixed phase cloud is a necessary condition for the production of lake-effect thunderstorms are observational studies on thundersnow that find a sharp decrease in thundersnow events under very cold conditions (Michimoto 1993). If the air is too cold (e.g., -10°C isotherm <1 km AGL) then the cloud will not contain the graupel or super-cooled water needed to separate charge within the cloud (Steiger et al. 2009).

3. Data and Methods

a. Climatology

To construct a climatology of lake-effect thunderstorm events for all five of the Great Lakes, the method used by Steiger et al. (2009) to determine lake-effect thunderstorm events for the lower Great Lakes was repeated for the upper Great Lakes (Superior, Huron, Michigan). The time period between 1 September and 31 March was defined as the lake-effect season, since lake-effect storms are most prevalent during these months as relatively colder air occasionally crosses the warmer lake water. A study domain was then defined which encompassed all of the upper Great Lakes as well as areas which are at least 90 km downwind of each individual lake to ensure that no events would be overlooked (Fig. 1). Lightning data within this region were gathered for every day within the lake-effect season for the 12-year period from 1995-2007.

Fig. 1. Map of the Great Lakes region, [Obtainable online at http://www.google.com]. Outlined in red is the box in which lightning data were retrieved for the upper Great Lakes analysis.

Weather Surveillance Radar, 1988, Doppler (WSR-88D) Next Generation Radar (NEXRAD) data were then analyzed for each day across the region when lightning was present. Any days with radar signatures which resembled lake-effect storms were included in the lightning data set. This included radar imagery with any type of banded precipitation parallel to the lower mean wind vector occurring over or downwind of any Great Lake. Radar imagery presenting lingering or persistent precipitation concentrated around one or more of the Great Lakes were also included.

Proximity sounding data between 0000 UTC and 0000 UTC for each lightning day remaining in the data set were then examined in order to determine whether or not environmental conditions were conducive for lake-effect storms. The sounding data were obtained from the University of Wyoming [UWYO] Department of Atmospheric Science [Available online at http://weather.uwyo.edu/upperair/sounding.html] or as an alternate source from Plymouth State Weather Center [Available online at: http://vortex.plymouth.edu/]. The first variable studied was the difference between lake surface temperatures obtained from the Great Lakes Environmental Research Laboratory (GLERL 2009) and the 850 mb temperature. If this difference was less than 13°C, the critical temperature difference required for sufficient instability to be present for significant lake-effect storms to form (Holroyd 1971), then the day was removed from the data set. The sounding data were also analyzed for the presence and level of any lower to mid-tropospheric stable layer that acts to inhibit lake-effect convection. An ideal thermodynamic sounding for lake-effect storms are one in which there is no significant temperature inversion present in the lower-troposphere, allowing for deeper convection. If a significant temperature inversion was present and located below the 850 mb level, then the day was removed from the data set.

The third sounding variable analyzed was low-level wind shear. If there was strong (i.e., >30°) directional wind shear between the surface and the base of the stable layer, then the day was re-examined to ensure that the lightning was associated with lake-effect precipitation. For cases in which the lowest stable layer present in the atmosphere was the tropopause, the wind shear was examined between the surface and the tropopause. In a couple of rare cases, the soundings available were confirmed (by radar data) to have been launched into a lake-effect storm. In these cases, the day was left in the data set regardless of whether or not the sounding met the above criterion.

Once the soundings were studied for environmental conditions, cloud-to-ground (CG) lightning flash density plots were created for each day remaining within the data set using National Lightning Detection Network (NLDN) data (Cummins et al. 2006). The final list of lightning days was created by analyzing the flash density plots [flashes km^{-2}]. If lightning flashes appeared over or downwind of any of the three upper Great Lakes, then the day was included in the climatology. The lake-effect thunderstorm days were then combined into discrete lightning events by combining any consecutive days in which lake-effect thunderstorms occurred into one event, similar to Steiger et al. (2009).

Next, individual climatologies for each of the five Great Lakes were created. To accomplish this, the data set of lightning events created for the upper Great Lakes and the data set already created by Steiger et al. (2009) for the lower Great Lakes, were used to investigate each individual Great Lake. First, the daily lightning plots created for the region surrounding the lower Great Lakes were analyzed to determine over or near which lake the lightning flashes occurred. These lightning plots were then compared with NEXRAD data in order to determine from which lake the lightning-producing precipitation was originating. In some cases it was difficult to determine which lake was producing lake-effect lightning, due in part to missing radar data or radar data containing large amounts of noise. For these cases, the Buffalo, New York sounding (KBUF) nearest to the time of the event was analyzed. Specifically, the low-level wind direction was examined in order to determine the trajectory of the lake-effect precipitation. By comparing the wind direction recorded by the KBUF sounding to the location of the lightning strikes, the upwind lake responsible for producing the flashes was then identified.

This same methodology was then applied to the data set over the upper Great Lakes. However, in cases requiring the analysis of sounding data, the sounding station nearest to the event in question was used (Buffalo [BUF], Detroit/Pontiac [DTX], Green Bay [GRB], Gaylord [APX], International Falls [INL]).

b. Precipitation typing

Lake-effect thunderstorms which occurred in the late winter months (January-March) were assumed to be snow. This is a reasonable assumption because by the mid-winter months (January) the lake temperatures of the Great Lakes are significantly cooled (<4°C) and air cold enough to form lake-effect precipitation will be cold enough to support only snow. The methodology used to determine precipitation typing for the remaining months was more rigorous.

The first step in the precipitation typing process was to choose a sounding representative of the nearby environment. Then, the temperature at 850 mb was examined for each event. If this temperature was greater than 0°C, then the precipitation type was diagnosed as rain. This is a reasonable initial criterion since lake-effect storms need an unstable environment in the lower atmosphere to initiate and maintain convection. If the temperature at 850 mb was greater than 0°C and there was an unstable low-level environment beneath this level, then only rain can be generated; and a significant portion of the cloud was assumed to be a "warm" cloud.

For the remaining lightning events, nearby surface weather observations were examined in order to determine the surface temperatures and current weather conditions. These observations were obtained from the National Severe Storms Laboratory [Available online at http://data.nssl.noaa.gov]. Infrequently, surface observations are located within a lake-effect storm, such that the precipitation type is clearly determined; however, in the majority of cases surface observations can only be used to determine the surface temperatures located near the lake-effect precipitation. If the proximity area surface temperatures were greater than 4°C (39°F), then it was assumed that the precipitation was rain. Previous work in determining precipitation type shows that if there is a near-surface layer of above-freezing air (365 m or greater thickness), then any frozen precipitation that passes through it will melt completely (Vasquez 2002). The dry adiabatic mixing of a temperature of 0°C from 365 m AGL to the surface yields a temperature of 3.65°C (39°F), and defines the maximum surface temperature which can support any frozen precipitation during a lake-effect storm.

In each remaining case, the upwind sounding nearest to the location of lightning on the flash density plot was examined. A "modified" top-down method was then used to make a final determination of the precipitation type. The top-down method (Vasquez 2002) was modified by ignoring the atmosphere above the mid-tropospheric stable layer usually present during lake-effect storms. The near-surface warm-layer (T > 0°C) depths of 183 meters for mixed precipitation and 365 meters for liquid precipitation were used to classify the precipitation type of each event (Vasquez 2002). The geographical location of each lake impacts near-surface meteorological conditions; so events that were diagnosed as rain for one lake may have been diagnosed as a mixed event or snow for a different lake. For example lake-effect lightning produced downwind of Lake Erie may have been associated with rain, whereas a lake-effect storm downwind of Lake Huron on the same day may have been associated with snow. The precipitation type was determined by the precipitation associated with the lake which produced the lightning. If the event started out as one type of precipitation and ended as another (e.g., rain-to-snow) the event was determined to be a mix.

4. Results

Thirty-one separate lake-effect thunderstorm events were found in this climatology study over the upper Great Lakes region during the period 1995-2007. Twenty-one of these events were multi-lake events. Table 1 shows the distribution of lightning events over each Great Lake, including the 70 events (25 of which were multi-lake) determined by Steiger et al. (2009). These results indicate that the majority of lake-effect thunderstorms (69%) are found over the lower Great Lakes. This finding coincides well with previous research (Kristovich and Steve 1995), regarding long fetch shore-parallel lake-effect storms which are most prevalent over the lower Great Lakes, and most likely to produce lightning (Moore and Orville 1990). Lake Huron produced lightning in the majority (94%) of the lake-effect thunderstorm events over the upper Great Lakes. However, the results indicate that Lake Michigan also has a significant contribution to the lightning climatology, producing lightning in 18 (58%) of the upper Great Lake events. Lake Superior produced the least amount of lake-effect thunderstorms of the five Great Lakes.

In order to provide a more detailed climatology, the events were organized by month so that seasonal trends with regards to lake-effect thunderstorm event frequency can be observed. Figure 2 illustrates the number of events over the 12-year period organized by month over each lake. One interesting feature present in this graph is the near uniform number of events between all five Great Lakes during the month of September. September was also the month in which Lake Superior produced the majority of its lightning events. The results for Lakes Huron and Michigan are similar to the lower Great Lakes, in that the majority of lake-effect thunderstorm events occurred in October and November. In the late winter months (January-February) it is shown that Lake Ontario

Lake	Superior	Michigan	Huron	Erie	Ontario
Total Events	7	18	29	52	55
Percentage	4.3	11.2	18	32.2	34.2
Annual Mean	0.58	1.5	2.4	4.3	4.6
Standard Dev	0.7	1.4	1.8	2.2	2.1

Table 1. Lake-effect thunderstorm events (1995-2007) for each lake with lake percentages, annual means and standard deviations.

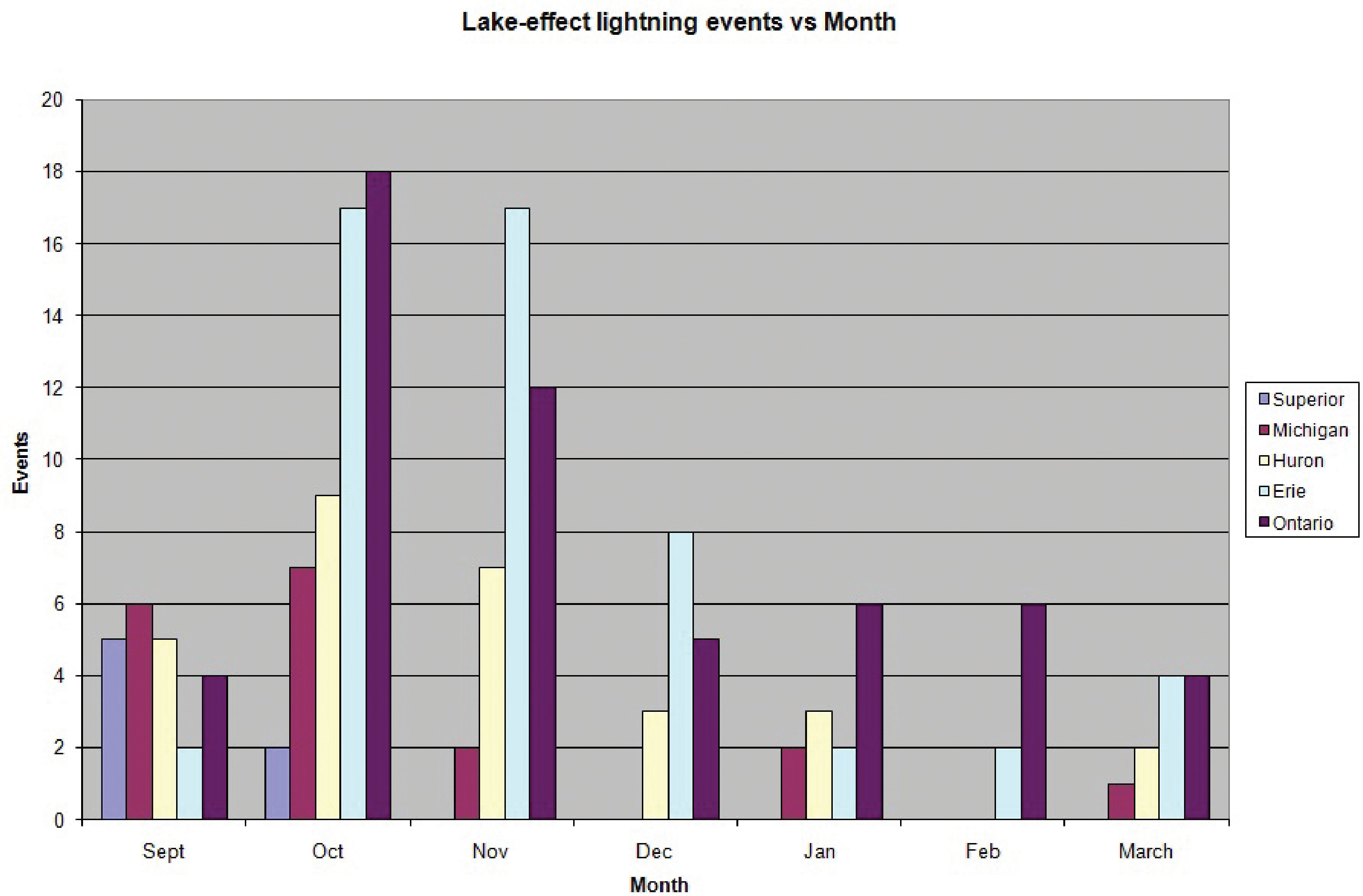

Fig. 2. Frequency of lake-effect lightning events per month (1995-2007) for each Great Lake.

was the major producer of lake-effect thunderstorms.

One interesting phenomenon that appeared while analyzing lightning flash density plots was the occurrence of a Lake Huron-to-Erie Connection (LHEC). An LHEC event was defined as any lake-effect thunderstorm occurring downwind of Lake Erie under a northwest flow and in conjunction with lake-effect precipitation (shown on radar) originating from Lake Huron and extending southeast across Lake Erie (Fig. 3). A total of 15 LHECs were found in the twelve year climatology. The occurrence of LHECs indicate that a significant portion (29%) of lake-effect thunderstorms downwind of Lake Erie are attributed to short fetch, LHEC storms, contradicting some of the previous work done on lake-effect lightning stating that lake-effect lightning is most likely to occur with type-I lake-effect storms (Moore and Orville 1990). It also illustrates how lake-effect storms originating from the upper Great Lakes can contribute significantly to the intensity of lake-effect storms downwind of the lower Great Lakes.

The precipitation type climatology of these lightning events revealed an interesting result - the majority of lake-effect thunderstorm events were thundersnow events. Table 2 illustrates the lake-effect precipitation type of all the lightning events identified during this study, arranged by month and lake. Not surprisingly, the bulk of the rain events occurred in September and early October. October also marked the maximum for mixed event frequency, and the first appearance of thundersnow events. November had a sharp decline in rain and mixed events and a predominance of snow events. The remainder of the lake-effect season was characterized by all snow events. Table 3 displays the distribution of events by lake. In order to eliminate any discrepancies attributed to the varying number of lake-effect thunderstorm events per lake, percentages of each precipitation type were calculated for each lake (Table 4).

The lower Great Lakes produced the bulk of the thundersnow events, which peaked in the month of November. Lake Erie produced slightly more thundersnow events than Lake Ontario, even though Lake Ontario continued to produce lake-effect thunderstorms late in the winter season.

The upper Great Lakes were not as productive with respect to thundersnow events. For example, the percentages of thundersnow events for Lakes Michigan

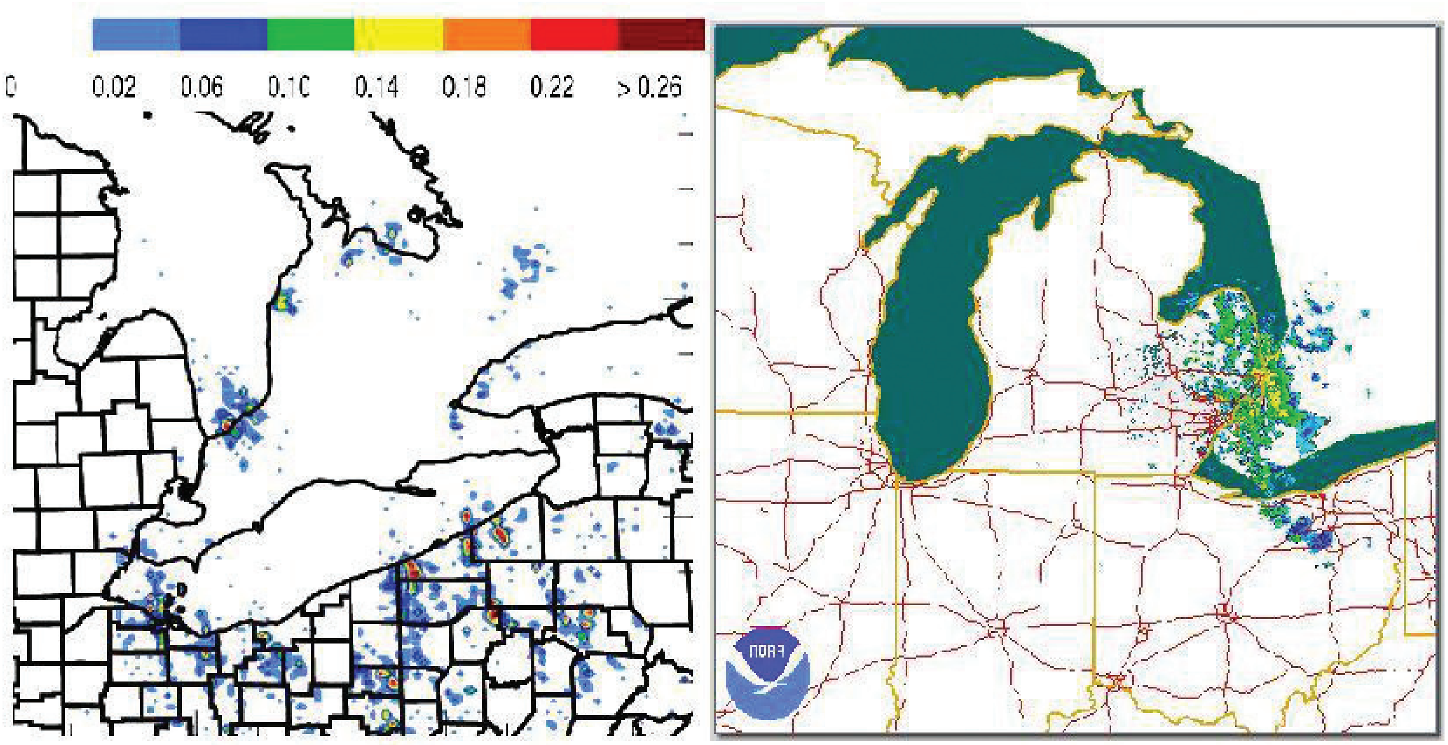

Fig. 3. Daily cloud-to-ground (CG) lightning flash density plot (flashes km^{-2}) valid 8 September 1998 shown on the left. The Radar reflectivity image valid 1730 UTC, 8 September 1998 is shown on the right.

	Superior			Michigan			Huron			Erie			Ontario		
	Rain	Mix	Snow	Rain	Mix	Snow	Rain	Mix	Snow	Rain	Mix	Snow	Rain	Mix	Snow
September	4	1	0	5	1	0	4	1	0	2	0	0	4	0	0
October	0	2	0	1	5	1	1	4	4	9	5	3	14	2	2
November	0	0	0	0	0	2	0	1	6	0	2	15	2	2	8
December	0	0	0	0	0	0	0	0	3	0	0	8	0	0	5
January	0	0	0	0	0	2	0	0	3	0	0	2	0	0	6
February	0	0	0	0	0	0	0	0	0	0	0	2	0	0	6
March	0	0	0	0	0	1	0	0	2	0	0	4	0	0	4

Table 2. Lake-effect thunderstorm events (1995-2007) for each lake categorized by month, and precipitation type.

Lake	Superior	Michigan	Huron	Erie	Ontario
Rain	4	6	5	11	20
Mix	3	6	6	7	4
Snow	0	6	18	34	31

Table 3. Total number of lake-effect thunderstorm events (1995-2007) for each lake, categorized by precipitation type.

and Superior (Table 4) were significantly lower (33% and 0% respectively) than the percentages of thundersnow events for Lakes Erie and Ontario (65% and 56% respectively). The percentage of thundersnow events for Lake Huron was similar to that for the lower Great Lakes (~59%).

5. Discussion

Much of the previous research on lake-effect storms and thundersnow is supported by the results of this climatological study. With the exception of Lake Superior, the Great Lakes show their greatest frequency of lake-effect thunderstorm events in October similar to the lower Great Lakes (Steiger et al. 2009). This study also shows that the majority of lake-effect lightning occurs downwind of the lower Great Lakes. In addressing the question as to why lake-effect thunderstorms are more prevalent over the lower than the upper Great Lakes, it is important to investigate the features that inhibit lake-effect thunderstorms over the upper Great Lakes.

a. Lake Michigan

Lake Michigan's long-shore axis is oriented in a north-south direction. The predominant lower-tropospheric wind direction across the Great Lakes region during the lake-effect season is northwest to southeast (NOAA-ESRL, 2009), indicating that the fetch across Lake Michigan is short and more conducive to weaker multi-band wind-parallel rolls (Kelly, 1982). This finding is also supported by the cloud-to-ground lightning flash density plot of the combined lake-effect thunderstorm events across the upper Great Lakes (Fig. 4). Note that there is not nearly as much CG lightning downwind of Lake Michigan compared with the lakes to the east (Huron, Erie and Ontario). The highest flash density values associated with Lake Michigan occur in the southeast vicinity of the lake, suggesting that most of the lightning attributed to Lake Michigan occurs under north-south oriented shore-parallel storms.

b. Lake Superior

Of all five Great Lakes, Lake Superior produces the least amount of lightning (7 events in 12 years) with no lake-effect thundersnow events. This is interesting considering that Lake Superior's major axis is oriented west-northwest to east-southeast and parallel to the

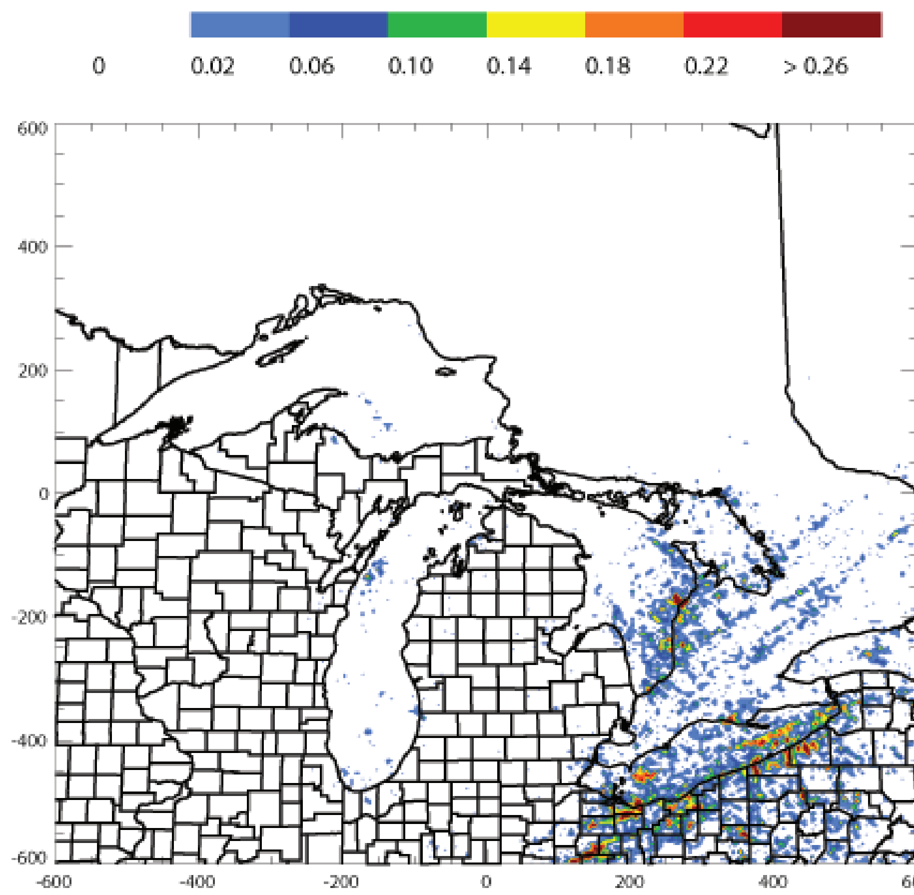

Fig. 4. Cloud-to-ground (CG) lightning flash density plot (flashes km-2) of the entire climatology for the upper Great Lakes.

Lake	Superior	Michigan	Huron	Erie	Ontario
Percentage Rain Events	57	33	17	21	36
Percentage Mix Events	43	33	21	13	7
Percentage Snow Events	0	33	62	65	56

Table 4. Lake-relative percentages of lake-effect thunderstorm precipitation types for each lake (1995-2007).

mean lower tropospheric, geostrophic flow, indicating a predominantly long fetch (NOAA-ESRL 2009). Even with such a long fetch across lake, other features associated with Lake Superior may be responsible for the dearth of lake-effect thunderstorms. Lake Superior has the largest volume of water by a wide margin (12,100 km^3 compared to 4920 km^3 Lake Michigan, which ranks 2nd; GLERL 2009). It is also the northern-most Great Lake. These two features coincide to make Lake Superior's surface temperature significantly colder than the other four Great Lakes in the summer and fall months (Fig. 5). Relative to the other Great Lakes, the large volume of water responds very slowly in warming with the summer air. The lake's higher latitude indicates that Lake Superior has a shorter, cooler summer period as well.

At the onset of the lake-effect season (September) during a typical year, Lake Superior's surface is anywhere from 4-7 °C cooler than the other four Great Lakes. Hence, a significantly colder airmass is required over Lake Superior in order to create the instability required to produce lake-effect storms. While the hypothesis that a cooler lake surface temperature can be an inhibiting factor in lake-effect thunderstorm production seems reasonable, it is important to note that lake-induced instability over Lake Superior was not studied throughout the course of this research. In order to better support the cooler lake surface temperature hypothesis, lake-induced convective available potential energy (CAPE) over Lake Superior must be analyzed and compared to the other four lakes. An inhibiting factor which can contribute to the dearth of lake-effect thunderstorms during the colder months of the season is that the colder temperatures required for the instability may be too cold for a cloud with mixed phase microphysics to form. As previously mentioned in section 2, the mixed ice and liquid phase cloud is thought to be critical to charge separation and lightning production (Reynolds et al. 1957). More support for this idea is found in Schultz (1999), indicating that lower-tropospheric temperature is a more important parameter than lake-induced CAPE for predicting lake-effect thunderstorms.

Another factor that inhibits the production of lake-effect thunderstorms downwind of Lake Superior is the width of the lake along the direction of the prevailing low-level wind. Lake Superior is the widest of the Great Lakes, with the short axis of the lake approximately 160% wider than the next widest lake (Lake Huron). Intense lake-effect storms which form along the long axis of the lower Great Lakes are often enhanced by the presence

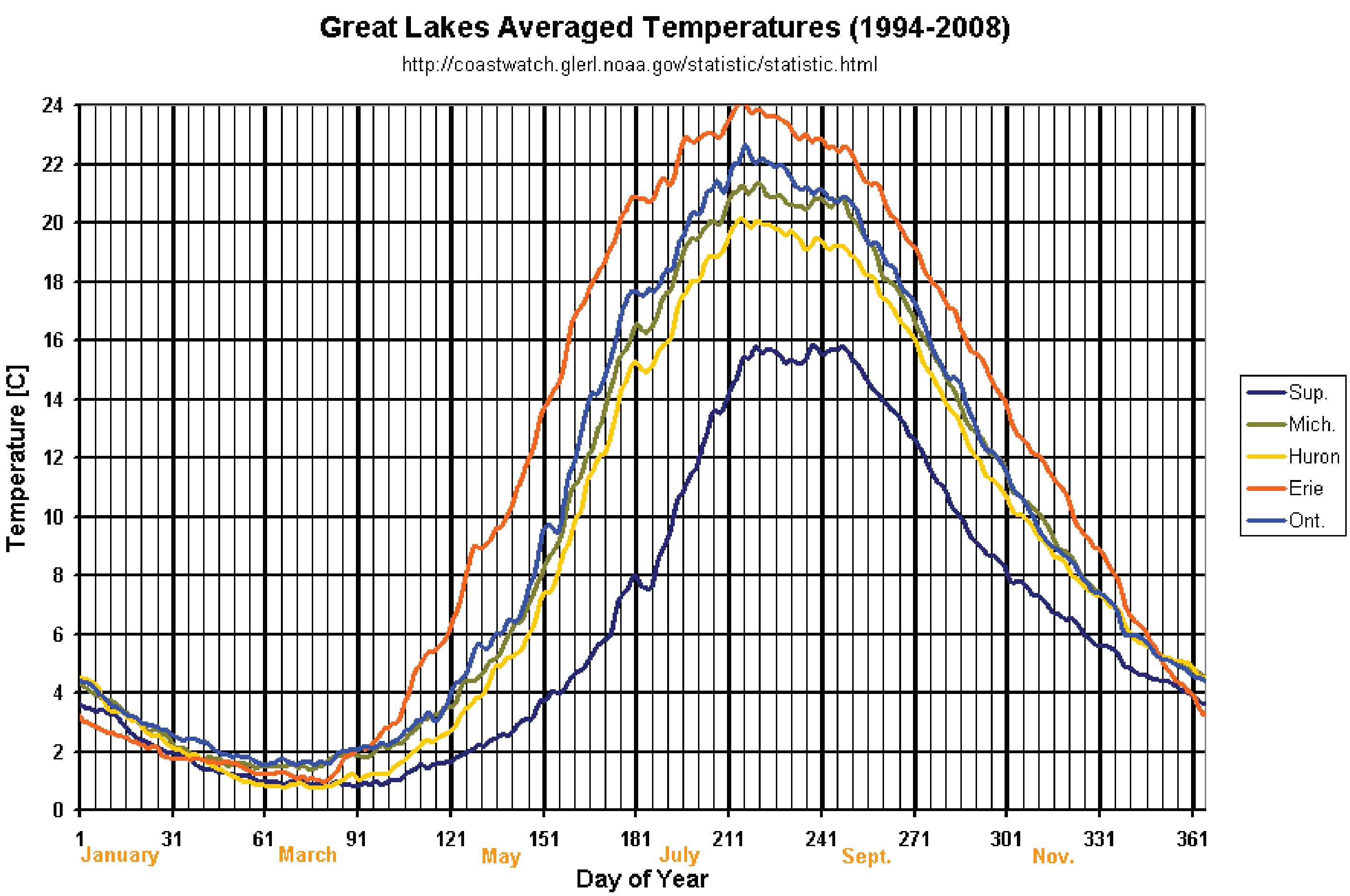

Fig. 5. Average lake-surface temperature versus month for each Great Lake from 1994-2008 (GLERL 2009)

Fig. 6. MODerate resolution Imaging Spectroradiometer (MODIS) polar orbiting satellite image of wind-parallel rolls extending downwind of Lake Superior under a long fetch lake-effect event. Image composite created for 20 January 2008 (SSEC 2009).

of lake-shore land breeze convergence zones which act to consolidate the precipitation into one band near the center of the lake (type-I bands; Niziol et al. 1995). The absence of these lake-shore convergence zones near the center of Lake Superior allows for a multi-banded organization of lake-effect storms, even under a long fetch (Fig. 6). Climatological studies by Kristovich and Steve (1995) and by Rodriguez et al. (2007) also show type-I bands occur relatively infrequently here compared to the lower Great Lakes. Multi-banded storms are usually not as intense or well-organized as single-banded lake-effect storms (Niziol et al. 1995), and therefore are less likely to produce lightning.

Lake Superior is also the western-most Great Lake, indicating under westerly lower tropospheric wind flow conditions, it is the first lake to affect the lower troposphere. Lake Superior more often acts to modify the atmosphere by adding heat and moisture which will often enhance lake-effect storms on downwind lakes (Mann et al. 2002). It is likely that this effect doesn't hinder lake-effect thunderstorm development off of Lake Superior, but instead enhances lake-effect thunderstorm development on downwind lakes creating a greater difference in lightning production between Lake Superior and the other four Great Lakes. A dramatic example of this enhancement is the connection between Lakes Huron and Erie.

c. Lake Huron

Lake Huron shares with Lakes Michigan and Superior many of the same lightning inhibiting features including a north-south major axis and a large width relative to the long axis. Nevertheless, Lake Huron produces a significantly higher amount of lightning than Lakes Michigan and Superior. The relatively high occurrence of lake-effect thunderstorms produced is explained in part by Huron's location downwind of Lakes Michigan and Superior, under westerly flow. Thus, lake-modified air likely enhances the development of storms over Lake Huron (Mann et al. 2002). It is also noteworthy that a high percentage (62%) of the lake-effect thunderstorms produced by Lake Huron was associated with thundersnow events. This percentage of thundersnow events is similar to the lower Great Lake's thundersnow percentage.

Close inspection of individual thunderstorm events revealed an interesting finding regarding flash density associated with Lake Huron. Figure 4 shows the combined flash density plot of the lake-effect lightning across the upper Great Lakes, and indicates a maximum across the entire eastern shore of Lake Huron. However, one event in particular (15 September 2000) accounted for a significant fraction of Lake Huron's flash density. This early-season lake-effect event was associated with a deep upper-level trough that became centered directly over Lake Huron. At the 850 mb level, temperatures were near 0°C, and the winds were well-aligned out of the north-northwest (NCDC 2009). The surface temperature for Lake Huron was 17°C, yielding a difference of 17°C between the lake surface and the 850 mb temperature. The 1200 UTC sounding from Gaylord, Michigan (APX) showed a conditionally unstable layer between the surface and 600 mb level with no indication of a mid-tropospheric inversion layer. The WSR-88D data (not shown) indicated a multi-lake lake-effect event with precipitation originating from all three of the upper Great Lakes (NESDIS 2009). This event was likely a significant lightning producer because of the potential depth of the convective cloud and the relatively steep lapse rate between the base and the top of the cloud. The resulting lake-effect storms were therefore likely deep with copious amounts of super-cooled water, graupel and ice.

d. Lake-Huron-to-Erie connection (LHEC)

Lake Huron-to-Erie connections (LHEC) indicate that many of the lake-effect thunderstorms attributed to Lake Erie were enhanced by Lake Huron. These connections were observed most often under a northwest flow in which the distance between the two lakes was minimized (~80 km). The hypothesis that one Great Lake can enhance lake-effect storms over downwind lakes is well documented in previous studies such as Niziol et al. (1995), Rodriguez et al. (2007), and Mann et al. (2002). The LHEC provides a good indication that lake-enhancement is tied to lake-effect thunderstorm production. Several factors associated with lake-air modification can contribute to an atmosphere more conducive to lake-effect thunderstorms. For example, under colder conditions, warmer lake-modified air crossing over Lake Erie can potentially be more supportive of a mixed phase cloud. Also, a lake-modified atmosphere likely increases the downwind lake-induced CAPE providing more instability for lake-effect storms to develop. Another potential contributing factor is that lake-effect processes occurring over Lake Huron could potentially mix air higher into the atmosphere, weakening and/or raising any low-level inversion layers, allowing for deeper lake-effect convection to develop over and downwind of Lake Erie. The purposes of this study were limited to developing a climatology of lake-effect thunderstorms associated with the Great Lakes, so the above mentioned contributing factors have not been studied, and are only speculative inferences that warrant further research.

e. Lower versus upper Great Lakes

It is appropriate to separate the lower Great Lakes from the upper Great Lakes in this climatology study because of the large differences between them with respect to lake-effect lightning density and the frequency of events. Subtle differences in the lake-effect thunderstorm climatology across the lower Great Lakes are found when comparing the frequency of events on a monthly scale. Thunderstorm events from Lakes Erie and Ontario peak during the month of October. Lake Ontario, however, has a larger number of events than Lake Erie between January and March. Lake Ontario does not produce as many lake-effect thunderstorms as Lake Erie in the early part of the lake-effect season; however, lake-effect thunderstorm events associated with Lake Ontario continue to be present throughout the entire season. These results appear to be closely related to the surface temperatures of each lake. Lake Erie has the smallest water volume of all the Great Lakes, and responds relatively quickly to the cold temperatures that accompany the late fall and winter months (GLERL 2009). With the colder lake-surface temperature on Lake Erie in the late winter, a colder airmass is needed to produce lake-effect storms, and it is likely that lightning production in lake-effect clouds ceases due to either less lake-induced instability over Lake Erie, or a predominantly snow and ice cloud. Also, Lake Erie freezes by early February during a typical winter season (GLERL 2009), greatly reducing the heat and moisture fluxes from the lake surface and thus the intensity of lake-effect storms (Niziol et al. 1995).

Lake-effect precipitation type also appears to be linked to the lake surface temperature differences between Lakes Ontario and Erie (Table 2). Precipitation associated with lake-effect thunderstorms originating from Lake Erie changes over to snow earlier in the season than it does over Ontario. The presence of lake-effect rain as late as mid November near Lake Ontario can be due to a warmer lake-modified airmass originating over Lake Ontario, than over Lake Erie. However, this study did not examine the precipitation type of all lake-effect storms, only lightning producing ones. A more complete understanding of the role that lake-modification has on lake-effect precipitation type can be found by evaluating the climatology of all lake-effect storms.

6. Conclusion

The principal results of this lightning climatology study across the upper and lower Great Lakes for the 12-year period from 1995 to 2007 indicate that the aggregate lower Great Lakes are much more conducive to lake-effect thunderstorm development than the upper Great Lakes. The findings of this study also indicate that the majority of lake-effect thunderstorm events over the lower Great Lakes are thundersnow events, whereas lake-effect thunderstorms over the upper Great Lakes tend to occur more often as early season rain or mixed phase events. Inferences made between lake-effect thunderstorm production and individual lake features indicate that several different variables contribute to the efficiency of thunderstorm production for each lake. Some of these features include varying lake surface temperatures, lake width, proximity to other nearby Great Lakes, and long axis orientation with respect to the prevailing lower tropospheric wind.

This research also supports many of the findings from previous research on lake-effect weather and thundersnow such as those by Reynolds et al. (1957) and Michimoto (1993) showing a relative dearth of lake-effect thundersnow events under colder conditions. Also, the significantly greater frequency of lake-effect thunderstorm events over the lower Great Lakes supports the findings of Moore and Orville (1990) and Kristovich and Steve (1995) on lake-effect storms, relating a higher frequency of type-I lake-effect bands to a higher frequency of lake-effect thunderstorms. A notable finding in this research for operational forecasters is the appearance and frequency of Lake Huron-to-Erie Connections (LHEC). It is important to understand the potential significance of LHECs since it is a situation in which multi-banded short-fetch lake-effect storms can produce lightning downwind of Lake Erie under a northwest flow.

Finally, this study can provide forecasters with a better understanding of lake-effect thunderstorm trends over the Great Lakes region. It also poses new questions regarding the behavior and occurrence of lake-effect thunderstorm events within the Great Lakes region, providing the basis for more specialized research on the subject. Future research on this topic could perhaps focus on inhibiting factors associated with Lake Superior or on the effects that lake-enhancement has on lightning production.

Authors

Ted Letcher received his B.S degree in Meteorology at SUNY Oswego (2009). His research interests include lake-effect meteorology, mountain meteorology and convective boundary layer processes. Ted is currently attending graduate school at Colorado State University, where he is studying aerosol effects on cloud micro-physics in orographic snowstorms over the Rocky Mountains.

Dr. Scott Steiger is an Assistant Professor of Meteorology at the State University of New York (SUNY) at Oswego. He received his B.S. degree in Meteorology from SUNY Oswego in 1999 and his M.S. and Ph.D. degrees in Atmospheric Sciences at Texas A&M University in 2001 and 2005, respectively. His research interests include lake-effect storm precipitation and wind structures, lightning characteristics of storms, and tornadogenesis. Dr. Steiger's main responsibilities revolve around teaching undergraduates and involving them in research.

References

Cummins, K.L., J. A. Cramer, C. J. Biagi, E. P. Krider, J. Jeauld, M. A.. Uman, and V. A. Rakov, 2006: The U.S. National Lightning Detection Network: Post-upgrade status. Preprints, *Second Conf. on Meteorological Applications of Lightning Data,* Atlanta, GA, Amer.Meteor. Soc., CD-ROM, 6.1.

Great Lakes Environmental Research Laboratory (GLERL), cited 2009: Great Lakes statistics [Available online at http://coastwatch.glerl.noaa.gov/statistic/statistic.html]

Holroyd, E.W., 1971: Lake-effect cloud bands as seen from weather satellites. *J. Atmos. Sci*., 28, 1165–1170.

Kelly, R.D., 1982: A single Doppler radar study of horizontal-roll convection in a lake-effect snow storm. *J. Atmos. Sci.,* 39, 1521–1531.

Kristovich, D.A., and R.A. Steve, 1995: A satellite study of cloud-band frequencies over the Great Lakes. *J. Appl. Meteor.*, 34, 2083–2090.

Mann, G.E., R.B. Wagenmaker, and P.J. Sousounis, 2002: The influence of multiple lake interactions upon lake-effect storms. *Mon. Wea. Rev*., 130, 1510–1530.

Michimoto, K., 1993: A study of radar echoes and their relation to lightning discharges of thunderclouds in the Hokuriku District. Part II: Observation and analysis of ''single-flash'' thunderclouds in midwinter. *J. Meteor. Soc. Japan*, 71, 195–204.

Moore, P.K., and R.E. Orville, 1990: Lightning characteristics in lake-effect thunderstorms. *Mon. Wea. Rev.*, 118, 1767–1782.

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National Climatic Data Center (NCDC), cited 2009: *Upper air data.* [Available online at: http://www.ncdc.noaa.gov/oa/upperair.html]

National Environmental Satellite, Data and Information Service (NESDIS), cited 2009: National mosaic reflectivity images. [Available online at http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwnexrad~images2]

National Oceanic and Atmospheric Administration (NOAA)-Earth System Research Laboratory (ESRL) Physical Sciences Division, cited 2009: NCEP reanalysis monthly mean plots. [Available online at http://www.esrl.noaa.gov/psd/data/gridded/reanalysis/]

Niziol, T.A., W.R. Snyder, and J.S. Waldstreicher, 1995: Winter weather forecasting throughout the eastern United States. Part IV: Lake effect snow. *Wea. Forecasting*, 10, 61–77.

Reynolds, S.E., M. Brook, and M.F. Gourley, 1957: Thunderstorm charge separation. *J. Atmos. Sci.*, 14, 426–436.

Rodriguez, Y., D.A.R. Kristovich, and M.R. Hjelmfelt, 2007: Lake-to-lake cloud bands: Frequencies and locations. *Mon. Wea. Rev.*, 135, 4202–4213.

Schultz, D.M., 1999: Lake-effect snowstorms in northern Utah and western New York with and without lightning. *Wea. Forecasting*, 14, 1023–1031.

Space Science and Engineering Center (SSEC), University of Wisconsin, cited 2009: High resolution satellite image. [Available online at http://ge.ssec.wisc.edu/modis-today/]

Steiger, S.M., R. Hamilton, J. Keeler, and R.E. Orville, 2009: Lake-effect thunderstorms in the lower Great Lakes. *J. Appl. Meteor. Climatol.*, 48, 889–902.

Vasquez, Tim, 2002: *Weather Forecasting Handbook*. Weather Graphics Technologies. 204 pp.