PICTURE OF THE MONTH

Lake-to-Lake Cloud Bands: Frequencies and Locations

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ABSTRACT

Premodification of the atmosphere by upwind lakes is known to influence lake-effect snowstorm intensity and locations over downwind lakes. This study highlights perhaps the most visible manifestation of the link between convection over two or more of the Great Lakes lake-to-lake (L2L) cloud bands. Emphasis is placed on L2L cloud bands observed in high-resolution satellite imagery on 2 December 2003. These L2L cloud bands developed over Lake Superior and were modified as they passed over Lakes Michigan and Erie and intervening land areas. This event is put into a longer-term context through documentation of the frequency with which lake-effect and, particularly, L2L cloud bands occurred over a 5-yr time period over different areas of the Great Lakes region.

1. Introduction

Lake-effect (LE) snowstorms in the Great Lakes region of North America are responsible for locally increased winter snowfall amounts and can produce 1–2 m of snow in single extreme events (e.g., Scott and Huff 1996; Schmidlin and Kosarik 1999). Enhanced snowfall near the Great Lakes has both positive and negative effects on human activities. Daily activities can be hampered as increased property damage, accidents, and injuries affect many people. Heavy snowfall amounts cause transportation problems at area airports and for daily commuters. Governments endure elevated costs to keep thoroughfares clear and occasionally scramble to alert citizens in the region of possible hazards (Schmidlin 1993; Schmidlin and Kosarik 1999; Kunkel et al. 2002). On the other hand, snow removal companies, winter sports, and hospitality services can flourish in the wake of enhanced snowfall (Kunkel et al. 2002).

While forecasts of the occurrence of LE snows have steadily improved, prediction of which communities will be impacted by the snowbands (as well as snowfall amounts and timing) remain problematic. A number of studies have documented LE snowband types in order to aid in the classification and understanding of these systems (e.g., Hjelmfelt 1990; Niziol et al. 1995) and examined the frequency with which the types occur based on satellite and surface data (e.g., Kelly 1986; Kristovich and Steve 1995).

Despite recognition of their importance to lake-effect processes, much less attention has been given to lake-effect snowbands that extend from one of the Great Lakes to another. Interactions between lake-

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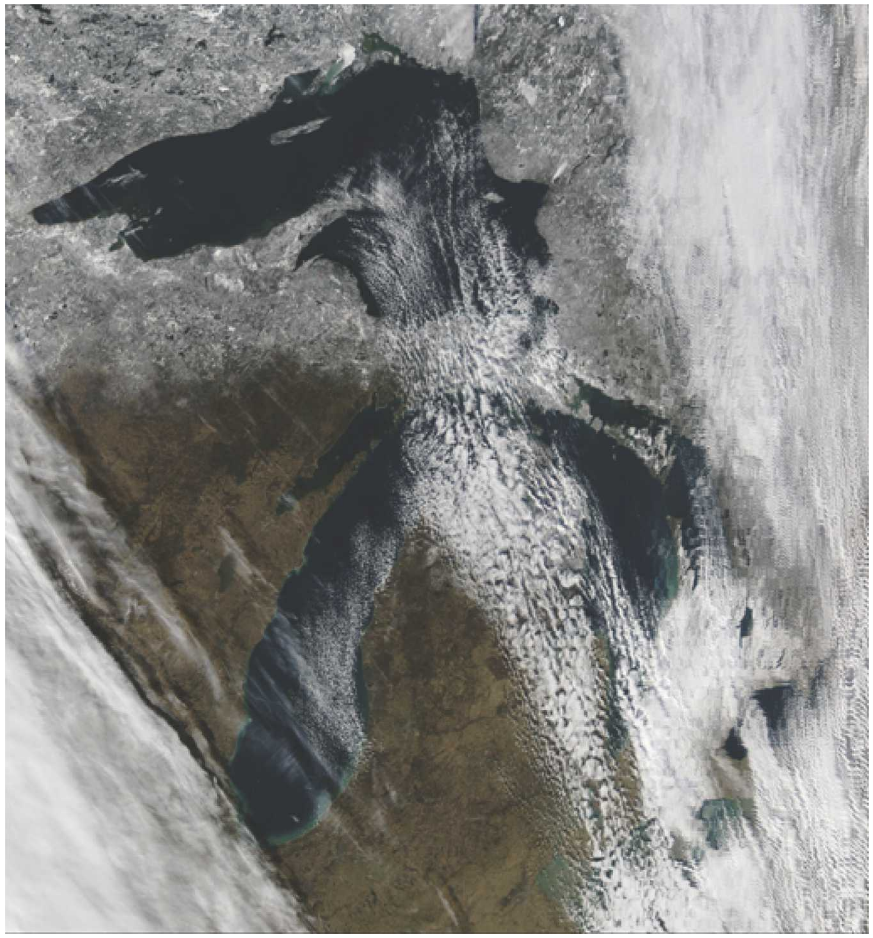

FIG. 1. *Terra* MODIS visible wavelength satellite image of the Great Lakes at 1715 UTC 2 Dec 2003. L2L cloud bands can be seen extending from (top) Lake Superior, across northern Lake Michigan, to (lower right) Lake Erie.

effect systems from each of the Great Lakes occur over a wide range of size and time scales (e.g., Sousounis and Mann 2000; Mann et al. 2002). Previous studies of individual lake-to-lake (L2L) events suggest that the influence of upwind lakes can strengthen lake-effect snowstorm intensities over downwind lakes, and several processes responsible for this increase have been proposed (e.g., Yuen and Young 1986; Agee and Gilbert 1989; Niziol et al. 1995; Byrd et al. 1995; Ballentine et al. 1998; Sousounis and Mann 2000; Rose 2000). Direct influences of upwind lakes on lake-effect systems over downwind lakes, hereafter referred to as L2L influences, have proven to be "a particularly difficult forecast problem" (Niziol et al. 1995).

The present study seeks to illustrate the most visible manifestations of direct influences of lake-effect processes between lakes through documentation of a L2L cloud band captured in high-resolution satellite imagery. This event is placed in the context of their frequency of occurrence in the Great Lakes region. Using visible satellite imagery from a 5-yr period, information on the common locations of L2L cloud band occurrence and how their frequencies change over the winter season are documented.

2. The 2 December 2003 L2L cloud band event

Figure 1 shows an image of L2L cloud bands obtained by the *Terra* Moderate Resolution Imaging Spectroradiometer (MODIS; see online at http://rapidfire.sci.gsfc.nasa.gov/; 250-m resolution) at 1715 UTC 2 December 2003. As cold air flowed southeastward over the Great Lakes, LE clouds developed over southeastern Lake Superior and extended over northern Lake Michigan and central Lake Erie. Regional composite reflectivity fields obtained by Weather Surveillance Radar-1988 Doppler radars in the Great Lakes (not shown) indicate regions of light snow along these bands. Surface and radar observations indicate that the heaviest snow from the cloud bands occurred over northern Lower Michigan (just east of northern Lake Michigan) and northern Ohio (just south of Lake Erie), although weak radar reflectivities were observed along the entire L2L cloud bands during much of the day.

Changes in the structure of the clouds along the L2L cloud bands are suggestive of alterations in the LE boundary layer and mesoscale circulations as the air crossed over lake and land surfaces. For example, Fig. 1 indicates cloud bands with wavelengths of generally less than 3 km (with a few larger cloud bands) over southeastern Lake Superior. Over northern Lake Michigan, the clouds occupied more of the area (i.e., a greater percentage of cloud cover) and the cloud band wavelengths rapidly increased (e.g., average wavelengths of 5–7 km). Such increases in LE cloud feature sizes are generally associated with increases in the depth of the convective boundary layer (e.g., Kristovich et al. 2003), which would be anticipated as the LE clouds crossed over the relatively warm waters of northern Lake Michigan (e.g., Hjelmfelt et al. 2004). Indeed, 1200 UTC soundings at Detroit and Alpena, Michigan, show surface-based mixed layers of approximately 1700-m depth, which were not observed at sites upwind or to the west of the Great Lakes at this time. Cloud bands continued to increase in coverage and wavelength over northern Lower Michigan within several tens of kilometers of the eastern shore of Lake Michigan, a region where near-surface convergence associated with increases in surface friction would be expected. The clouds then decreased to the southeast over land areas before again increasing in coverage over and downwind of Lake Erie.

The L2L cloud bands shown in Fig. 1 formed in response to cold near-surface air flowing from northwest to southeast over the relatively warm waters of the Great Lakes. At 1643 UTC, just before the time of the satellite image shown in Fig. 1, surface air temperatures were between about −7° and −10°C upwind of Lake Superior. Air temperatures increased along the axis of the L2L cloud bands, reaching 0° to −3°C across much of Lower Michigan and close to 0°C over northern Ohio. This warming was due primarily to sensible heat fluxes from the lake surfaces (which were as much as 10° warmer than nearby air temperatures; see online at http://coastwatch.glerl.noaa.gov/glsea/glsea.html) and intervening land areas (which were largely not snow covered; Fig. 1).

As the center of high pressure moved from Missouri to Michigan during the day, wind speeds decreased and wind directions became variable. The decrease in winds, along with the diurnal increase in air temperatures in the Great Lakes region resulted in a narrowing, and then dissipation of the L2L clouds and snow by around 2000 UTC.

3. Background on L2L bands

Previous studies have generally classified LE storms into four types of convective cloud bands; wind-parallel bands (WPB) or widespread disorganized convection, shore-parallel bands (SPB), mesoscale vortices (MSV), and L2L bands (e.g., Hjelmfelt 1990; Kristovich and Steve 1995; Niziol et al. 1995; Laird et al. 2003a,b; Laird and Kristovich 2004). While numerous observational and numerical modeling studies have been conducted on WPB (e.g., Kelly 1982, 1984; Kristovich 1993; Kristovich et al. 1999, 2003; Cooper et al. 2000; Liu and Moore 2004), SPB (e.g., Schoenberger 1984; Passarelli and Braham 1981; Grim et al. 2004), and MSV (e.g., Forbes and Merritt 1984; Laird 1999; Laird et al. 2001), much less research has been carried out on L2L cloud bands. L2L cloud bands, such as those shown in Fig. 1, are very difficult to predict in part because of insufficient research and documentation (Niziol et al. 1995).

Much of the research on L2L influences have utilized numerical modeling of individual LE cases or idealized numerical experiments, usually over a limited range of atmospheric conditions. For example, Mann et al. (2002) conducted a careful analysis of multiple-lake influences for an event, quantifying both the direct (influence of nearest upwind lake) and indirect (synergistic) influences. That work built on a series of numerical modeling studies examining the multiscale atmospheric responses to the Great Lakes (Sousounis and Fritsch 1994; Sousounis 1997, 1998; Weiss and Sousounis 1999, Sousounis et al. 1999; Sousounis and Mann 2000). Rose (2000) pointed out that while some authors indicated that a minimum of 80-km fetch over open lake waters is typically needed for formation of significant LE clouds and precipitation (e.g., Lavoie 1972; Niziol 1987), preconditioning of the atmosphere by upstream lakes (Ballentine et al. 1998) can allow for much more rapid development. Using numerical modeling techniques, Rose (2000) found that thermal preconditioning led to deeper and more intense LE circulations, which would tend to enhance LE precipitation, and longer persistence of the LE system. In some situations, he found that mesoscale circulation patterns induced by upwind lakes can also enhance circulations over downwind lakes, as previously suggested by Byrd et al. (1995).

The remainder of the present study seeks to develop an observational database of the frequency of occurrence, favorable locations, and seasonal variability of

TABLE 1. L2L cloud classifications for 10 dates during January 2000. Lake Superior, as the originating lake, was divided into seven classifications according to observed L2L organizations extending over other lakes. Lakes Michigan and Huron were divided into four classifications. Interactions between Lakes Erie and Ontario were also categorized.

	Lake Superior						
Date	Superior–Huron	Superior–Huron–Erie	Superior–Huron–Ontario	Superior–Michigan	Superior–Michigan–Erie	Superior–Michigan–Huron	Superior–Michigan–Huron–Erie
7 Jan			✓				
13 Jan							
16 Jan				✓			
20 Jan				✓			
21 Jan		✓					
25 Jan				✓			
26 Jan				✓			
27 Jan				✓			
28 Jan		✓					

L2L cloud bands. It is anticipated that the archive of L2L cases observed in this study will provide a useful database for continued observational analyses as well as validation of numerical modeling investigations of these questions.

4. Methodology

Cloud band frequencies were investigated using the *Geostationary Operational Environmental Satellite (GOES-8)* visible satellite images (1-km resolution) obtained every 15 min during daylight hours. Operational infrared imagery are often not useful for distinguishing between LE clouds and cold surfaces in winter, so were not used in this study. The analyses in this study are based on visible satellite images obtained from the Research Applications Program at the National Center for Atmospheric Research (see online at http://www.rap.ucar.edu/weather/satellite) and the National Weather Service Aviation Digital Data Service (see online at http://adds.aviationweather.gov). Infrared satellite images archived at Plymouth State College (http://vortex.plymouth.edu/) provided supplemental information for analyses of non-lake-effect events.

To obtain a large sample of L2L events, we sought to examine imagery for 5 yr of each of the six cold-season months (October–March). Imagery was readily available for analysis for the time period January 2000–December 2004. Days with inadequate daytime images to determine cloud types were treated as missing for all analyses. There were less than 5% of days with inadequate satellite data for October, November, February, and March. More days had inadequate satellite data in December (17%) and January (10%). The missing data are thought to have minimal impacts on the calculated cloud band frequencies since excluded days were not dependent on weather conditions.

Cloud bands were identified for each date and for each of the five Great Lakes. Cloud patterns for each day and lake (called "cases" below) were given only one classification. Analysis of the data was in two parts: identification of cases where the clouds were due to LE processes and identification of LE cases where the clouds extended from one Great Lake to another (L2L). Identification of LE clouds were based on the criteria used by Kristovich and Steve (1995). In summary, clouds over each individual lake were classified as *synoptic* if they were observed to be of a larger scale than the lake size and/or they did not appear to originate at the lake. Clouds over each individual lake were classified as *lake effect* if they were observed over the lake and fit these specific criteria: 1) the cloud area was of similar size to the lake; 2) the clouds appeared to originate over the lake, where they were clearly separate from nearby synoptic clouds; and 3) at least one shoreline was visible. In an attempt to ensure that the cloud patterns classified as LE were indeed lake-induced clouds, those unclear cases that were not separated from nearby synoptic clouds, including lake enhancement of synoptic clouds, were classified as synoptic. Given this criterion, the frequencies of LE clouds reported here are thought to be underestimates. For each case identified as LE, the cloud patterns were further classified as WPB, SPB, MSV, coincident WPB and SPB, or unclear LE pattern. A comparison of the observed frequencies with those by Kristovich and Steve (1995) is given in section 5.

Of the cases with LE clouds, L2L cloud bands were identified as those where continuous LE clouds were seen to extend between at least two of the Great Lakes. L2L cloud bands were identified by originating lake and subclassified by the lake(s) over which the cloud bands spread. Classifications for a sample of L2L days are given in Table 1. For example, L2L cloud bands

TABLE 1. (*Extended*)

Lake Michigan				Lake Huron				Lake Erie	Lake Ontario
Michigan–Huron	Michigan–Erie	Michigan–Huron–Erie	Michigan–Huron–Ontario	Huron–Michigan	Huron–Erie	Huron–Ontario	Huron–Erie–Ontario	Erie–Ontario	Ontario–Erie
✓	✓								
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originating over Lake Superior were observed to fall into seven classifications, depending on the observed extension of clouds over downwind lakes. Lakes Michigan and Huron were divided into four classifications. L2L cases originating over Lakes Erie and Ontario were found to not affect the remaining Great Lakes. Figure 2 shows the cloud pattern for one of the dates in Table 1, 20 January 2000. For this date, L2L cloud bands were identified between Lakes Superior and Michigan and Lakes Huron and Erie.

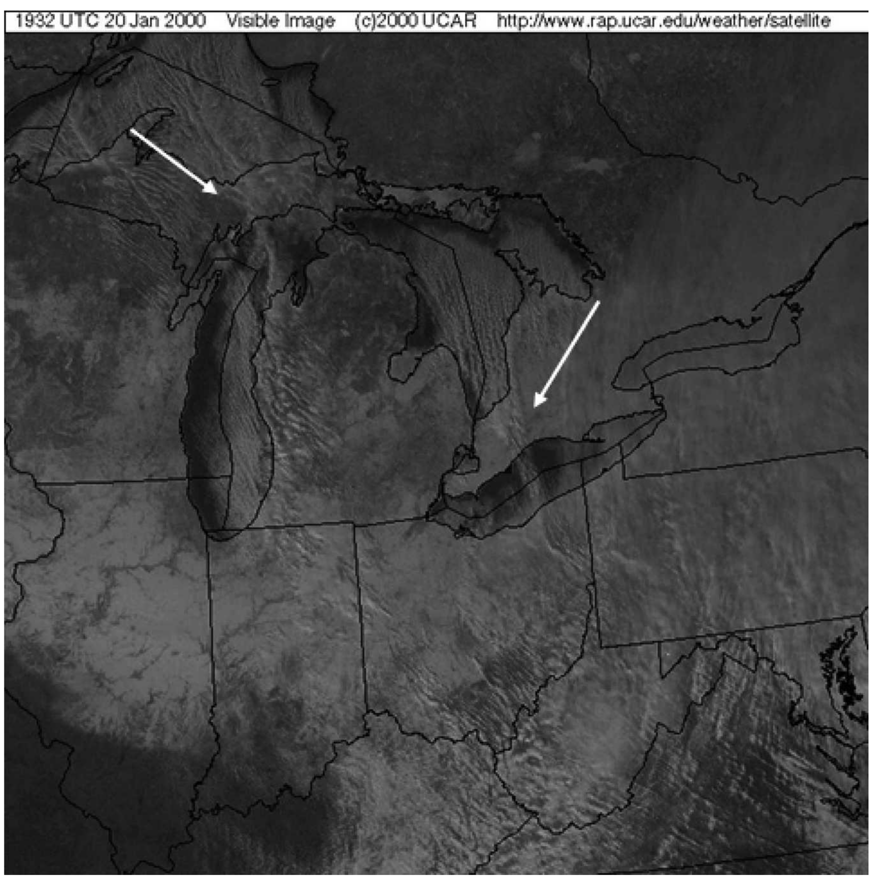

FIG. 2. *GOES-8* visible satellite image of the Great Lakes at 1932 UTC 20 Jan 2000. Arrows indicate L2L cloud bands between Lakes Superior and Michigan and between Lakes Huron and Erie.

Table 2. Percentage of cases classified as clear skies/no LE, unclassified/unknown, synoptic, and LE cloud organizations over the Great Lakes (2000–04).

Lake		Oct	Nov	Dec	Jan	Feb	Mar	Winter
All lakes	No. of cases	154	146	129	139	137	155	860
Superior	Clear skies (%)	7	2	2	0	0	3	2
	Unclassified (%)	5	9	2	1	1	2	3
	Synoptic (%)	70	60	52	47	48	65	56
	LE (%)	20	30	44	53	51	30	37
Michigan	Clear skies (%)	9	3	2	2	5	1	3
	Unclassified (%)	1	4	1	0	1	1	2
	Synoptic (%)	75	63	56	55	54	72	62
	LE (%)	17	29	42	42	41	25	32
Huron	Clear skies (%)	4	2	0	0	1	4	2
	Unclassified (%)	3	3	3	0	2	1	3
	Synoptic (%)	74	60	57	48	53	70	60
	LE (%)	20	35	40	51	43	25	35
Erie	Clear skies (%)	9	3	1	1	8	4	4
	Unclassified (%)	3	5	2	0	2	3	3
	Synoptic (%)	69	67	68	61	66	77	67
	LE (%)	18	27	29	38	24	16	25
Ontario	Clear skies (%)	8	3	2	1	5	5	4
	Unclassified (%)	6	4	3	1	2	1	3
	Synoptic (%)	74	68	66	58	60	76	67
	LE (%)	13	25	29	40	33	18	26

5. Findings

a. *Lake-effect cloud band frequencies*

Because L2L cloud bands occur during a subset of LE conditions, it is useful to examine the frequency and type of LE clouds observed during the study period. Table 2 gives frequencies of the major cloud classifications for each of the Great Lakes for all dates with adequate visible satellite data. Days with no clouds were infrequent over all of the lakes, ranging from an average of 2% to 4% of winter days. Cloudiness associated with synoptic weather systems occurred less often over the western lakes (Superior, Michigan, and Huron) than over Lakes Erie and Ontario.

Lake-effect cloudiness was the second most common major cloud type observed over each of the Great Lakes during the five winters studied. It occurred most frequently over the western lakes (especially Superior and Huron), consistent with the increased frequency of cold-air outbreaks over the northern Great Plains region and the increasing presence of synoptic systems over and to the east of the Great Lakes (e.g., Angel and Isard 1997, 1998). The seasonal variation in LE cloudiness exhibited some variations between lakes, but generally peaked from December to February over all of the lakes. This trend is consistent with previous LE cloud climatologies (i.e., Kelly 1986; Kristovich and Steve 1995), and reflects the broad trends in lake–air temperature differences shown in Niziol et al. (1995) and trends in surface fluxes of heat given in Laird and Kristovich (2002).

Figure 3 shows the percentage of cases with LE clouds identified as WPB, SPB, coincident WPB and SPB (combined), unclear LE cloudiness, and vortices. Averaged over the entire winter, WPB was the most frequently observed LE cloud type over all of the lakes except for Lake Huron, where SPB occurred more often. There was a general decline of WPB occurrence from west to east. SPB cases were the next most common identifiable LE cloud type, occurring from 10% to 41% of the LE events, averaged over the entire winter. There were a significant number of LE cases that could not clearly be classified into the major types above (16%–34%). Cases with coincident WPB and SPB occurred during less than 1% of all LE cases over all of the Great Lakes.

Vortices occurred less than 3% of the days over the entire winter period (Fig. 3), most frequently over Lakes Michigan and Huron. Vortices occurred over the remaining lakes 1% or less of winter days. The observed peaks in vortex frequency at the ends of the season are questionable because of the low frequency of observed vortices and because conditions favorable for vortex formation (large lake–air temperature differ-

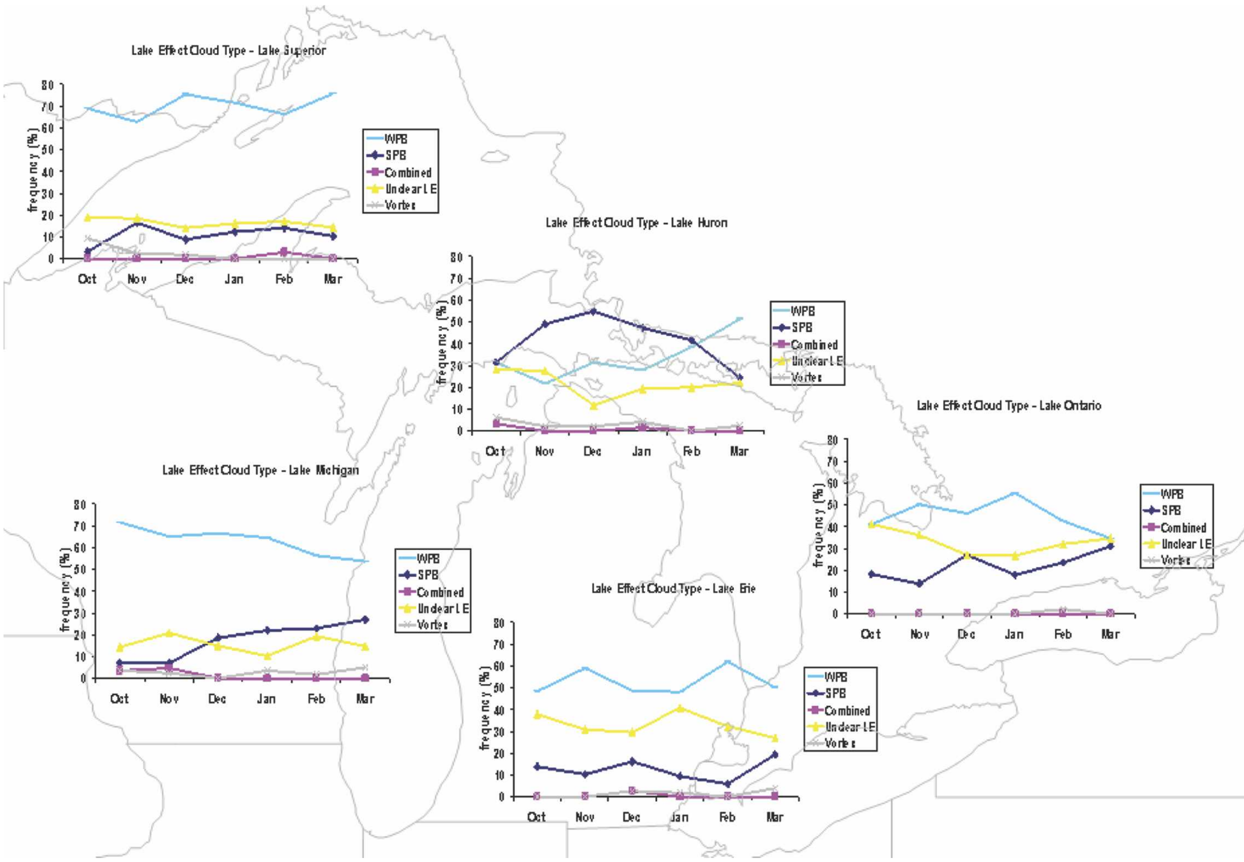

FIG. 3. Cloud-type frequencies observed over the Great Lakes during the 5-yr winter period (2000–04). The cloud types are separated by lake and month into five specific cloud patterns: 1) WPB, 2) SPB, 3) coincident (combined) LE cloud organizations, 4) unclear LE clouds, and 5) vortices. The values were calculated from dividing the monthly frequency of specific cloud patterns by the total frequency of LE clouds observed per month.

ences, low wind speeds; summarized in Laird 1999) are most likely during midwinter months.

b. Lake-to-lake cloud band frequencies

Occurrences of L2L cloud bands, identified in visible satellite imagery as lake-effect clouds continuously extending over two or more of the Great Lakes, were tabulated according to their originating lake. Table 3 and Fig. 4 give the number of L2L cloud bands originating over each of the Great Lakes during the 2000–04 time period and the percentage of these bands extending over different combinations of downwind lakes. Note that L2L cloud bands were only observed for those combinations of lakes listed. Most occurrences of L2L cloud bands originated over Lake Superior (S), with more than half of those extending downwind to Lake Michigan (M; hereafter the first letter denotes the respective lake; S–M) or beyond to other lakes (S–M–E, S–M–H, and S–M–H–E). The dominance of S–M over S–H L2L cloud bands may reflect a tendency for more north-northwest or northerly winds during their development, rather than northwest or west winds, which would favor bands extending over Lake Huron. Bands continuously extending over only two lakes were more frequent than those extending over three or more lakes.

L2L cloud bands originating over Lake Huron were the next most frequently observed events, occurring somewhat less than half as often as those originating over Lake Superior. Bands continuously extending from Huron to Erie (H–E) were more frequent than bands from Huron to Ontario (H–O), at 62% and 34%, respectively. As seen for L2L bands originating over Lake Superior, this is suggestive of more northerly wind components during L2L events; low-level winds with more westerly components would be expected to favor H–O L2L occurrence.

For Lake Michigan, L2L cloud bands, which occurred about half as often as over Lake Huron, tended to extend from Michigan to Huron (M–H) and Michigan to Erie (M–E). The overall lower frequencies for Lake Michigan than for Lakes Superior or Huron likely reflect the lack of lakes to the southeast and perhaps

TABLE 3. Percentages of L2L cloud bands classified by originating lake (2000–04). L2L clouds originate from each of the Great Lakes. Subclassifications for each classification were created based on the downwind lakes over which the L2L cloud bands extended. For example, L2L cloud bands originating from Lake Superior and extending over Lake Huron are denoted as (S–H) and L2L clouds originating from Lake Superior that extend over Lakes Huron and Erie are denoted as (S–H–E).

Originating lake		Oct	Nov	Dec	Jan	Feb	Mar	Winter
All lakes L2L	Tot cases (No.)	25	60	68	81	69	42	345
L2L originating over Superior	Tot cases (No.)	14	28	45	46	42	27	202
Superior (S)	S–H (%)	7	21	36	13	17	26	21
	S–H–E (%)	7	4	7	11	14	7	9
	S–H–O (%)	14	7	4	9	17	7	9
	S–M (%)	43	46	44	59	36	44	46
	S–M–E(%)	0	7	4	0	5	7	4
	S–M–H(%)	21	14	4	7	10	7	9
	S–M–H–E (%)	7	0	0	1	1	0	1
L2L originating over Michigan	Tot cases (No.)	5	6	11	16	10	0	48
Michigan (M)	M–H (%)	60	33	73	19	30	0	40
	M–E (%)	20	33	27	38	50	0	35
	M–H–E (%)	20	33	0	31	20	0	21
	M–H–O (%)	0	0	0	13	0	0	4
L2L originating over Huron	Tot cases (No.)	4	24	12	19	17	14	90
Huron (H)	H–M (%)	25	0	8	0	6	0	3
	H–E (%)	25	6750	79	65	50	62	
	H–O (%)	50	33	42	21	29	50	34
	H–E–O (%)	0	0	0	0	0	0	0
L2L originating over Erie	Tot cases (No.)	1	2	0	0	0	1	4
Erie (E)	E–O (%)	100	100	0	0	0	100	100
L2L originating over Ontario	Tot cases (No.)	100	0	0	0	0	0	1
Ontario (O)	O–E (%)	100	0	0	0	0	0	100

the long overland fetch to the neighboring lakes to the east. Many other intriguing patterns can be seen in infrequent L2L band occurrence. For example, L2L cloud bands originating over Lakes Erie and Ontario were infrequent and did not extend to the other lakes. However, 5 yr of observations is inadequate for full documentation of the occurrence of such infrequent L2L bands.

L2L cloud bands originating over Lakes Superior, Michigan, and Huron generally had midwinter peaks in frequency of occurrence. Interannual variations in monthly L2L frequencies (not shown) also indicate distinct midwinter peaks, despite considerable year-to-year variations. This agrees well with the midwinter peak in LE occurrence discussed above and previously observed in Kristovich and Steve (1995). Over Lakes Erie and Ontario, L2L cloud bands were observed less than once per year, on average, making it impossible to discern month-to-month variations.

6. Discussion

One goal of this study is to develop an understanding of the frequency and locations of lake-effect cloud bands extending between two or more of the Great Lakes. L2L cloud bands were identified using visible satellite imagery because of its extensive and consistent aerial coverage (as compared with surface observations and radar observations of shallow LE convection) and the relative ease of identifying LE cloud bands in the visible spectrum (as compared with infrared wavelengths). However, it is important to note that the absence of L2L cloud bands on a given day does not imply that there is not a physical link between convection on different lakes. Byrd et al. (1995) and Niziol et al. (1995) point out thermodynamic and radiative processes that can link convection from one lake with a downstream lake whether or not clouds are present over the intervening land areas. Rose (2000) found links between convection over Lakes Michigan and Erie using dry (no clouds or precipitation) mesoscale numerical model simulations. Clearly, the frequency of L2L cloud bands discussed here are underestimates of the wider range of L2L linkages in the Great Lakes region.

The analysis techniques used to identify LE cloud patterns in the present study were based on those em-

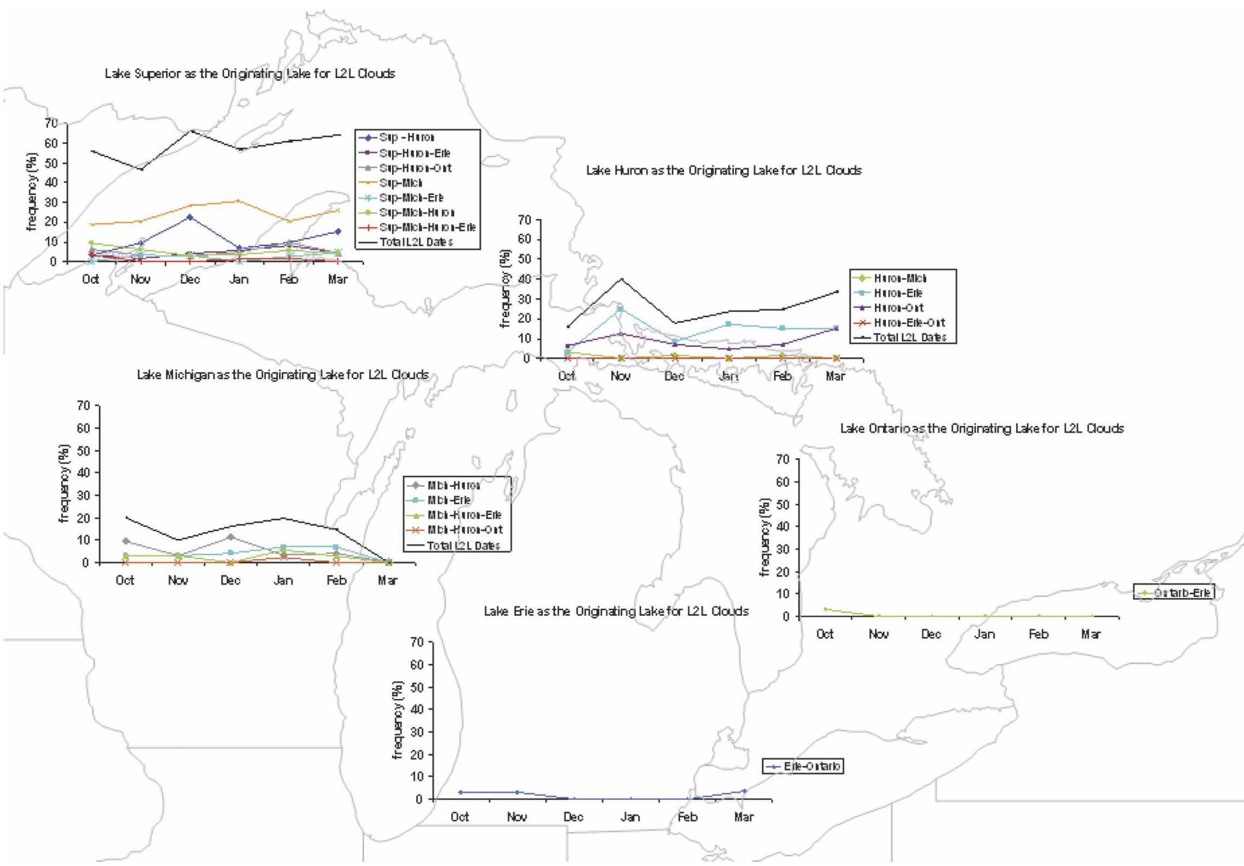

FIG. 4. L2L frequencies observed over the Great Lakes for the 5-yr period, 2000–04. L2L cloud bands were classified by originating lake. For example, L2L clouds originating from Lake Superior that extend over Lake Huron are denoted as Sup-Huron and clouds originating from Lake Superior that extend over Lakes Huron and Erie are denoted as Sup-Huron-Erie. Percentages were calculated by adding L2L cloud amounts per month and dividing by the total number of L2L cloud bands observed over the 5-yr period.

ployed by Kristovich and Steve (1995). Both studies found that synoptic clouds were the most commonly observed cloud organization over all of the Great Lakes. The overall seasonal and spatial variations in frequencies of LE cloud band types were in general agreement with those of Kelly (1986) and Kristovich and Steve (1995). WPB were the most common organization of LE convection over most of the lakes, with a general west–east decrease in WPB frequency. Perhaps the largest difference was for Lake Huron. The present study found that SPB were most frequent, while Kristovich and Steve (1995) found that WPB were most frequent. Such disagreements are not surprising for Lake Huron because of its highly complex shoreline shape. It is common to observe multiple WPB with one or two dominant bands extending northwest–southeast along the Lake's major axis.

The frequency and locations with which L2L cloud bands occurred over a 5-yr period were documented based on analyses of visible satellite imagery. L2L cloud bands were observed to originate over each of the five Great Lakes, with the highest frequencies over the western lakes as anticipated by the mean airflow during cold-air outbreaks in this region. Cloud bands originating over Lakes Superior, Michigan, or Huron were observed to extend most often over a single downwind lake, but cases of bands extending over up to three downwind lakes were also observed. The pattern of most frequent L2L bands suggests that low-level northerly component winds were more common than northwest or westerly winds in these events.

It is important to note that analysis of 5 yr of L2L band occurrence may not be adequate to fully describe their spatial and temporal variations. To gain some information on the potential representativeness of the frequencies observed in 2000–04, the climatic characteristics of those years were compared with long-term averages and the year-to-year variations in L2L band occurrence were examined.

To ascertain whether the 5 yr were near 30-yr climate averages, monthly departures of temperature and precipitation were examined for five first-order surface observation sites near (and west of) each of the Great Lakes (Duluth, Minnesota; Milwaukee, Wisconsin; Gaylord, Michigan; Toledo, Ohio; and Flint, Michigan). These departures were obtained from Climatological Data Annual Summaries (available online at http://www5.ncdc.noaa.gov/pubs/publications.html#CLIM81). In general, months under consideration for this study were warmer and drier than 30-yr average values (e.g., 1961–90 for 2000–02, 1971–2000 for 2003–04). The greatest average monthly temperature departures of approximately 2°–3°C were generally observed in the midwinter time periods (November–February). The greatest precipitation departures were observed at the southern sites (Milwaukee and Flint). Substantial month-to-month variations in departures were observed at all sites, but these variations appeared to be well within the normal long-term variability in temperature and precipitation. Because lake-effect snows would be anticipated to decrease in warmer time periods, it is anticipated that the frequencies described here are below long-term averages. Because the greatest temperature departures tended to be in midwinter months, it is suspected that the midwinter peaks in L2L frequencies observed here are underestimated.

The interannual variability of the observed occurrence of L2L cloud bands also gives information on the representativeness of the 5-yr time period. Figure 5a gives the annual frequencies of L2L bands originating over each of the Great Lakes. While there is considerable interannual variation in L2L band occurrence, a clear west–east trend is observed. L2L frequencies were more than 30 yr^{-1} from Lake Superior, decreasing to 10–30 yr^{-1} for Lakes Michigan and Huron, to fewer than 5 yr^{-1} over Lakes Erie and Ontario. This west–east trend is expected because of the typical westerly component of winds during cold-air outbreaks in this region (e.g., Kristovich and Steve 1995).

Examination of specific locations of L2L bands show far more relative variability from year to year. Figure 5b gives the annual values of the major L2L cloud bands extending between two lakes. Infrequent two-lake L2L bands (see Fig. 1; L2L bands originating over the eastern lakes, south–north orientations, or east–west orientations) are not shown, and clearly would require more than 5 yr of data to understand their occurrence. L2L frequencies shown in Fig. 5b indicate a great deal of interannual variability, but overall trends can be clearly seen. L2L bands between the northern and southern lakes (i.e., Superior to Michigan, Huron to Erie) tend to occur most often with lower, but consistent frequencies for west–east L2L bands. L2L bands between three or more lakes occur much less frequently (Fig. 4) with large interannual variations (not shown),

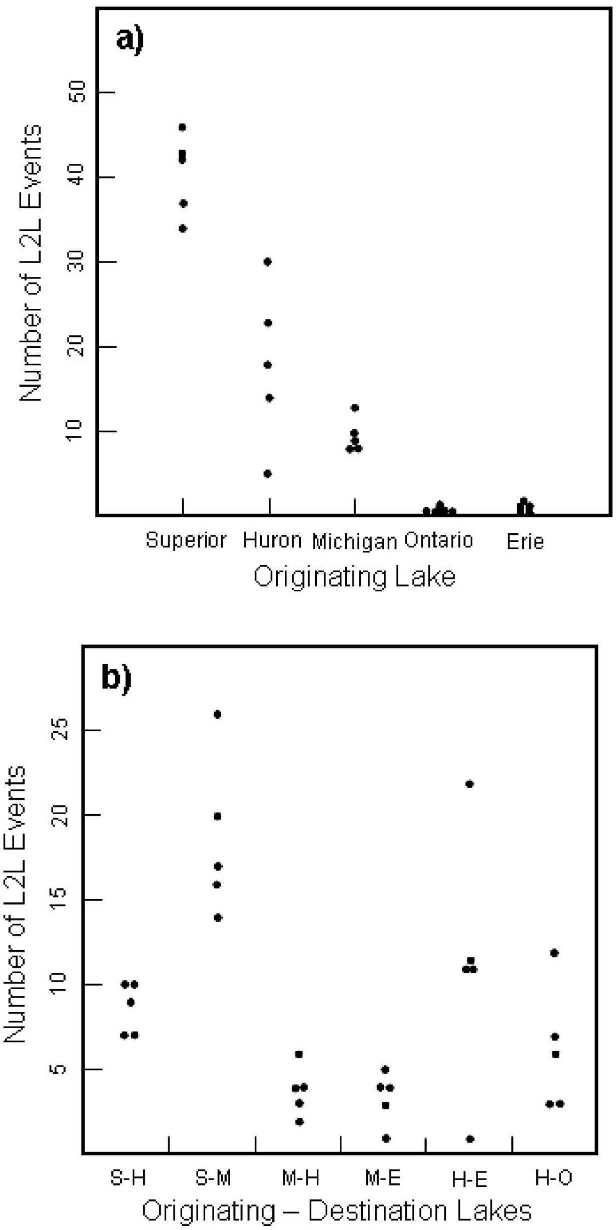

FIG. 5. The total number of L2L events for the calendar years 2000–04 as functions of (a) lake of origin of the L2L cloud bands and (b) originating and destination lakes. In (b), S, H, M, O, and E, represent each of the five Great Lakes by the respective first letter of each.

suggesting more than 5 yr of data are needed to fully understand their occurrence.

The distance to which some of these cloud bands extend, sometimes hundreds of kilometers over relatively cold land surfaces, raises several important research questions. To what extent are circulations associated with the L2L cloud bands still present as the bands reach the shore of the downwind lake? What processes control the distance over which an organized mesoscale circulation generated over a warm lake can remain intact over colder land surfaces with relatively high surface friction? How does the convectively mixed layer evolve over land surfaces and how does this depend on larger-scale environmental conditions? What are the relative roles of condensation–evaporation, circulations, and radiative processes in maintaining the L2L clouds themselves? The archive of L2L cases observed in this study should provide a useful database for continued observational analyses as well as validation of numerical modeling investigations of these questions.

7. Summary and future work

MODIS satellite imagery provided a clear illustration of LE cloud bands extending between Lakes Superior, Michigan, and Erie on 2 December 2003. Surface, satellite, and radar data indicated that LE cloud and snowbands originated over Lake Superior, and were enhanced over and downwind of Lakes Michigan and Erie. Spatial and temporal changes in the bands were described.

Visible *GOES-8* satellite images were used to analyze LE cloudiness and, in particular, LE cloud bands extending between two or more of the Great Lakes during five winters (2000–04). Lake-effect cloud frequencies were similar to those observed by Kristovich and Steve (1995). The ability to animate visible satellite imagery in the present study is thought to improve the ability to identify LE cloudiness.

With the exception of a few minor differences, overall frequencies of LE cloud patterns were consistent with past studies. WPB were the most common organization of LE clouds observed over all the Great Lakes except for Lake Huron during the study period. WPB percentages tended to decrease from west to east. SPB were the most prevalent cloud type over Lake Huron. Vortices were observed the least of all LE cloud types at less than 3% of the entire winter season.

L2L clouds were classified by the originating lake and identified through visible satellite imagery as was done for LE cases. L2L cloud bands were observed to originate over each of the Great Lakes, but predominated over Lakes Superior, Huron, and Michigan. This would be expected given the typical northwest–southeast flow experienced over the region during wintertime cold-air outbreaks. L2L cloud bands over Lakes Erie and Ontario only extended between these two lakes.

To fully understand L2L influences, it is important to determine environmental conditions (both at the surface and aloft and on scales from mesoscale to synoptic scale) favorable for L2L development. A further understanding of the evolution of mesoscale circulations over intervening land surfaces and how this evolution depends on environmental and surface characteristics is important. Further studies are needed to determine the impacts of L2L cloud bands on snowfall intensities and distributions as well as societal impacts of the snow.

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