NOTES AND CORRESPONDENCE

A Satellite Study of Cloud-Band Frequencies over the Great Lakes

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ABSTRACT

Lake-effect cloud bands over each of the North American Great Lakes were studied, using five winters of visible satellite data (1988–93) in order to better document the frequency of mesoscale boundary layer flows that led to their development. Several cloud-band classifications, based on boundary layer circulations identified by past authors, were used. The two most common cloud features over the Great Lakes were widespread lake-effect clouds, usually exhibiting multiple wind-parallel bands, and single or double bands parallel to the long axis of the lakes. Wind-parallel bands of lake-effect clouds have been shown in previous studies to form in the updraft regions of boundary layer roll vortices. Cloud bands parallel to the long axis of each of the Great Lakes have been shown to be organized primarily by land breezes.

October–March frequencies revealed that clouds were more prevalent over the western lakes (Superior, Michigan, and Huron) than over the eastern lakes (Erie, Ontario) due to differences in the frequencies of lake-induced clouds. The frequency of clouds due to larger-scale systems did not vary appreciably from lake to lake. Lake-induced cloudiness ranged from about 16% of the days over Lake Ontario to about 30% of the days over Lake Superior. Widespread cloudiness was the most frequent lake-effect cloud organization over the Great Lakes, with the exception of Lake Ontario where they occurred about as often as shore-parallel bands. However, their frequency decreased from west to east, with wind-parallel bands occurring nearly twice as often over Lake Superior as over Lake Erie. Bands parallel to the long axis of the lakes were much more common over the eastern lakes than the western lakes. Variations in monthly mean convective band frequencies were documented. Observed frequencies were consistent with the annual cycle of air–lake temperature difference and wind direction trends.

1. Introduction

Cloud patterns near the tops of convective boundary layers are reflections of flow fields within and above those boundary layers. This study documents cloud organizations over each of the Great Lakes in order to gain insight into the frequency of mesoscale circulations that give rise to them. Five years of daytime GOES (Geostationary Operational Environmental Satellite) visible satellite images were examined and cloud patterns over each of the Great Lakes were recorded. Cloud patterns were initially classified as either large-scale (synoptic scale) or lake-induced. If the clouds were judged to be lake-induced, the case was then classified according to the most obvious cloud-band pattern.

A limited number of studies have examined frequencies of boundary layer cloud patterns over water bodies. For example, Agee (1982) determined oceanic regions of open and closed mesoscale cellular convection. Kelly (1986) used satellite and surface snowfall data near Lake Michigan to examine the frequency of wind-parallel bands (often called cloud streets), bands along the eastern shore of the lake, and midlake bands oriented roughly north–south. He estimated the amount of snowfall contributed by each type of lake-effect convective organization. The present paper examines frequencies of cloud bands over a 5-yr period in order to give insight into the development of boundary layer circulations over each of the Great Lakes.

The organization of convection within lake-effect boundary layers has profound impacts on the precipitation received over the nearby shores (Braham and Dungey 1984; Niziol 1987). Many of the factors that control lake-effect convective patterns are the same as those in convective boundary layers over the oceans. The balance between thermal, radiational, and shear

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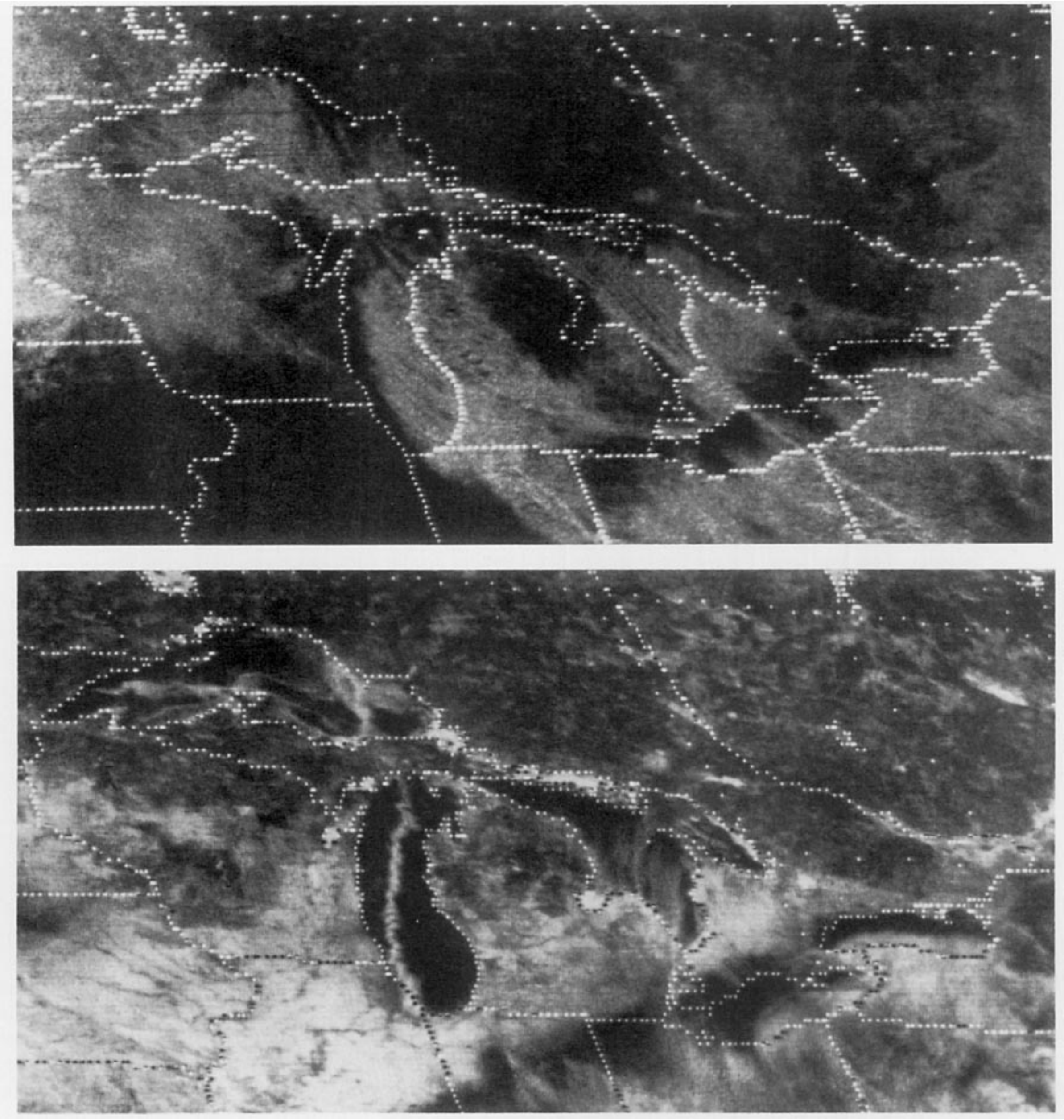

FIG. 1. GOES visible satellite photos during lake-effect events at 1731 UTC 3 December 1989 (top) and 1631 UTC 23 February 1989 (bottom).

forcing of boundary layer circulations controls the development of either cellular or wind-parallel linear convective patterns (e.g., Grossman 1982). Other factors, such as latent heat release due to cloud and precipitation development, may also play important roles (Hjelmfelt 1990). Convection over the Great Lakes, however, is also influenced by the shape of the lakes' shoreline, topography of the land near the lakes, orientation of the lake with respect to the wind, and lake–land temperature differences (e.g., Lavoie 1972; Hjelmfelt 1990, 1992; Reinking et al. 1993).

Lake-effect convective clouds over each of the Great Lakes can be classified into two general categories: 1) widespread stratocumulus, usually exhibiting multiple wind-parallel bands; and 2) single or double bands oriented roughly parallel to the long axis of the lake. Examples of these cloud patterns are shown in Fig. 1. Widespread stratocumulus clouds were present over all of the Great Lakes on 3 December 1989 (Fig. 1, top) and over the eastern Great Lakes on 23 February 1989 (Fig. 1, bottom). A shore-parallel band was present over Lake Michigan and was developing over Lake

Superior in Fig. 1 (bottom). A combination of wind-parallel and shore-parallel bands was observed over Lake Huron in Fig. 1 (top). For this paper, widespread lake-effect cloud cases will be denoted "WPB cases" (for wind-parallel bands). Bands parallel to the long axis of each lake will be called "SPB cases" (for shore-parallel bands).

These two convective organizations are due to very different boundary layer processes. Wind-parallel cloud bands over Lake Michigan tend to form in the upward-moving portions of boundary layer roll vortices (Kelly 1984). Past authors have pointed out the importance of wind shear (e.g., Asai 1972), wind profile curvature (Kuettner 1971), inflection points in the cross-roll wind profile (Brown 1980), interactions with gravity waves in the stable air above the boundary layer (Clark et al. 1986), and other factors that force convection into multiple longitudinal bands. A recent review of the literature on this topic can be found in Etling and Brown (1993). Criteria that determine when wind-parallel bands would dominate over random or cellular convection were derived by various authors, such as Woodcock (1940), Grossman (1982), and Sykes and Henn (1989). These were based on various atmospheric wind, thermal, and shear stability characteristics. Kristovich (1993a) found that lake-effect rolls observed over Lake Michigan often occurred with atmospheric conditions that these authors found favored cellular or random convective organizations. He attributed roll formation to intense shear within the surface layer, which developed due to reduced surface friction over the lake.

Shore-parallel bands form in response to the influence of nearby lake shores. Passarelli and Braham (1981) and Schoenberger (1984) showed that in conditions when the westerly wind component over Lake Michigan is small, land breezes can form and organize lake-effect convection into SPB. Using a mesoscale model, Hjelmfelt (1990) found that air–lake temperature differences and the cross-lake wind component were the primary factors in the development of land breezes. Upwind humidity and potential temperature gradients, as well as latent heating effects due to cloud and snow development, were smaller factors. Other authors have noted that the development of land breezes are additionally influenced by differences in surface roughness between the lake and nearby land areas and details of the land topography (e.g., Estoque and Gross 1981; Andersson and Nilsson 1990).

These observational and numerical studies give important information on the processes by which boundary layer convection is organized over the Great Lakes. The present study uses satellite data to document cloud-band frequencies over each of the Great Lakes in order to give insight into the frequency with which these processes occur.

2. Methodology

Cloud patterns over each of the Great Lakes were determined from visible GOES satellite images taken during five winter periods from 1988 through 1993. The high resolution of the visible images gave the best opportunity for classifying mesoscale cloud features. The resolution of the infrared images made them less useful for classifying lake-effect cloud patterns. However, infrared imagery was used as a secondary aid, particularly in differentiating between high-level, synoptic clouds and boundary layer, lake-effect clouds. Visible satellite images, taken between 1431 and 1931 UTC, were examined for each date during the months of October through March. Data for this study were obtained from the Department of Atmospheric Sciences, University of Illinois. Visible satellite data over the lakes were not available for about 14% of the dates. For individual lakes, each day with available data was classified according to the criteria described below. Only one classification was chosen for each lake on a given day. Since visible satellite data were useful only for a 6-h time period on each date, it was not possible to determine diurnal changes in convective patterns from at most 6 h of images.

The cloud pattern over each lake was initially classified as either synoptic, lake effect, or unclassified (not clearly discernible). If clouds over a lake were of a larger scale than the lakes and did not appear to originate at the lakes (such as the clouds associated with synoptic-scale low pressure systems or frontal cloud bands), then they were classified as "synoptic" cases. The date was classified as a lake-effect case if the clouds appeared to originate over a lake, at least one upwind shore was visible, and the clouds were of the same size scale as the lake. Furthermore, a clear separation between lake-effect clouds and nearby synoptic clouds had to be present. There were occasional cases where clouds associated with a synoptic system were enhanced over the lakes. However, since it was not possible to determine with certainty that the lakes were responsible for this enhancement on a given day and convective organizations could not generally be determined, these dates were classified as synoptic. The frequencies of lake-effect cloudiness reported here are therefore thought to be underestimates.

Lake-effect cases were further classified as WPB, SPB, combinations of WPB and SPB, or unclear lake-effect cases. The upwind shoreline was cloudless in WPB cases, while clouds covered most of the rest of the lake and downwind shore (see Fig. 1, top). The upwind edge of the clouds often exhibited the shape of the upwind shoreline. If multiple bands were present, such as those associated with rolls, then the case was classified as WPB. SPB cases usually consisted of single (or occasionally double) cloud bands oriented roughly along the long axis of the lake (see clouds over Lake Michigan in Fig. 1, bottom). Often, much of both shorelines were visible in the satellite images. The cloud band in SPB cases usually crossed the shoreline only at one location, rather than over a wide area as observed in WPB cases.

Cloud patterns showing both WPB and SPB characteristics were classified as combined lake-effect clouds. An example is shown over Lake Huron in Fig. 1 (top), where both wind-parallel bands and an enhanced shore-parallel band were observed. This category includes cases where clouds over a lake evolved from one organization to another during a day. If the clouds appeared to be due to one or more of the lakes, but could not be distinctly classified into any of the above groups, it was classified an unclear lake-effect case.

This classification method was developed to allow for as clear a distinction between the two primary processes that organize lake-effect convection as could be determined with certainty from visible satellite images. However, some interesting features of lake-effect convection could not be classified separately in this study. For example, the WPB cases generally exhibited wind-parallel banded structures (Kelly 1984), cellular structures (Braham 1986), or combinations of the two (Kristovich 1993b). In SPB cases, lake-scale (100-km-scale) vortices occasionally form over southern Lake Michigan, due in part to the shape of the lake (e.g., Hjelmfelt 1990). A separate classification for these was not included in these analyses in order to use the same criteria for each of the five Great Lakes. Small-scale vortices (10-km scale) are also frequently observed along SPB by radar (Schoenberger 1986, personal communication; WSR-88D radar reflectivity plots obtained from meteorologists at the National Weather Service Offices in Romeoville, Illinois and Milwaukee, Wisconsin). The shore-parallel band over Lake Michigan in Fig. 1 (bottom) shows a wavy pattern that may reflect the development of misoscale vortices. However, small-scale vortices could not be classified with certainty from most satellite images. These criteria do not include any surface-based measurements, so a direct statement about the frequency of lake-effect snow cannot be made from these analyses.

3. Findings

Table 1 gives the results of our analyses for each of the Great Lakes. Clear skies over the Great Lakes are fairly rare in winter, generally being observed in less than 20% of the cases in this study period. Skies were clear more frequently over the eastern lakes, occurring nearly twice as often over Lakes Ontario and Erie than over Lakes Superior and Huron. This trend is due primarily to the higher frequency of lake-effect clouds over the western lakes. On average, Lake Superior was covered by lake-effect clouds in about 30% of the cases, while Lake Ontario was covered by lake-effect clouds only in 16% of the cases. Cloudiness due to large-scale, synoptic events covered the lakes about 55% of the time, and this frequency changed little from east to west. November had the highest incidence of synoptic cases in this sample, but otherwise there was little consistent trend from month to month.

WPB cases were the most frequent lake-effect cloud organization over the Great Lakes. However, their frequency decreased from west to east. Two-thirds of lake-effect cloud organizations over Lake Superior were classified as WPB cases, while over Lake Ontario, WPB cases accounted for only 34% of the lake-effect cases. The fraction of lake-effect clouds that organized into either SPB or combined WPB and SPB cases increased sharply from west to east, ranging from 11% of lake-effect cases over Lake Superior to 40% over Lake Ontario. On average, about 30% of lake-effect clouds could not be classified clearly over the lakes. Lake-effect clouds over Lake Huron were the most difficult to classify, largely due to the complex shoreline of the lake.

Overall, the 6-month-average frequency of WPB cases (not given in Table 1) decreased from 20% to 6% from west to east. Shore-parallel bands occurred relatively rarely over the Great Lakes. The frequency of SPB cases increased from 2% to 6% of the cases from west to east. Adding cases of combined WPB and SPB to SPB-only cases increases these percentages to 3%–7% of the days. When SPB do occur, however, they can be accompanied by severe winter weather (Niziol 1987).

Figure 2 illustrates how the frequency of lake-effect cloud organizations changes with month over each of the Great Lakes. Lake-effect clouds increased in frequency over all of the lakes from October through February, and then decreased rapidly in March. As will be discussed in the next section, the January frequencies may be somewhat underestimated because January surface air temperatures were generally warmer than the 30-yr means during this study period. During October through December, WPB cases tended to increase in frequency, particularly over the western lakes. After February, the frequency of WPB cases decreased rapidly. The frequency of shore-parallel bands tended to increase from October through February, particularly over the eastern lakes. Indeed, over Lake Ontario, SPB cases occurred as frequently as WPB cases during January through March.

4. Discussion

Spatial and temporal trends in air and lake water temperatures would be expected to be major factors in determining the frequency with which lake-effect boundary layers develop. For example, the typical west-to-east temperature increase over the Great Lakes is reflected in higher frequencies of lake-effect convection over the western lakes.

The annual temperature cycle of the air and lakes is also reflected in observations of lake-effect cloud fre-

TABLE 1. Percentage of cases classified as each cloud organization over the Great Lakes (1988–93).

Lake		October	November	December	January	February	March	Winter
All lakes	Total number of dates	150*	136	109	120	123	147	785*
Superior	no clouds (% of total number)	20	3	3	3	2	20	9
	unclassified (%)	12	7	4	6	6	6	7
	synoptic-scale clouds (%)	52	67	55	48	48	53	54
	lake-effect clouds (%)	15	24	39	43	44	21	30
	widespread/WPB (% of LE)**	**57**	**84**	**67**	**65**	**59**	**58**	**65**
	shore-parallel/SPB (% of LE)	**13**	**3**	**2**	**12**	**11**	**3**	**8**
	combined organiz. (% of LE)	**0**	**3**	**2**	**6**	**2**	**0**	**3**
	unclear lake-effect (% of LE)	**30**	**9**	**29**	**17**	**28**	**39**	**25**
Michigan	no clouds (% of total number)	24	8	7	13	11	26	16
	unclassified (%)	7	3	6	3	3	3	4
	synoptic-scale clouds (%)	49	72	52	46	47	59	55
	lake-effect clouds (%)	20	17	35	38	38	13	26
	widespread/WPB (% of LE)**	**30**	**57**	**61**	**54**	**40**	**32**	**47**
	shore-parallel/SPB (% of LE)	**13**	**13**	**5**	**9**	**11**	**21**	**11**
	combined organiz. (% of LE)	**13**	**4**	**3**	**11**	**15**	**11**	**10**
	unclear lake-effect (% of LE)	**43**	**26**	**32**	**26**	**34**	**37**	**33**
Huron	no clouds (% of total number)	21	4	4	3	2	22	10
	unclassified (%)	13	7	9	4	10	9	9
	synoptic-scale clouds (%)	57	74	57	58	46	56	58
	lake-effect clouds (%)	10	15	30	34	42	12	23
	widespread/WPB (% of LE)**	**47**	**57**	**52**	**44**	**27**	**61**	**44**
	shore-parallel/SPB (% of LE)	**7**	**5**	**3**	**15**	**15**	**17**	**11**
	combined organiz. (% of LE)	**0**	**10**	**3**	**7**	**12**	**6**	**7**
	unclear lake-effect (% of LE)	**47**	**29**	**42**	**34**	**46**	**17**	**38**
Erie	no clouds (% of total number)	31	10	14	9	10	22	17
	unclassified (%)	8	8	8	7	9	5	8
	synoptic-scale clouds (%)	48	68	54	62	58	67	59
	lake-effect clouds (%)	13	13	24	23	24	6	16
	widespread/WPB (% of LE)**	**53**	**50**	**54**	**41**	**45**	**22**	**46**
	shore-parallel/SPB (% of LE)	**26**	**28**	**19**	**11**	**21**	**0**	**19**
	combined organiz. (% of LE)	**0**	**0**	**4**	**7**	**3**	**0**	**3**
	unclear lake-effect (% of LE)	**21**	**22**	**23**	**41**	**31**	**78**	**32**
Ontario	no clouds (% of total number)	34	13	12	8	15	29	19
	unclassified (%)	9	10	8	7	4	4	7
	synoptic-scale clouds (%)	51	68	53	59	47	57	56
	lake-effect clouds (%)	6	10	27	27	34	10	18
	widespread/WPB (% of LE)**	**56**	**43**	**41**	**28**	**31**	**21**	**34**
	shore-parallel/SPB (% of LE)	**22**	**36**	**28**	**38**	**31**	**36**	**32**
	combined organiz. (% of LE)	**0**	**0**	**7**	**9**	**7**	**21**	**8**
	unclear lake-effect (% of LE)	**22**	**21**	**24**	**25**	**31**	**21**	**26**

* 149 October cases and 784 winter cases over Lake Superior.

** Boldface portions are percentage of lake-effect cases.

quencies. Between October and January, air temperatures generally decrease rapidly over the Great Lakes region (based on data available over much of the Great Lakes region through the Midwest Climate Information System, MCIS; Kunkel et al. 1990) as water temperatures decrease more slowly (GLERL 1993). This results in increasingly large differences in air and lake temperatures, which is reflected in observed rapid increases in lake-effect frequency. Between February and March, the lake surface temperatures are close to their annual minimum while the average air temperature increases. Consequently, the frequency of lake-effect cloudiness decreases rapidly. The exception to this pattern was Lake Erie, where lake-effect cases appeared to peak in December. This is consistent with the frequently observed freezing of Lake Erie, during parts of January and February (GLERL 1990), resulting in a cutoff of the source of heat and moisture needed for lake-effect convection.

In addition to annual lake-effect cycles, diurnal variations in lake-effect cloud frequencies may also be expected, through the combined influences of changing air–lake temperature differences and radiation balances within the lake-effect boundary layer. However, since only 6 h of visible satellite data per day were used for this study, diurnal variations could not be documented.

The direction of the low-level wind relative to the orientation of the long axis of each lake, the wind speed,

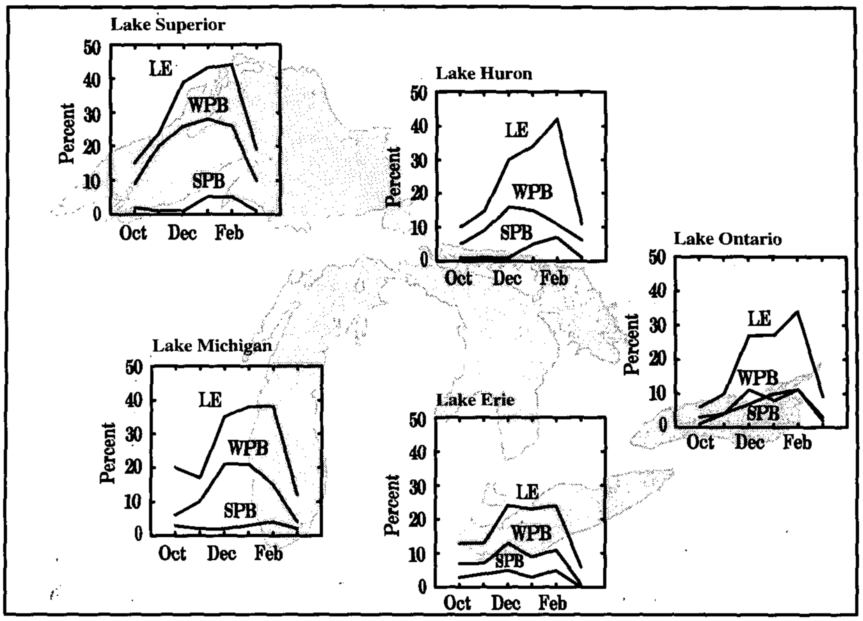

FIG. 2. Percent of all cases categorized as lake-effect (LE), wind-parallel bands (WPB, widespread), and shore-parallel bands (SPB). These are plotted for each month and for each of the five Great Lakes shown.

and air–lake temperature differences are thought to primarily control the organization of convection in lake-effect boundary layers. Shore-parallel bands form due to land breezes (e.g., Passarelli and Braham 1981; Hjelmfelt 1990), which are forced by temperature differences between air just above the lake and the nearby land. Therefore, the greater the difference in lake–land temperatures, the greater the chances for the formation of SPBs. Widespread lake-effect clouds (WPB) occur if the cross-lake component of the winds is strong enough that air density differences are not sufficient to produce land breezes.

These concepts of boundary layer processes are consistent with observed cloud-band frequencies. The most common convective organization over the Great Lakes in lake-effect situations was WPB. This would be expected since strong winds, with large cross-lake components, often accompany cold-air outbreaks during the fall and winter over the Great Lakes region. SPB cases were more frequent over the eastern lakes, reflecting the increased incidence of winds parallel to the long axes of Lakes Erie and Ontario (east–west orientation) during cold-air outbreaks.

Our observations show that from October through February, the frequency of SPB cases increased, particularly over the eastern lakes, apparently reflecting larger land–lake temperature differences. An examination of monthly average winds and temperatures reported at several land stations in the Great Lakes area revealed that monthly mean air temperatures were observed to decrease steadily from October to February and increase again in March during the study period, mirroring the SPB frequency trends. Colder air temperatures would tend to increase the density differences between air over the lakes and over the land, enhancing the likelihood of land breezes (e.g., Hjelmfelt 1990).

Theoretically, wind direction may also play a role in increasing the frequency of SPB late in the winter. However, a preliminary examination of wind directions in the Great Lakes region suggests that wind direction variations are not primarily responsible for these variations in the frequency of SPB. Monthly average data (from MCIS) suggest that wind directions became more parallel to the long axis of Lakes Michigan and Huron between January and March of the years studied, but became less parallel to the long axis of Lake Superior. Monthly average wind directions appeared to be fairly close to the long axes of Lake Erie throughout the winter months. No obvious monthly average trends in wind speed were noted. Therefore, these data suggest that variations of temperature differences between air over the lakes and air over the nearby land areas primarily determine monthly frequencies of SPB, with winds playing a minor role. A detailed examination of wind and temperature variations (and other factors) during cold-air outbreaks and resulting cloud patterns are left for a later study.

Without long-term convective organization studies to compare to, it is difficult to give a definitive statement as to the representativeness of these data. Note, however, that convective frequencies found here agree well with those found by Kelly (1986) for the winters of 1978 and 1979. Long-term data do exist for some of the atmospheric characteristics that past authors have found to play important roles in lake-effect convective formation. Several studies have concluded that the dominant surface factors controlling the development of lake-effect convection include wind speed, wind direction relative to the long axis of the lake (which affects the air's fetch over the lake), and air–lake temperature differences (e.g., Niziol 1987). Ideally, the frequency with which air–lake temperature differences and wind speeds exceeded threshold values during these 5 years should be compared to long-term frequencies. This detailed comparison will be left for future studies. Instead, we examined the surface air temperatures over each of the Great Lakes relative to 30-yr mean temperatures, based on temperature anomaly maps in the *Weekly Climate Bulletin* (Climate Analysis Center 1988–1993).

It was found that for the most part, monthly temperatures during the 5-yr period averaged close to the 30-yr mean values, even though unusually warm or cold individual months were recorded (e.g., GLERL 1993). Overall, there was a slight tendency for the months of December through March to be warmer than average. January was the only month that appeared to have temperatures that were much different than the long-term average. January temperature anomalies were more than 2° warmer than the 30-yr mean values over all of the Great Lakes for every year but 1991. Lake-effect cloudiness in January may therefore be underestimated in our sample. The effects of warm Januaries on lake-effect cloud frequencies in February and March are unknown. Overall, these temperature comparisons suggest that lake-effect cloud frequencies found in this study are close to long-term mean values early in the winter, and may be underestimated during January.

5. Summary and conclusions

This study examines the frequency with which lake-effect clouds occurred over each of the Great Lakes, and the primary organization of clouds, during a 5-yr time period. These analyses use visible satellite images between October and March, during a 6-h time period (1431–1931 UTC) on each date. Infrared images were used as a secondary aid. It was found that lake-effect convection resulted in higher frequencies of wintertime cloudiness over the western Great Lakes than over the eastern lakes. Widespread lake-effect cloudiness (usually exhibiting wind-parallel bands of clouds) was the most common lake-effect cloud organization over the Great Lakes, except over Lake Ontario where shore-parallel bands were nearly as frequent. Bands parallel to the long axis of the lakes were much more common over the eastern Great Lakes than over the western lakes. Variations in monthly mean convective band frequencies were found to be consistent with the annual cycle of air–lake temperature difference and wind direction trends.

Future work should take advantage of new datasets (e.g., from NOAA *GOES-8* satellite and WSR-88D radars) to obtain information on diurnal variations of lake-effect events and on lake enhancements of precipitation associated with synoptic-scale storm systems. Additional observational and numerical studies are necessary to determine the impacts of variations of cloudiness across the Great Lakes region on the radiation budgets and climate in the Great Lakes region.

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