Climatology of Cold Season Lake-effect Cloud Bands for the North American Great Lakes

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ABSTRACT

Geostationary Operational Environmental Satellite (GOES) visible imagery was used to identify lake-effect (LE) clouds in the North American Great Lakes region for the cold seasons (October–March) of 1997/1998 through 2013/2014 to provide a comprehensive climatological description of the seasonal and interannual variability of LE cloud bands. During the average cold season, at least 60% of days each month had LE clouds over some portion of the Great Lakes region and nearly 75% of all LE days had LE clouds present over several lakes simultaneously. Wind-parallel bands (WPB) are observed far more frequently than any other type of LE over Lakes Superior, Michigan, and Huron during the months of December, January, and February. Over Lake Erie, the occurrence of days per month with WPB was found to be approximately 5%−10% greater than days with shore-parallel bands (SPB) throughout the entire cold season. The greatest frequency of SPB occurrences in the Great Lakes region was over Lake Ontario during the months of January and February (~20% of days). Additionally, Lake Ontario was the only lake where the frequencies of WPB and SPB occurrences were fairly similar each month.

The annual frequency of WPB occurrences are the most variable among the Great Lakes, decreasing in frequency from the western lakes toward the eastern lakes. Lake Ontario has the largest annual frequency of SPB occurrences and the greatest variation in SPB annual frequency. Lake Huron has the second largest annual frequency of SPB days with small interannual

variation. The primary differences of the annual frequency of lake-to-lake (L2L) LE occurrences when compared to previous research were a greater variability in the L2L annual frequency of Superior-to-Michigan connections, greater frequency of Michigan-to-Huron connections, and less frequent occurrences for Superior-to-Huron and Michigan-to-Erie connections.

1. Introduction

Lake-effect (LE) clouds are common throughout the North American Great Lakes region during the winter, when the lakes act as a local moisture source and their relatively warm waters lead to a destabilization of colder air masses moving through the region. These clouds are often organized having specific LE morphologies that result from particular boundary layer profiles of heat, moisture, and momentum present when a cold air mass traverses over an underlying lake in a state ranging from open water to complete ice cover. The mesoscale cloud patterns and presence of cloud bands are direct indicators of LE systems, whether precipitating or not, and the mesoscale circulations that are associated with these systems.

The approach used in this study should have widespread application as similar mesoscale systems and cloud bands have been observed in a large number of locations beyond the Great Lakes region. These systems develop in similar atmospheric environments where boundary layer destabilization occurs from cold airmasses moving over relatively warm water, and have been observed and investigated in regions including: the English Channel and Irish Sea (Norris et al., 2013), the Gulf of Finland (Mazon et al., 2015; Savijärvi, 2015), the Baltic Sea (Andersson and Nilsson, 1990; Andersson and Gustafsson, 1994), the Labrador Sea (Renfrew and Moore, 1999; Liu et al., 2006), the Greenland Sea (Brümmer et al., 1992; Brümmer and Pohlmann, 2000), the Beaufort Sea (Mourad and Walter, 1996), the Bering Sea (Walter, 1980), the Sea of Japan (Asai and Miura, 1981; Tusboki et al., 1989; Nakai et al., 2005) and several other North American bodies of water, such as the Chesapeake and Delaware Bays (Sikora and Halverson, 2002), Lake

Champlain (Laird et al., 2009a), the Finger Lakes (Laird et al., 2009b), Lake Tahoe and Pyramid Lake (Laird et al., 2015), and the Great Salt Lake (Alcott et al., 2012).

Occurrences of LE clouds and the differing classifications of LE snow storms in the Great Lakes region have previously been documented by several studies (e.g., Hill, 1971; Forbes and Merritt, 1984; Kelly, 1986; Hjelmfelt, 1990; Niziol et al., 1995; Kristovich and Steve, 1995; Rodriguez et al., 2007; Ackerman et al., 2013); however, these studies have focused on specific events, specific lake regions (e.g., Lake Michigan), rather limited time periods (d 5 winters), or regional cloud coverage and cloud properties. Niziol et al. (1995) grouped LE systems into five different classifications (Type I through Type V). They defined Type I systems as a single cloud band or pair of prominent bands that forms when winds are parallel to the long axis of the lake. These LE systems have also been termed shore-parallel bands (SPB) (e.g., Braham, 1983), shoreline bands (e.g., Laird et al., 2003), or long lake-axis-parallel (LLAP) bands (Steiger et al., 2013; Veals and Steenburgh, 2015). Type II systems are comprised of multiple cloud bands that form when winds are perpendicular to the long axis of the lake (i.e., shorter fetch). These LE systems have also been referred to as wind-parallel bands (WPB) or widespread LE (e.g., Laird et al., 2003) and are comprised primarily of horizontal roll convection (e.g., Kristovich, 1993). Type III systems are LE cloud bands that develop over an upstream lake (e.g., Lake Huron), extend across the intervening land mass, and continue over a downstream lake (e.g., Lake Ontario). These have been called lake-to-lake (L2L) cloud bands (e.g., Rodriguez et al., 2007) or multi-lake bands (e.g., Mann et al., 2002) and can form when lake-aggregate processes contribute substantially to the development of LE systems (e.g., Sousounis and Fritsch, 1994).

Type IV systems are similar in appearance to shore-parallel bands and primarily develop during weak ambient wind conditions along a land-breeze convergence zone moving offshore. These have also been referred to as mid-lake LE bands (e.g., Passarelli and Braham, 1981; Hjelmfelt, 1990), shore-parallel bands, or shoreline bands. Lastly, Type V systems appear as an isolated cyclonic circulation in the cloud or precipitation fields on the spatial scale of a lake basin and are called mesoscale vortices (e.g., Pease et al., 1988; Laird, 1999; Laird et al., 2001). Forbes and Merritt (1984) identified LE mesoscale vortices (MSV) by the presence of a miniature comma cloud, a swirl of cloud bands, or a swirl of cloud streets. Small mesoscale and misoscale vortices have been observed along shore-parallel bands (e.g., Grim et al., 2004; Steiger et al., 2013); however, the current analyses of LE cloud patterns include identification of only lake-basin-scale vortices and not smaller scale vortices imbedded within individual snow bands.

Kristovich and Steve (1995) investigated the occurrence of LE clouds in the Great Lakes region using visible satellite images across five cold seasons from 1988/1989 through 1992/1993. They classified LE clouds into four groups: 1) widespread stratocumulus comprised of multiple wind-parallel bands (WPB), 2) shore-parallel bands (SPB), 3) cloud patterns showing both WPB and SPB combined, and 4) an unclear classification where the pattern of LE clouds was not distinctly in any of the previous three groups. Rodriguez et al. (2007) investigated the frequency of LE clouds for an additional five cold seasons (from January 2000 through December 2004). In addition to the four classifications documented by Kristovich and Steve (1995), they identified LE days with mesoscale vortices (MSV) as well as days with lake-to-lake (L2L) cloud bands. Both Kristovich and Steve (1995) and Rodriguez et al. (2007) recorded only the primary classification for each lake on a given day, even if several types of LE cloud bands were present. This approach was necessary based on the quality and resolution of the satellite imagery used in these studies and undoubtedly resulted in an underestimate of the frequency of LE in several, if not all, classification groups.

The current study provides a comprehensive climatological description of the seasonal and interannual variability of LE cloud bands through the use of satellite imagery and provides an unmatched database related to the occurrence of cold-season lake effects in the Great Lakes region. This study differs from previous LE satellite-based studies in two important ways. First, satellite imagery from 17 consecutive cold seasons provides an extended period to investigate the variability of LE clouds over each of the Great Lakes. Second, high-spatial and high-temporal resolution visible satellite imagery (digital images with 1-km resolution at 15 minute interval) provided the ability to confidently identify and understand the evolution of LE clouds for each day during the cold seasons. This imagery allowed for the documentation of multiple cloud types, if present, over a lake during one daylight period rather than reporting only the dominant cloud type for a given day or relying on a very small number of images from overpasses of polar-orbiting satellites per day.

2. Data and methods

Geostationary Operational Environmental Satellite (GOES) visible imagery was used to identify LE clouds in the North American Great Lakes region for the cold seasons (October–March) of 1997/1998 through 2013/2014. Satellite imagery were retrieved from the National Oceanic and Atmospheric Administration (NOAA) Comprehensive Large Array-data

Stewardship System (CLASS) archive (URL: www.class.noaa.gov). Data were extracted for the North American Great Lakes region using the latitude and longitude coordinates of 50.5 N, -95.0 W, -71.0 E, 37.5 S (Figure 1) for each date during the 17 cold seasons between the hours of 1100 UTC and 2359 UTC (i.e., daylight hours) with a time interval of approximately 15 minutes. Only 68 days during the 17 seasons did not have sufficient GOES visible imagery to investigate the presence of LE clouds in the Great Lakes region (i.e., average of 4 days per 6-month cold season).

The use of satellite imagery to identify LE situations offers important benefits as an alternative to the use of land-based radar systems; namely, (a) the capability of identifying LE situations that may not be producing measurable precipitation and (b) the ability to observe shallow LE clouds over all areas of the Great Lakes. The current United States Weather Surveillance Radar – 1988 Doppler (WSR–88D) radar network is unable to monitor low atmospheric levels and shallow LE systems over several lake areas (e.g., Brown et al., 2007). The use of only GOES visible imagery restricted identification of LE clouds to daylight hours from October through March. Although other satellite imagery and products, such as infrared imagery, would have provided continuous temporal coverage, these were not used because of lower spatial resolution and unsatisfactory ability to distinguish relatively warm boundary layer LE clouds from the underlying lake waters (e.g., Niziol et al., 1995).

Several studies have found notable diurnal variation of LE systems with a greater frequency of development (Laird et al., 2009a, Laird et al., 2009b; Alcott et al., 2012) and a maximum in LE precipitation frequency (Kristovich and Spinar, 2005) during the morning hours.

Alternatively, Veals and Steenburgh (2015) found that the frequency of Lake Ontario LE precipitation observed by WSR–88D radar had no diurnal variation during winter (DJF), but had weak modulation in fall (SON) and spring (MAM). These previous findings suggest that the frequency of LE days determined in this current study may be an underestimate since nighttime events would not have been observed using visible satellite imagery. The authors suspect that this underestimate is relatively small across each cold season since LE systems in the Great Lakes region often have event durations greater than 12 hours (e.g., Veals and Steenburgh, 2015). For example, Veals and Steenburgh (2015) found the mean (median) duration of Lake Ontario LE precipitation periods to be 19.5 (13.2) hours. Situations when mesoscale LE bands were (a) embedded within or positioned underneath a widespread synoptic cloud shield or (b) located over areas of extensive ice and snow cover which provide a highly reflective surface preventing conclusive identification of LE clouds could also contribute to an underestimate of LE occurrence.

Images for each LE day were visually inspected using stepwise animation to identify LE mesoscale cloud bands and to examine the temporal evolution of clouds over each of the Great Lakes. Although a subjective approach, the analysis methodology incorporated multiple iterations of reviewing potential LE GOES imagery. Individual co-authors identified potential LE days from the entirety of the GOES imagery and then a small group, which always included the lead author to allow for analysis consistency, reviewed imagery of each potential LE day to determine whether LE clouds were present and which LE classification best represented the morphology. Important factors used in the current study for identifying LE clouds over a lake were (a) the cloud pattern needed to be temporally consistent and be visible for at least one hour (i.e., ≥ 4 consecutive visible images), (b) the clouds must have originated over the lake rather than developed over land and extended downstream over a lake, and (c) the cloud patterns needed to exhibit features consistent with the mesoscale nature of LE systems rather than broad cloud shields associated with larger synoptic-scale forcing. The three primary types of classifications used in this study were wind-parallel bands (WPB), shore-parallel bands (SPB), and mesoscale vortices (MSV).

The LE cloud pattern over a lake often changed during a day or different LE cloud patterns were simultaneously present over separate areas of a lake. Using the high-resolution GOES visible imagery, the current study was able to document when more than one LE cloud classification occurred over an individual lake during a day. For example, three different classifications (WPB, SPB, and MSV) of LE clouds were recorded for over Lake Michigan on 20 February, 2008 (Figure 1). Additionally, WPB were present over Lake Superior, WPB and MSV were present over Lake Huron, a SPB was present over Lake Ontario, and synoptic clouds covered Lake Erie on 20 February, 2008 (Figure 1).

The current study also documented LE clouds that occurred in an unorganized pattern with mesoscale features that were not clearly WPB, SPB or MSV. The classification of these mesoscale LE clouds was termed unorganized (UNCL). Lastly, occurrences of L2L cloud bands were documented. L2L cloud bands are visible extending from Lake Superior to over northern Lake Michigan in Figure 1. Undoubtedly, upstream lakes modify the original continental air mass traversing the lake by upward heat and moisture fluxes or several lakes act collectively through lake-aggregate processes (Sousounis and Shirer, 1992); however, L2L bands were recorded only when temporally and structurally coherent cloud bands were present extending from an upstream lake, across land, and over a downstream lake.

3. Results

In total across the 17 cold seasons, 2123 (70.1%) days had one or multiple occurrences of LE clouds in the Great Lakes region. Lake Superior had 1424 (47%) days, Lake Michigan had 1325 (43.7%) days, Lake Huron had 1282 (42.3%) days, Lake Erie had 864 (28.5%) days, and Lake Ontario had 1054 (34.8%) days with LE clouds. In the Great Lakes region, there were 1540 (50.8%) days with WPB over at least one lake, 913 (30.1%) days with SPB, 71 (2.3%) days with MSV, 1128 (37.2%) days with UNCL, and 472 (15.6%) days with L2L LE clouds.

The current study found that about 25% of LE days have only one lake in the Great Lakes region active with LE and nearly 75% of LE days have LE clouds present over several lakes simultaneously (Figure 2). This suggests that a large area of the Great Lakes region is often covered by a polar or Arctic airmass during North American cold-air outbreaks (CAOs) and more than one region may be impacted by LE precipitation. The number of LE days with two or three lakes having LE clouds was very similar during most cold season months and collectively represented about 5%–7% of LE days in any month. The greatest variation across the cold season occurred for the number of LE days with four or five lakes having LE clouds. The fewest LE days with LE clouds over four or five lakes occurred during October, November, and March; each month with < 2.5% of total LE days. December, January, and February had a noticeably greater number of LE days with four or five lakes having LE; combining for about 7.5% in December, 8.5% in January, and 6.6% in February of the total LE days (Figure 2).

a. *Monthly frequency of LE cloud bands*

Across the cold season, about 60% to 80% of days per month have LE clouds over some portion of the Great Lakes region (Figure 3a). For each individual lake approximately 25% to 39% of days per month have LE clouds during October and November. December, January, and February (DJF) have the greatest percentage of days with LE clouds; Lake Superior has the most LE days (55%–62% of all days each month) followed by Lakes Michigan and Huron, which have near 50% during each of DJF. Lake Ontario also has its greatest percentage of days with LE clouds during DJF with values close to 45% each month. Lake Erie exhibits a much different seasonal progression with early season values in October and November of about 31%, a slight maximum in December of 37%, and then a steady decrease in the percentage of days having LE clouds through the remainder of the cold season.

The frequencies of days per month in DJF with WPB are substantially larger compared with any other type of LE that occurs on Lakes Superior, Michigan, and Huron (Figures 3b,c,d). During these months, Lake Superior experiences the greatest frequency of WPB occurrences, followed by Lake Michigan and then by Lake Huron. The frequencies of SPB and UNCL LE occurrences are very similar and remain fairly consistent from the early to late cold season for Lakes Superior, Michigan, and Huron. The frequency of UNCL days each month remains in the range of 10%–15% across all lakes.

Over Lake Erie, the occurrence of days per month with WPB was found to be approximately 5%–10% greater than SPB occurrences throughout the entire cold season (Figure 3e). The greatest frequency of SPB occurrences (~20%) in the Great Lakes region was over Lake Ontario during the months of January and February (Figure 3f). Additionally, Lake Ontario was the only lake where the frequencies of WPB and SPB occurrences were fairly similar each month and ranged from about 10%–20%. The monthly LE frequency information that is shown graphically in Figure 3 is provided in Table 1.

Lastly, as noted in earlier studies (e.g., Forbes and Merritt, 1984; Rodriguez et al., 2007), MSVs were a rare occurrence and most frequently occurred over Lakes Superior and Michigan. Across the 17 cold seasons, MSV occurrences were observed on 31 days over Lake Superior, 22 days over Lake Michigan, 16 days over Lake Huron, 7 days over Lake Erie, and only on 4 days over Lake Ontario. Clearly, the atmospheric conditions to support the development of lake-basin-scale MSVs are quite specific (e.g., Hjelmfelt, 1990; Laird, 1999) and most often lead to MSV development when the conditions exist over lake shorelines of favorable curvature, such as southern Lake Michigan (Pease et al., 1988).

b. Frequency of LE classifications

The variation in annual frequency of LE classifications (i.e., WPB, SPB, UNCL, and MSV) exhibits dependence on the specific Great Lake (Figure 4). WPB occurrences are the most variable in annual frequency across the Great Lakes region. The annual frequency of WPB steadily decreases from west to east with the largest median of about 34% of cold season days for Lake Superior to median values of approximately 31% and 25% of cold season days for

Lakes Michigan and Huron, respectively. The annual WPB frequencies for these three western lakes are statistically greater at a 95% confidence interval using a two-sample t-test than WPB frequencies for Lakes Erie and Ontario, which have statistically similar WPB frequencies and median values of ~15%.

Lake Ontario has the largest median annual frequency of nearly 14% for SPB occurrences and the greatest variation in SPB annual frequency (Figure 4). The largest annual frequency of SPB days on Lake Ontario (29% or 52 days) occurred during the cold season of 2013/2014 and the smallest annual frequency (5% or 9 days) occurred during 1997/1998. Lake Huron has the second largest median annual frequency of about 11% for SPB days with small interannual variation similar to that of Lakes Michigan, Superior, and Erie. Across all the lakes, the annual frequency is very similar for the UNCL classification with median values around 10%. For all lakes except Lake Ontario, UNCL days tend to occur more often and have a greater interannual variation than SPB days.

c. *Annual frequency of LE cloud bands*

The determination of LE activity across 17 cold seasons provides an opportunity to explore the interannual variability of LE clouds across the entire Great Lakes region and over each of the Great Lakes (Figure 5). The number of days with LE clouds occurring over one or more Great Lakes (Figure 5; black line) ranged from 141 days during the cold season of 2008/2009 (~77% of days) to 96 days during the cold season of 2011/2012 (~53% of days).

There were several cold seasons where a relatively large frequency of LE occurred over nearly all the Great Lakes. These cold seasons included 2000/2001, 2002/2003, 2008/2009, 2012/2013, and 2013/2014. For example, during 2008/2009 Lakes Superior, Michigan, Huron, Erie, and Ontario had LE clouds occur on 52%, 49%, 47%, 30%, and 44% of cold season days, respectively. There was notable interannual variation of LE frequency for Lake Erie, and the cold seasons having the largest annual frequency were not always consistent with the annual activity over the other four Great Lakes (Figure 5). During colder winters that would be more favorable for a greater frequency of lake effect (e.g., 2002/2003; 2008/2009), Lake Erie exhibited relatively low frequencies suggesting that during these colder seasons extensive ice cover developed across Lake Erie, thereby, limiting some of the lake-surface heat and moisture fluxes required for LE mesoscale circulations and clouds (Assel, 2005; Gerbush et al, 2008; Cordeira and Laird, 2008).

Across the 17 cold seasons, there were also several time periods with relatively small annual frequencies (e.g., 2001/2002, 2009/2010, and 2011/2012) over the entire Great Lakes region and individual lakes. For example, during the 2009/2010 cold season, Lakes Superior, Michigan, Huron, Erie, and Ontario had LE clouds occur on 34%, 27%, 26%, 17%, and 23% of cold season days. The interannual variations identified across the 17 cold seasons are a result of contributions from numerous factors ranging from lake water temperatures, regional air temperatures, and ice cover, to seasonal global climate patterns controlling both the mesoscale and synoptic-scale atmospheric environments. An investigation of the factors causing the interannual variation of Great Lakes LE activity is not the purpose of the current study. However, the large number of LE events identified across the 17 cold seasons will be used in subsequent studies to explore the variability and significance of numerous factors influencing LE activity and snowfall trends that others have investigated with much smaller subsets of LE cases (e.g., Braham and Dungey, 1984; Norton and Bolsenga, 1993; Serreze et al., 1998; Kunkel et al., 2002; Burnett et al., 2003; Ellis and Johnson, 2004; Grimaldi, 2008; Kunkel et al., 2009; Bard and Kristovich, 2012; Hartnett et al., 2014).

d. Multi-lake cloud bands

The Great Lakes can act collectively to produce an aggregate atmospheric response to the localized heat and moisture transfer from the warm lake waters to the overlying air during the cold season (e.g., Sousounis and Shirer, 1992). An aggregate circulation can influence mesoscale weather systems and result in a LE storm that develops in association with an upstream lake extending to a downstream lake over the intervening land surface (e.g., Sousounis and Fritsch, 1994; Mann et al., 2002). This LE situation is often referred to as a L2L connection or multi-lake connection and is most evident when a snow band or cloud band develops (Rodriguez et al., 2007), such as the cloud bands extending from Lake Superior to northern Lake Michigan on 20 February 2008 (Figure 1). As an alternative to a Great Lakes lake aggregate situation, the curvature of the synoptic-scale flow may provide a favorable environment for a L2L connection. For example, a synoptic-scale trough positioned over or to the east of Lake Ontario in southern Quebec, Canada often provides a cyclonic parcel trajectory from western Lake Huron along the primary axis of Lake Ontario leading to the development of a L2L connection.

L2L connections resulting in LE cloud bands occur throughout the Great Lakes region often across two or sometimes three lakes. An examination of the annual frequency of L2L cloud bands for eight combinations of upstream and downstream lakes shows the connection from

Lake Superior to Lake Michigan occurs most often and also has the largest interannual variation (Figure 6). The median annual frequency for the Lake Superior to Lake Michigan (S-M) connection is 12 days during a cold season and ranges from a maximum of 26 days to a minimum of 3 days across the 17 cold seasons examined. Areas of the Great Lakes region with the least frequent occurrence of L2L connections were Lake Michigan to Lake Erie (M-E), Lake Erie to Lake Ontario (E-O), and Lake Ontario to Lake Erie (O-E) with typically less than 2 days per cold season.

Rodriguez et al. (2007) examined a five-season time period and reported on the frequency of multi-lake cloud bands for six areas in the Great Lakes region; their study did not explore E-O or O-E connections. Although a shorter time period was inspected by Rodriguez et al. (2007), the annual frequencies were generally comparable. The primary differences in the current 17-season analysis were a greater variability in the annual frequency of S-M connections, greater frequency of M-H connections, and less frequent occurrences for S-H and M-E connections (Figure 6).

4. Discussion and summary

The current study presents a climatology of LE cloud bands for the Great Lakes region of North America across 17 cold seasons (i.e., 1997/1998–2013/2014). Maximum LE frequency was found to range from about 20% to nearly 60%, depending on the specific month and lake. Both Kristovich and Steve (1995) and Rodriguez et al. (2007) found the frequency of LE cloud bands to be lower using much shorter time periods; 1988/1989–1992/1993 and January 2000–December 2004, respectively (Figure 7). The LE frequencies found by Kristovich and

Steve (1995) were systematically the lowest and the LE frequencies from the current study were nearly always the largest, except for the months of January, February, and March over Lake Erie. During several months, the mean LE frequency in the current study differed by as much as 20% when compared to Kristovich and Steve (1995) (Figure 7). On average, the mean monthly LE frequencies reported by Kristovich and Steve (1995) for Lakes Superior, Michigan, Huron, Erie and Ontario are 16.2%, 17.0%, 18.7%, 11.5%, and 15.7% lower than those found in the current study. The mean monthly LE frequencies reported by Rodriguez et al. (2007) were also less than results from the current study by 9.2%, 11.2%, 6.8%, 3.3%, and 8.3% for Lakes Superior, Michigan, Huron, Erie, and Ontario, respectively.

Some of these differences can likely be attributed to factors other than the natural variation of LE occurrences during differing time periods. For example, differences in results between the three studies may have occurred from variances in the (a) resolution of the GOES imagery, (b) method of subjective identification of LE, and (c) decision on amount of information to collect from GOES imagery; inclusion of all observed LE versus only dominant LE on a lake during a LE day. In an attempt to address the potential influence of non-homogeneous time periods, data from the current study was examined for the time period of 2000-2004 used by Rodriguez et al. (2007) and compared (Figure 7). Overall, the mean monthly LE frequencies from 2000-2004 remained similar to the results from the 17 cold seasons and continued to be greater than mean monthly LE frequencies found by Rodriguez et al. (2007) except for a few months over Lakes Erie and Ontario.

The visible satellite image for 20 February, 2008 provides an example of a day with LE clouds over four lakes (Figure 1). Interestingly, the number of LE days with LE clouds over five lakes was the largest compared to all other groups (one, two, three, and four lakes with LE) during December and January (Figure 2). This result suggests that during these two months the Great Lakes region experiences frequent intrusions of spatially large CAOs that produce a widespread area of favorable conditions for LE systems, consistent with a North American CAO climatology completed by Wheeler et al. (2011) that found CAOs had the largest latitudinal and longitudinal extent (reaching into the Great Lakes region) during the months of December and January.

The steady decrease in LE clouds over Lake Erie from December through March suggests a close relationship to the Lake Erie ice cycle. Although LE systems can occur with extensive ice cover on Lake Erie (Cordeira and Laird 2008), there is often a significant reduction in LE snowfall and system development because of greatly reduced surface heat fluxes (e.g., Gerbush et al., 2008; Vavrus et al., 2013). Lake Erie often develops the most extensive ice cover on the Great Lakes, with the typical ice cover cycle beginning in the shallow western basin during late December, increasing to maximum ice cover in all basins of the lake by middle February, and experiencing rapid loss of ice cover from middle to late March (Assel, 2005).

L2L cloud band frequencies in the Great Lakes region were found to have several aspects similar to those reported by Rodriguez et al. (2007). The influence of L2L situations on LE systems existing over a downstream lake has been investigated by only a few studies (e.g., Sousounis and Fritsch, 1994; Mann et al., 2002) despite its importance to forecasting periods of heavy snowfall during LE events and the frequent consideration of these complex interactions by operational forecasters. As a supplement to the numerical modeling studies performed by Sousounis and Fritsch (1994) and Mann et al. (2002) there is a need for additional case studies and climatological investigations to examine L2L LE situations. For example, studies should be conducted to examine (a) the typical environmental conditions necessary for L2L occurrence in different areas of the Great Lakes region, (b) the influence of factors such as lake temperature, ice cover, parcel trajectory, over-lake residence times on L2L events, and (c) the degree that snowfall in the vicinity of the downstream lake may be altered during L2L events in comparison to LE event without a robust upstream connection to another Great Lake.

In summary, GOES visible imagery was used to identify LE clouds in the North American Great Lakes region for the cold seasons (October–March) of 1997/1998 through 2013/2014 to provide a comprehensive climatological description of the seasonal and interannual variability of LE cloud bands. Across the cold season, about 60% to 80% of days per month have LE clouds over some portion of the Great Lakes region. Nearly 75% of all LE days had LE clouds present over several lakes simultaneously. The frequencies of days per month with wind-parallel bands (WPB) during December, January, and February are substantially larger compared with any other type of LE over Lakes Superior, Michigan, and Huron. Over Lake Erie, the occurrence of days per month with WPB was found to be approximately 5%–10% greater than days with shore-parallel bands (SPB) throughout the entire cold season. The greatest frequency of SPB occurrences (i.e., nearly 20%) anywhere in the Great Lakes region was over Lake Ontario during the months of January and February. Additionally, Lake Ontario was the only lake where the frequencies of WPB and SPB occurrences were fairly similar each month.

WPB occurrences are the most variable in annual frequency across the Great Lakes region, decreasing in frequency from the western lakes toward the eastern lakes. Lake Ontario has the largest annual frequency of SPB occurrences and the greatest variation in SPB annual frequency. Lake Huron has the second largest annual frequency of SPB days with small interannual variation. The primary differences of the annual frequency of L2L occurrences when compared to previous research were a greater variability in the L2L annual frequency of Superior-to-Michigan connections, greater frequency of Michigan-to-Huron connections, and less frequent occurrences for Superior-to-Huron and Michigan-to-Erie connections.

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Figure List & Captions

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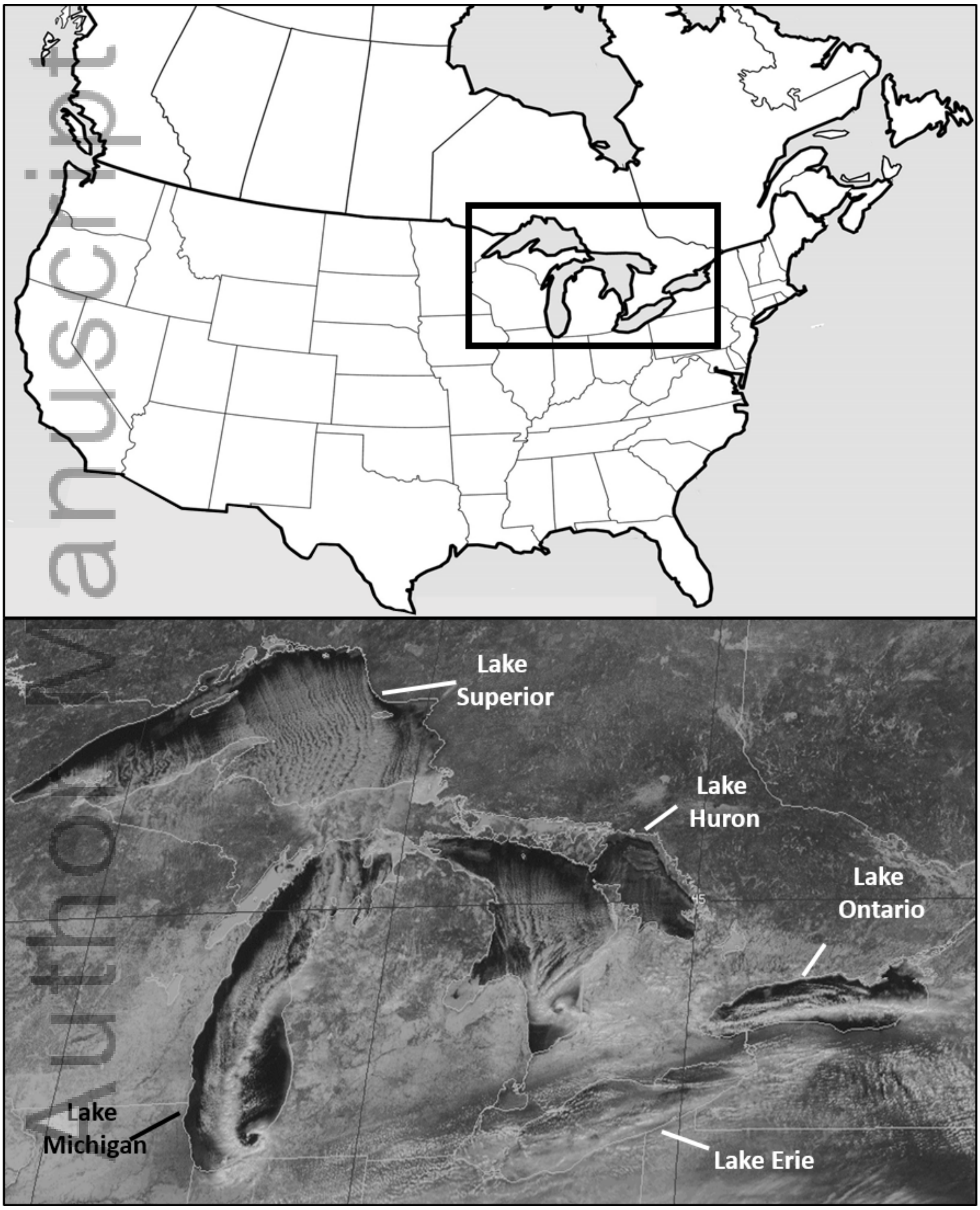
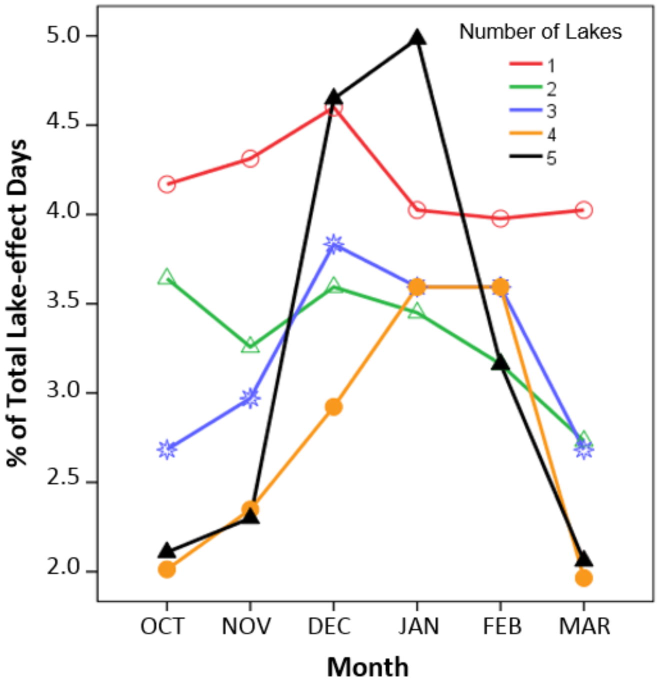


Figure-1-GreatLakes-map-GOES-vis-image.tif



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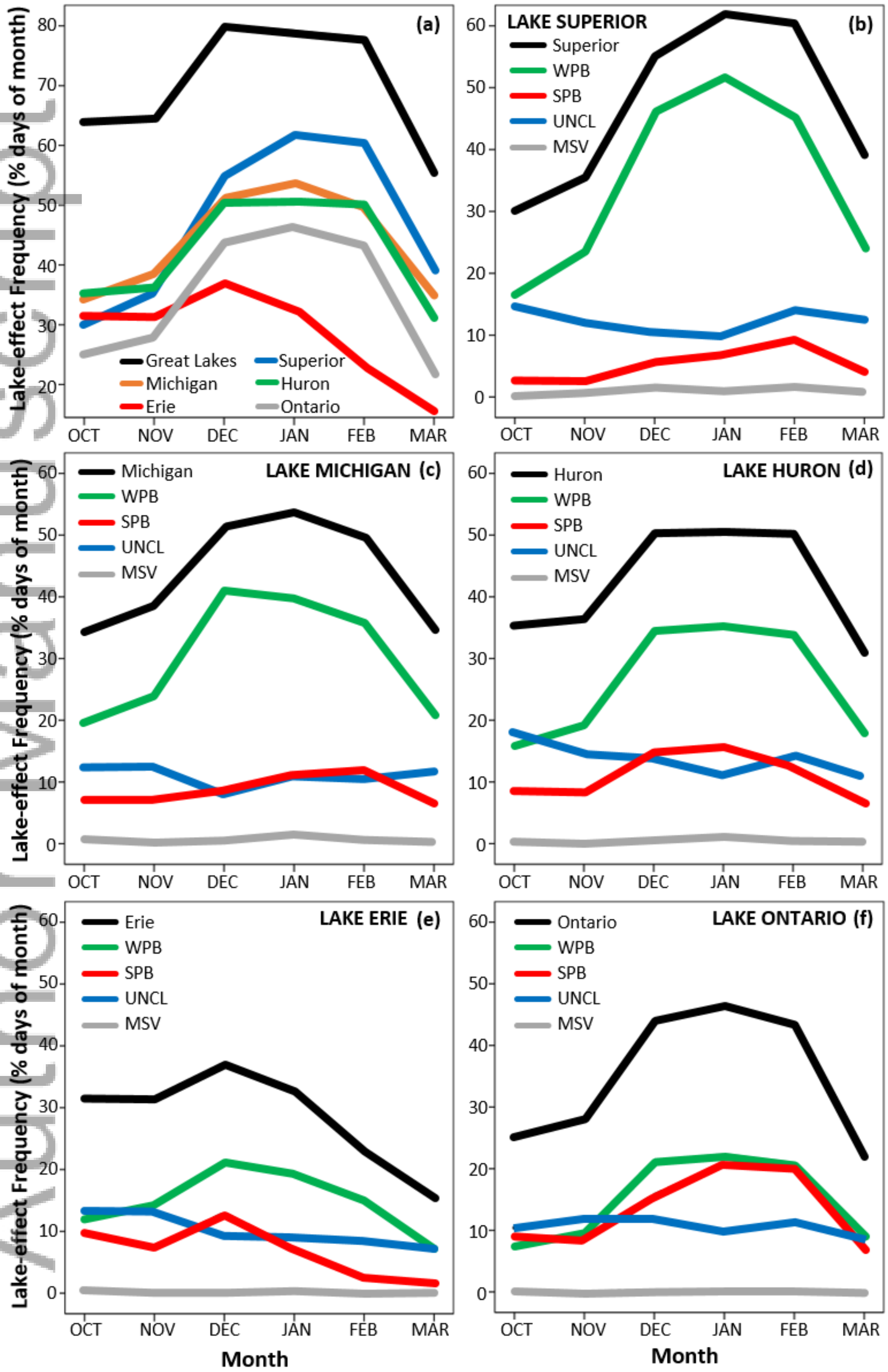

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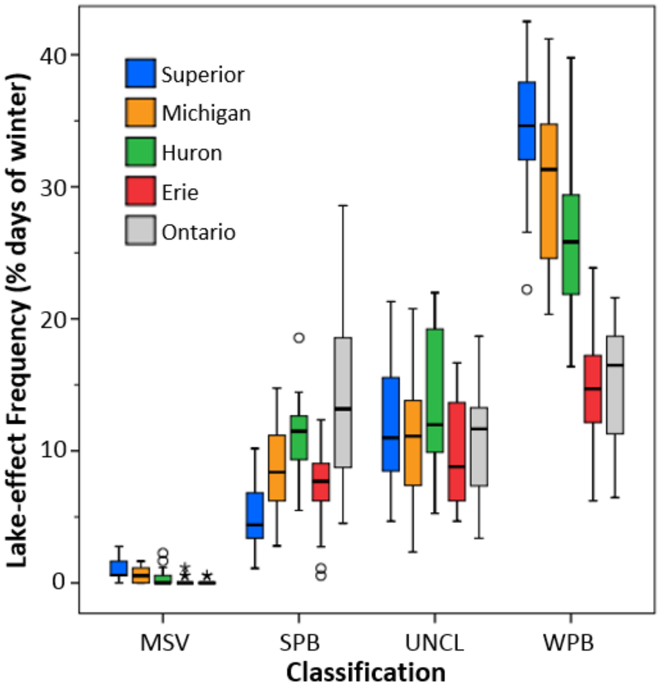

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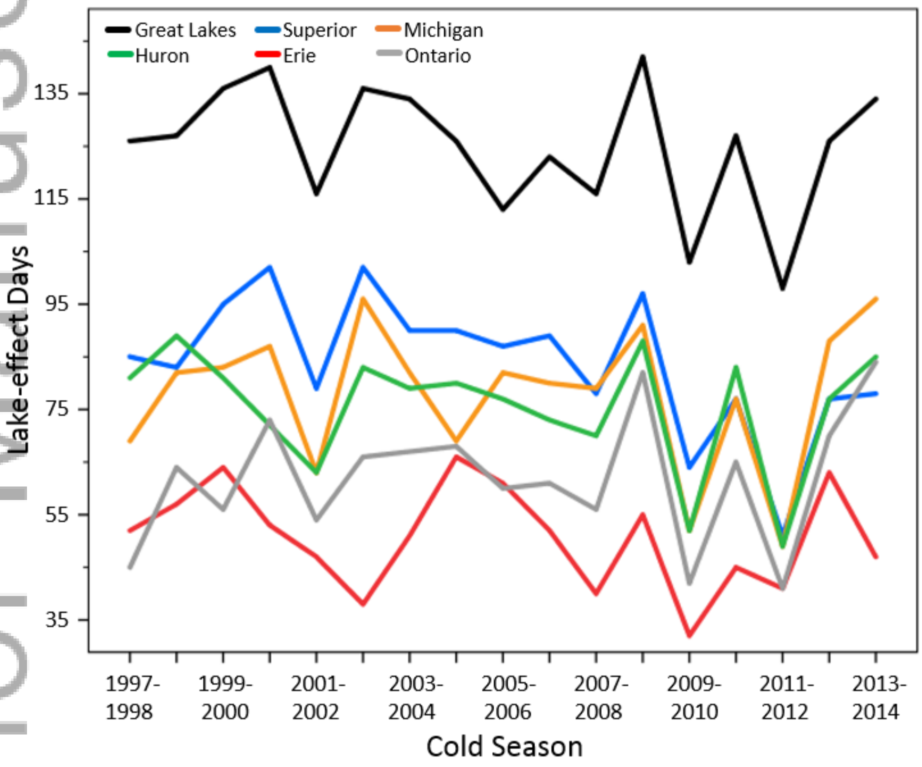

Figure-5-LE-annual-freq.tif

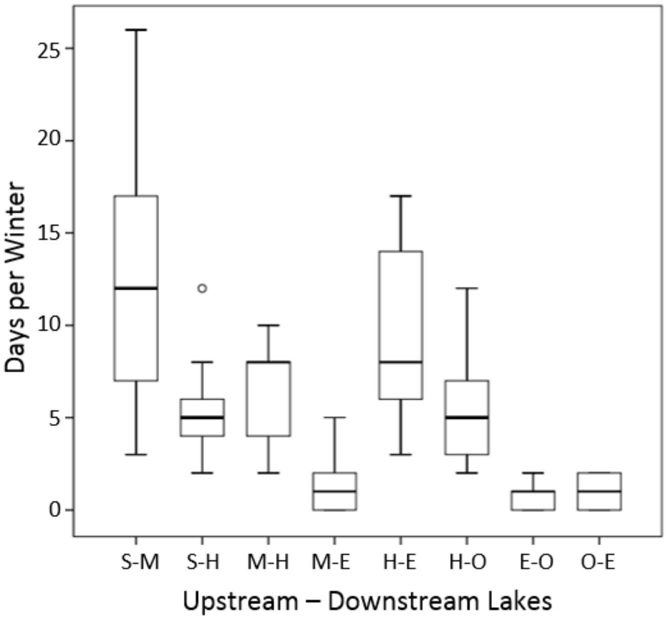

Figure-6-L2L-frequency.tif

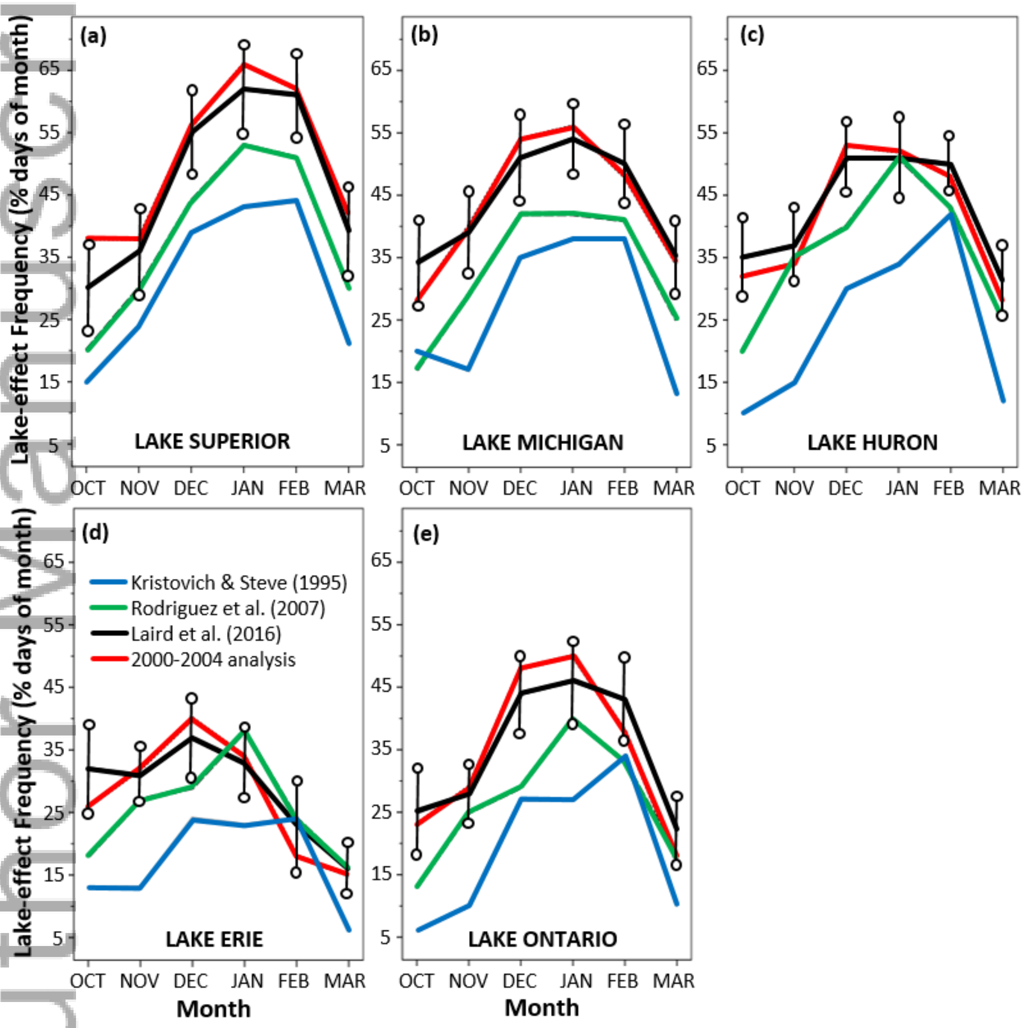

Figure-7-study-LE-freq-comparison.tif

Climatology of Cold Season Lake-effect Cloud Bands for the North American Great Lakes

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ABSTRACT

Geostationary Operational Environmental Satellite (GOES) visible imagery was used to identify lake-effect (LE) clouds in the North American Great Lakes region for the cold seasons (October–March) of 1997/1998 through 2013/2014 to provide a comprehensive climatological description of the seasonal and interannual variability of LE cloud bands. During the average cold season, at least 60% of days each month had LE clouds over some portion of the Great Lakes region and nearly 75% of all LE days had LE clouds present over several lakes simultaneously. Wind-parallel bands (WPB) are observed far more frequently than any other type of LE over Lakes Superior, Michigan, and Huron during the months of December, January, and February. Over Lake Erie, the occurrence of days per month with WPB was found to be approximately 5%−10% greater than days with shore-parallel bands (SPB) throughout the entire cold season. The greatest frequency of SPB occurrences in the Great Lakes region was over Lake Ontario during the months of January and February (~20% of days). Additionally, Lake Ontario was the only lake where the frequencies of WPB and SPB occurrences were fairly similar each month.

The annual frequency of WPB occurrences are the most variable among the Great Lakes, decreasing in frequency from the western lakes toward the eastern lakes. Lake Ontario has the largest annual frequency of SPB occurrences and the greatest variation in SPB annual frequency. Lake Huron has the second largest annual frequency of SPB days with small interannual variation. The primary differences of the annual frequency of lake-to-lake (L2L) LE occurrences when compared to previous research were a greater variability in the L2L annual frequency of Superior-to-Michigan connections, greater frequency of Michigan-to-Huron connections, and less frequent occurrences for Superior-to-Huron and Michigan-to-Erie connections.

1. Introduction

Lake-effect (LE) clouds are common throughout the North American Great Lakes region during the winter, when the lakes act as a local moisture source and their relatively warm waters lead to a destabilization of colder air masses moving through the region. These clouds are often organized having specific LE morphologies that result from particular boundary layer profiles of heat, moisture, and momentum present when a cold air mass traverses over an underlying lake in a state ranging from open water to complete ice cover. The mesoscale cloud patterns and presence of cloud bands are direct indicators of LE systems, whether precipitating or not, and the mesoscale circulations that are associated with these systems.

The approach used in this study should have widespread application as similar mesoscale systems and cloud bands have been observed in a large number of locations beyond the Great Lakes region. These systems develop in similar atmospheric environments where boundary layer destabilization occurs from cold airmasses moving over relatively warm water, and have been observed and investigated in regions including: the English Channel and Irish Sea (Norris et al., 2013), the Gulf of Finland (Mazon et al., 2015; Savijärvi, 2015), the Baltic Sea (Andersson and Nilsson, 1990; Andersson and Gustafsson, 1994), the Labrador Sea (Renfrew and Moore, 1999; Liu et al., 2006), the Greenland Sea (Brümmer et al., 1992; Brümmer and Pohlmann, 2000), the Beaufort Sea (Mourad and Walter, 1996), the Bering Sea (Walter, 1980), the Sea of Japan (Asai and Miura, 1981; Tusboki et al., 1989; Nakai et al., 2005) and several other North American bodies of water, such as the Chesapeake and Delaware Bays (Sikora and Halverson, 2002), Lake Champlain (Laird et al., 2009a), the Finger Lakes (Laird et al., 2009b), Lake Tahoe and Pyramid Lake (Laird et al., 2015), and the Great Salt Lake (Alcott et al., 2012).

Occurrences of LE clouds and the differing classifications of LE snow storms in the Great Lakes region have previously been documented by several studies (e.g., Hill, 1971; Forbes and Merritt, 1984; Kelly, 1986; Hjelmfelt, 1990; Niziol et al., 1995; Kristovich and Steve, 1995; Rodriguez et al., 2007; Ackerman et al., 2013); however, these studies have focused on specific events, specific lake regions (e.g., Lake Michigan), rather limited time periods (d 5 winters), or regional cloud coverage and cloud properties. Niziol et al. (1995) grouped LE systems into five different classifications (Type I through Type V). They defined Type I systems as a single cloud band or pair of prominent bands that forms when winds are parallel to the long axis of the lake. These LE systems have also been termed shore-parallel bands (SPB) (e.g., Braham, 1983), shoreline bands (e.g., Laird et al., 2003), or long lake-axis-parallel (LLAP) bands (Steiger et al., 2013; Veals and Steenburgh, 2015). Type II systems are comprised of multiple cloud bands that form when winds are perpendicular to the long axis of the lake (i.e., shorter fetch). These LE systems have also been referred to as wind-parallel bands (WPB) or widespread LE (e.g., Laird et al., 2003) and are comprised primarily of horizontal roll convection (e.g., Kristovich, 1993). Type III systems are LE cloud bands that develop over an upstream lake (e.g., Lake Huron), extend across the intervening land mass, and continue over a downstream lake (e.g., Lake Ontario). These have been called lake-to-lake (L2L) cloud bands (e.g., Rodriguez et al., 2007) or multi-lake bands (e.g., Mann et al., 2002) and can form when lake-aggregate processes contribute substantially to the development of LE systems (e.g., Sousounis and Fritsch, 1994). Type IV systems are similar in appearance to shore-parallel bands and primarily develop during weak ambient wind conditions along a land-breeze convergence zone moving offshore. These have also been referred to as mid-lake LE bands (e.g., Passarelli and Braham, 1981; Hjelmfelt, 1990), shore-parallel bands, or shoreline bands. Lastly, Type V systems appear as an isolated cyclonic circulation in the cloud or precipitation fields on the spatial scale of a lake basin and are called mesoscale vortices (e.g., Pease et al., 1988; Laird, 1999; Laird et al., 2001). Forbes and Merritt (1984) identified LE mesoscale vortices (MSV) by the presence of a miniature comma cloud, a swirl of cloud bands, or a swirl of cloud streets. Small mesoscale and misoscale vortices have been observed along shore-parallel bands (e.g., Grim et al., 2004; Steiger et al., 2013); however, the current analyses of LE cloud patterns include identification of only lake-basin-scale vortices and not smaller scale vortices imbedded within individual snow bands.

Kristovich and Steve (1995) investigated the occurrence of LE clouds in the Great Lakes region using visible satellite images across five cold seasons from 1988/1989 through 1992/1993. They classified LE clouds into four groups: 1) widespread stratocumulus comprised of multiple wind-parallel bands (WPB), 2) shore-parallel bands (SPB), 3) cloud patterns showing both WPB and SPB combined, and 4) an unclear classification where the pattern of LE clouds was not distinctly in any of the previous three groups. Rodriguez et al. (2007) investigated the frequency of LE clouds for an additional five cold seasons (from January 2000 through December 2004). In addition to the four classifications documented by Kristovich and Steve (1995), they identified LE days with mesoscale vortices (MSV) as well as days with lake-to-lake (L2L) cloud bands. Both Kristovich and Steve (1995) and Rodriguez et al. (2007) recorded only the primary classification for each lake on a given day, even if several types of LE cloud bands were present. This approach was necessary based on the quality and resolution of the satellite imagery used in these studies and undoubtedly resulted in an underestimate of the frequency of LE in several, if not all, classification groups.

The current study provides a comprehensive climatological description of the seasonal and interannual variability of LE cloud bands through the use of satellite imagery and provides an unmatched database related to the occurrence of cold-season lake effects in the Great Lakes region. This study differs from previous LE satellite-based studies in two important ways. First, satellite imagery from 17 consecutive cold seasons provides an extended period to investigate the variability of LE clouds over each of the Great Lakes. Second, high-spatial and high-temporal resolution visible satellite imagery (digital images with 1-km resolution at 15 minute interval) provided the ability to confidently identify and understand the evolution of LE clouds for each day during the cold seasons. This imagery allowed for the documentation of multiple cloud types, if present, over a lake during one daylight period rather than reporting only the dominant cloud type for a given day or relying on a very small number of images from overpasses of polar-orbiting satellites per day.

2. Data and methods

Geostationary Operational Environmental Satellite (GOES) visible imagery was used to identify LE clouds in the North American Great Lakes region for the cold seasons (October–March) of 1997/1998 through 2013/2014. Satellite imagery were retrieved from the National Oceanic and Atmospheric Administration (NOAA) Comprehensive Large Array-data Stewardship System (CLASS) archive (URL: www.class.noaa.gov). Data were extracted for the North American Great Lakes region using the latitude and longitude coordinates of 50.5 N, -95.0 W, -71.0 E, 37.5 S (Figure 1) for each date during the 17 cold seasons between the hours of 1100 UTC and 2359 UTC (i.e., daylight hours) with a time interval of approximately 15 minutes. Only 68 days during the 17 seasons did not have sufficient GOES visible imagery to investigate the presence of LE clouds in the Great Lakes region (i.e., average of 4 days per 6-month cold season).

The use of satellite imagery to identify LE situations offers important benefits as an alternative to the use of land-based radar systems; namely, (a) the capability of identifying LE situations that may not be producing measurable precipitation and (b) the ability to observe shallow LE clouds over all areas of the Great Lakes. The current United States Weather Surveillance Radar – 1988 Doppler (WSR–88D) radar network is unable to monitor low atmospheric levels and shallow LE systems over several lake areas (e.g., Brown et al., 2007). The use of only GOES visible imagery restricted identification of LE clouds to daylight hours from October through March. Although other satellite imagery and products, such as infrared imagery, would have provided continuous temporal coverage, these were not used because of lower spatial resolution and unsatisfactory ability to distinguish relatively warm boundary layer LE clouds from the underlying lake waters (e.g., Niziol et al., 1995).

Several studies have found notable diurnal variation of LE systems with a greater frequency of development (Laird et al., 2009a, Laird et al., 2009b; Alcott et al., 2012) and a maximum in LE precipitation frequency (Kristovich and Spinar, 2005) during the morning hours. Alternatively, Veals and Steenburgh (2015) found that the frequency of Lake Ontario LE precipitation observed by WSR–88D radar had no diurnal variation during winter (DJF), but had weak modulation in fall (SON) and spring (MAM). These previous findings suggest that the frequency of LE days determined in this current study may be an underestimate since nighttime events would not have been observed using visible satellite imagery. The authors suspect that this underestimate is relatively small across each cold season since LE systems in the Great Lakes region often have event durations greater than 12 hours (e.g., Veals and Steenburgh, 2015). For example, Veals and Steenburgh (2015) found the mean (median) duration of Lake Ontario LE precipitation periods to be 19.5 (13.2) hours. Situations when mesoscale LE bands were (a) embedded within or positioned underneath a widespread synoptic cloud shield or (b) located over areas of extensive ice and snow cover which provide a highly reflective surface preventing conclusive identification of LE clouds could also contribute to an underestimate of LE occurrence.

Images for each LE day were visually inspected using stepwise animation to identify LE mesoscale cloud bands and to examine the temporal evolution of clouds over each of the Great Lakes. Although a subjective approach, the analysis methodology incorporated multiple iterations of reviewing potential LE GOES imagery. Individual co-authors identified potential LE days from the entirety of the GOES imagery and then a small group, which always included the lead author to allow for analysis consistency, reviewed imagery of each potential LE day to determine whether LE clouds were present and which LE classification best represented the morphology. Important factors used in the current study for identifying LE clouds over a lake were (a) the cloud pattern needed to be temporally consistent and be visible for at least one hour (i.e., ≥ 4 consecutive visible images), (b) the clouds must have originated over the lake rather than developed over land and extended downstream over a lake, and (c) the cloud patterns needed to exhibit features consistent with the mesoscale nature of LE systems rather than broad cloud shields associated with larger synoptic-scale forcing. The three primary types of classifications used in this study were wind-parallel bands (WPB), shore-parallel bands (SPB), and mesoscale vortices (MSV).

The LE cloud pattern over a lake often changed during a day or different LE cloud patterns were simultaneously present over separate areas of a lake. Using the high-resolution GOES visible imagery, the current study was able to document when more than one LE cloud classification occurred over an individual lake during a day. For example, three different classifications (WPB, SPB, and MSV) of LE clouds were recorded for over Lake Michigan on 20 February, 2008 (Figure 1). Additionally, WPB were present over Lake Superior, WPB and MSV were present over Lake Huron, a SPB was present over Lake Ontario, and synoptic clouds covered Lake Erie on 20 February, 2008 (Figure 1).

The current study also documented LE clouds that occurred in an unorganized pattern with mesoscale features that were not clearly WPB, SPB or MSV. The classification of these mesoscale LE clouds was termed unorganized (UNCL). Lastly, occurrences of L2L cloud bands were documented. L2L cloud bands are visible extending from Lake Superior to over northern Lake Michigan in Figure 1. Undoubtedly, upstream lakes modify the original continental air mass traversing the lake by upward heat and moisture fluxes or several lakes act collectively through lake-aggregate processes (Sousounis and Shirer, 1992); however, L2L bands were recorded only when temporally and structurally coherent cloud bands were present extending from an upstream lake, across land, and over a downstream lake.

3. Results

In total across the 17 cold seasons, 2123 (70.1%) days had one or multiple occurrences of LE clouds in the Great Lakes region. Lake Superior had 1424 (47%) days, Lake Michigan had 1325 (43.7%) days, Lake Huron had 1282 (42.3%) days, Lake Erie had 864 (28.5%) days, and Lake Ontario had 1054 (34.8%) days with LE clouds. In the Great Lakes region, there were 1540 (50.8%) days with WPB over at least one lake, 913 (30.1%) days with SPB, 71 (2.3%) days with MSV, 1128 (37.2%) days with UNCL, and 472 (15.6%) days with L2L LE clouds.

The current study found that about 25% of LE days have only one lake in the Great Lakes region active with LE and nearly 75% of LE days have LE clouds present over several lakes simultaneously (Figure 2). This suggests that a large area of the Great Lakes region is often covered by a polar or Arctic airmass during North American cold-air outbreaks (CAOs) and more than one region may be impacted by LE precipitation. The number of LE days with two or three lakes having LE clouds was very similar during most cold season months and collectively represented about 5%–7% of LE days in any month. The greatest variation across the cold season occurred for the number of LE days with four or five lakes having LE clouds. The fewest LE days with LE clouds over four or five lakes occurred during October, November, and March; each month with < 2.5% of total LE days. December, January, and February had a noticeably greater number of LE days with four or five lakes having LE; combining for about 7.5% in December, 8.5% in January, and 6.6% in February of the total LE days (Figure 2).

a. Monthly frequency of LE cloud bands

Across the cold season, about 60% to 80% of days per month have LE clouds over some portion of the Great Lakes region (Figure 3a). For each individual lake approximately 25% to 39% of days per month have LE clouds during October and November. December, January, and February (DJF) have the greatest percentage of days with LE clouds; Lake Superior has the most LE days (55%–62% of all days each month) followed by Lakes Michigan and Huron, which have near 50% during each of DJF. Lake Ontario also has its greatest percentage of days with LE clouds during DJF with values close to 45% each month. Lake Erie exhibits a much different seasonal progression with early season values in October and November of about 31%, a slight maximum in December of 37%, and then a steady decrease in the percentage of days having LE clouds through the remainder of the cold season.

The frequencies of days per month in DJF with WPB are substantially larger compared with any other type of LE that occurs on Lakes Superior, Michigan, and Huron (Figures 3b,c,d). During these months, Lake Superior experiences the greatest frequency of WPB occurrences, followed by Lake Michigan and then by Lake Huron. The frequencies of SPB and UNCL LE occurrences are very similar and remain fairly consistent from the early to late cold season for Lakes Superior, Michigan, and Huron. The frequency of UNCL days each month remains in the range of 10%–15% across all lakes.

Over Lake Erie, the occurrence of days per month with WPB was found to be approximately 5%–10% greater than SPB occurrences throughout the entire cold season (Figure 3e). The greatest frequency of SPB occurrences (~20%) in the Great Lakes region was over Lake Ontario during the months of January and February (Figure 3f). Additionally, Lake Ontario was the only lake where the frequencies of WPB and SPB occurrences were fairly similar each month and ranged from about 10%–20%. The monthly LE frequency information that is shown graphically in Figure 3 is provided in Table 1.

Lastly, as noted in earlier studies (e.g., Forbes and Merritt, 1984; Rodriguez et al., 2007), MSVs were a rare occurrence and most frequently occurred over Lakes Superior and Michigan. Across the 17 cold seasons, MSV occurrences were observed on 31 days over Lake Superior, 22 days over Lake Michigan, 16 days over Lake Huron, 7 days over Lake Erie, and only on 4 days over Lake Ontario. Clearly, the atmospheric conditions to support the development of lake-basin-scale MSVs are quite specific (e.g., Hjelmfelt, 1990; Laird, 1999) and most often lead to MSV development when the conditions exist over lake shorelines of favorable curvature, such as southern Lake Michigan (Pease et al., 1988).

b. Frequency of LE classifications

The variation in annual frequency of LE classifications (i.e., WPB, SPB, UNCL, and MSV) exhibits dependence on the specific Great Lake (Figure 4). WPB occurrences are the most variable in annual frequency across the Great Lakes region. The annual frequency of WPB steadily decreases from west to east with the largest median of about 34% of cold season days for Lake Superior to median values of approximately 31% and 25% of cold season days for Lakes Michigan and Huron, respectively. The annual WPB frequencies for these three western lakes are statistically greater at a 95% confidence interval using a two-sample t test than WPB frequencies for Lakes Erie and Ontario, which have statistically similar WPB frequencies and median values of ~15%.

Lake Ontario has the largest median annual frequency of nearly 14% for SPB occurrences and the greatest variation in SPB annual frequency (Figure 4). The largest annual frequency of SPB days on Lake Ontario (29% or 52 days) occurred during the cold season of 2013/2014 and the smallest annual frequency (5% or 9 days) occurred during 1997/1998. Lake Huron has the second largest median annual frequency of about 11% for SPB days with small interannual variation similar to that of Lakes Michigan, Superior, and Erie. Across all the lakes, the annual frequency is very similar for the UNCL classification with median values around 10%. For all lakes except Lake Ontario, UNCL days tend to occur more often and have a greater interannual variation than SPB days.

c. *Annual frequency of LE cloud bands*

The determination of LE activity across 17 cold seasons provides an opportunity to explore the interannual variability of LE clouds across the entire Great Lakes region and over each of the Great Lakes (Figure 5). The number of days with LE clouds occurring over one or more Great Lakes (Figure 5; black line) ranged from 141 days during the cold season of 2008/2009 (~77% of days) to 96 days during the cold season of 2011/2012 (~53% of days).

There were several cold seasons where a relatively large frequency of LE occurred over nearly all the Great Lakes. These cold seasons included 2000/2001, 2002/2003, 2008/2009, 2012/2013, and 2013/2014. For example, during 2008/2009 Lakes Superior, Michigan, Huron, Erie, and Ontario had LE clouds occur on 52%, 49%, 47%, 30%, and 44% of cold season days, respectively. There was notable interannual variation of LE frequency for Lake Erie, and the cold seasons having the largest annual frequency were not always consistent with the annual activity over the other four Great Lakes (Figure 5). During colder winters that would be more favorable for a greater frequency of lake effect (e.g., 2002/2003; 2008/2009), Lake Erie exhibited relatively low frequencies suggesting that during these colder seasons extensive ice cover developed across Lake Erie, thereby, limiting some of the lake-surface heat and moisture fluxes required for LE mesoscale circulations and clouds (Assel, 2005; Gerbush et al, 2008; Cordeira and Laird, 2008).

Across the 17 cold seasons, there were also several time periods with relatively small annual frequencies (e.g., 2001/2002, 2009/2010, and 2011/2012) over the entire Great Lakes region and individual lakes. For example, during the 2009/2010 cold season, Lakes Superior, Michigan, Huron, Erie, and Ontario had LE clouds occur on 34%, 27%, 26%, 17%, and 23% of cold season days. The interannual variations identified across the 17 cold seasons are a result of contributions from numerous factors ranging from lake water temperatures, regional air temperatures, and ice cover, to seasonal global climate patterns controlling both the mesoscale and synoptic-scale atmospheric environments. An investigation of the factors causing the interannual variation of Great Lakes LE activity is not the purpose of the current study. However, the large number of LE events identified across the 17 cold seasons will be used in subsequent studies to explore the variability and significance of numerous factors influencing LE activity and snowfall trends that others have investigated with much smaller subsets of LE cases (e.g., Braham and Dungey, 1984; Norton and Bolsenga, 1993; Serreze et al., 1998; Kunkel et al., 2002; Burnett et al., 2003; Ellis and Johnson, 2004; Grimaldi, 2008; Kunkel et al., 2009; Bard and Kristovich, 2012; Hartnett et al., 2014).

d. Multi-lake cloud bands

The Great Lakes can act collectively to produce an aggregate atmospheric response to the localized heat and moisture transfer from the warm lake waters to the overlying air during the cold season (e.g., Sousounis and Shirer, 1992). An aggregate circulation can influence mesoscale weather systems and result in a LE storm that develops in association with an upstream lake extending to a downstream lake over the intervening land surface (e.g., Sousounis and Fritsch, 1994; Mann et al., 2002). This LE situation is often referred to as a L2L connection or multi-lake connection and is most evident when a snow band or cloud band develops (Rodriguez et al., 2007), such as the cloud bands extending from Lake Superior to northern Lake Michigan on 20 February 2008 (Figure 1). As an alternative to a Great Lakes lake aggregate situation, the curvature of the synoptic-scale flow may provide a favorable environment for a L2L connection. For example, a synoptic-scale trough positioned over or to the east of Lake Ontario in southern Quebec, Canada often provides a cyclonic parcel trajectory from western Lake Huron along the primary axis of Lake Ontario leading to the development of a L2L connection.

L2L connections resulting in LE cloud bands occur throughout the Great Lakes region often across two or sometimes three lakes. An examination of the annual frequency of L2L cloud bands for eight combinations of upstream and downstream lakes shows the connection from Lake Superior to Lake Michigan occurs most often and also has the largest interannual variation (Figure 6). The median annual frequency for the Lake Superior to Lake Michigan (S-M) connection is 12 days during a cold season and ranges from a maximum of 26 days to a minimum of 3 days across the 17 cold seasons examined. Areas of the Great Lakes region with the least frequent occurrence of L2L connections were Lake Michigan to Lake Erie (M-E), Lake Erie to Lake Ontario (E-O), and Lake Ontario to Lake Erie (O-E) with typically less than 2 days per cold season.

Rodriguez et al. (2007) examined a five-season time period and reported on the frequency of multi-lake cloud bands for six areas in the Great Lakes region; their study did not explore E-O or O-E connections. Although a shorter time period was inspected by Rodriguez et al. (2007), the annual frequencies were generally comparable. The primary differences in the current 17-season analysis were a greater variability in the annual frequency of S-M connections, greater frequency of M-H connections, and less frequent occurrences for S-H and M-E connections (Figure 6).

4. Discussion and summary

The current study presents a climatology of LE cloud bands for the Great Lakes region of North America across 17 cold seasons (i.e., 1997/1998–2013/2014). Maximum LE frequency was found to range from about 20% to nearly 60%, depending on the specific month and lake. Both Kristovich and Steve (1995) and Rodriguez et al. (2007) found the frequency of LE cloud bands to be lower using much shorter time periods; 1988/1989–1992/1993 and January 2000–December 2004, respectively (Figure 7). The LE frequencies found by Kristovich and Steve (1995) were systematically the lowest and the LE frequencies from the current study were nearly always the largest, except for the months of January, February, and March over Lake Erie. During several months, the mean LE frequency in the current study differed by as much as 20% when compared to Kristovich and Steve (1995) (Figure 7). On average, the mean monthly LE frequencies reported by Kristovich and Steve (1995) for Lakes Superior, Michigan, Huron, Erie and Ontario are 16.2%, 17.0%, 18.7%, 11.5%, and 15.7% lower than those found in the current study. The mean monthly LE frequencies reported by Rodriguez et al. (2007) were also less than results from the current study by 9.2%, 11.2%, 6.8%, 3.3%, and 8.3% for Lakes Superior, Michigan, Huron, Erie, and Ontario, respectively.

Some of these differences can likely be attributed to factors other than the natural variation of LE occurrences during differing time periods. For example, differences in results between the three studies may have occurred from variances in the (a) resolution of the GOES imagery, (b) method of subjective identification of LE, and (c) decision on amount of information to collect from GOES imagery; inclusion of all observed LE versus only dominant LE on a lake during a LE day. In an attempt to address the potential influence of non-homogeneous time periods, data from the current study was examined for the time period of 2000-2004 used by Rodriguez et al. (2007) and compared (Figure 7). Overall, the mean monthly LE frequencies from 2000-2004 remained similar to the results from the 17 cold seasons and continued to be greater than mean monthly LE frequencies found by Rodriguez et al. (2007) except for a few months over Lakes Erie and Ontario.

The visible satellite image for 20 February, 2008 provides an example of a day with LE clouds over four lakes (Figure 1). Interestingly, the number of LE days with LE clouds over five lakes was the largest compared to all other groups (one, two, three, and four lakes with LE) during December and January (Figure 2). This result suggests that during these two months the Great Lakes region experiences frequent intrusions of spatially large CAOs that produce a widespread area of favorable conditions for LE systems, consistent with a North American CAO climatology completed by Wheeler et al. (2011) that found CAOs had the largest latitudinal and longitudinal extent (reaching into the Great Lakes region) during the months of December and January.

The steady decrease in LE clouds over Lake Erie from December through March suggests a close relationship to the Lake Erie ice cycle. Although LE systems can occur with extensive ice cover on Lake Erie (Cordeira and Laird 2008), there is often a significant reduction in LE snowfall and system development because of greatly reduced surface heat fluxes (e.g., Gerbush et al., 2008; Vavrus et al., 2013). Lake Erie often develops the most extensive ice cover on the Great Lakes, with the typical ice cover cycle beginning in the shallow western basin during late December, increasing to maximum ice cover in all basins of the lake by middle February, and experiencing rapid loss of ice cover from middle to late March (Assel, 2005).

L2L cloud band frequencies in the Great Lakes region were found to have several aspects similar to those reported by Rodriguez et al. (2007). The influence of L2L situations on LE systems existing over a downstream lake has been investigated by only a few studies (e.g., Sousounis and Fritsch, 1994; Mann et al., 2002) despite its importance to forecasting periods of heavy snowfall during LE events and the frequent consideration of these complex interactions by operational forecasters. As a supplement to the numerical modeling studies performed by Sousounis and Fritsch (1994) and Mann et al. (2002) there is a need for additional case studies and climatological investigations to examine L2L LE situations. For example, studies should be conducted to examine (a) the typical environmental conditions necessary for L2L occurrence in different areas of the Great Lakes region, (b) the influence of factors such as lake temperature, ice cover, parcel trajectory, over-lake residence times on L2L events, and (c) the degree that snowfall in the vicinity of the downstream lake may be altered during L2L events in comparison to LE event without a robust upstream connection to another Great Lake.

In summary, GOES visible imagery was used to identify LE clouds in the North American Great Lakes region for the cold seasons (October–March) of 1997/1998 through 2013/2014 to provide a comprehensive climatological description of the seasonal and interannual variability of LE cloud bands. Across the cold season, about 60% to 80% of days per month have LE clouds over some portion of the Great Lakes region. Nearly 75% of all LE days had LE clouds present over several lakes simultaneously. The frequencies of days per month with wind-parallel bands (WPB) during December, January, and February are substantially larger compared with any other type of LE over Lakes Superior, Michigan, and Huron. Over Lake Erie, the occurrence of days per month with WPB was found to be approximately 5%–10% greater than days with shore-parallel bands (SPB) throughout the entire cold season. The greatest frequency of SPB occurrences (i.e., nearly 20%) anywhere in the Great Lakes region was over Lake Ontario during the months of January and February. Additionally, Lake Ontario was the only lake where the frequencies of WPB and SPB occurrences were fairly similar each month.

WPB occurrences are the most variable in annual frequency across the Great Lakes region, decreasing in frequency from the western lakes toward the eastern lakes. Lake Ontario has the largest annual frequency of SPB occurrences and the greatest variation in SPB annual frequency. Lake Huron has the second largest annual frequency of SPB days with small interannual variation. The primary differences of the annual frequency of L2L occurrences when compared to previous research were a greater variability in the L2L annual frequency of Superior-to-Michigan connections, greater frequency of Michigan-to-Huron connections, and less frequent occurrences for Superior-to-Huron and Michigan-to-Erie connections.

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Figure List & Captions

Figure 1 Location of Great Lakes region on North American continent (top) and GOES-12 visible satellite image of Great Lakes region on 20 February, 2008 at 1702 UTC (bottom).

Figure 2 Monthly distribution of the percent of all lake-effect (LE) days having LE clouds present simultaneously over one or more lakes.

Figure 3 (a) Mean monthly frequency of LE days for Great Lakes region and each individual Great Lake across 17 cold seasons (OCT – MAR; 1997/1998 – 2013/2014). (b-f) Mean monthly frequency of LE days for each Great Lake along with monthly frequency for LE classifications of wind-parallel bands (WPB; green), shore-parallel bands (SPB; red), unorganized (UNCL; blue), and mesoscale vortices (MSV; grey).

Figure 4 Distribution of frequency for LE days per season across 17 cold seasons for each of the individual Great Lakes with classifications of mesoscale vortex (MSV), shore-parallel bands (SPB), unorganized (UNCL), and wind-parallel bands (WPB). Box plots show median, upper and lower quartiles (box), largest and smallest unbooked sample values (whiskers), outliers (circles) and extreme values (stars).

Figure 5 Annual number of LE days for Great Lakes region and each of the individual Great Lakes from the cold seasons of 1997/1998 through 2013/2014.

Figure 6 Distribution of the number of days per season for each region of lake-to-lake (L2L) LE cloud bands across 17 cold seasons. For region of L2L connections, S, M, H, E, and O represent Lakes Superior, Michigan, Huron, Erie and Ontario, respectively. The first letter designates the upstream (originating) lake of cloud band and second letter corresponds to downstream lake where cloud band extends. Box plots show median, upper and lower quartiles (box), largest and smallest unbooked sample values (whiskers), and outliers (circles).

Figure 7 Mean monthly frequency of LE days for each Great Lake from current study (black), current study 2000-2004 (red), Rodriguez et al. (2007) (green), and Kristovich and Steve (1995) (blue). Also shown for each month is ±0.5 standard deviation from mean monthly frequency.