Comparison of Observations with Idealized Model Results for a Method to Resolve Winter Lake-Effect Mesoscale Morphology

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ABSTRACT

Forecasters in the Great Lakes region have for several decades recognized a general relationship of wind speed and overlake fetch to lake-effect snowstorm morphology. A recent study using idealized mesoscale model simulations of lake-effect conditions over circular and elliptical lakes showed the ratio of wind speed to maximum fetch distance (U/L) may be used to effectively predict lake-effect snowstorm morphology. The current investigation provides an assessment of the U/L criteria using observational datasets. Previously published Great Lakes lake-effect snowstorm observational studies were used to identify events of known mesoscale morphology. Hindcasts of nearly 640 lake-effect events were performed using historical observations with U/L as the predictor.

Results show that the quantity U/L contains important information on the different mesoscale lake-effect morphologies; however, it provides only a limited benefit when being used to predict mesoscale morphology in real lake-effect situations. The U/L criteria exhibited the greatest probability of detecting lake-effect shoreline band events, often the most intense, but also experienced a relatively large number of false hindcasts. For Lakes Erie and Ontario the false hindcasts and biases were reduced and shoreline band events that occurred under higher wind speed conditions were better identified.

In addition, the Great Lakes Environmental Research Laboratory ice cover digital dataset was used in combination with observations from past events to assess the impact of ice cover on the use of U/L as a predictor of lake-effect morphology. Results show that hindcasts using the U/L criteria were slightly improved when the reduction of open-water areas due to lake ice cover was taken into account.

1. Introduction

Predicting the development, morphology, movement, intensity, and total snowfall of lake-effect (LE) snowstorms continues to be a challenge for weather forecast offices in the Great Lakes region (e.g., Rothrock 1969; Niziol 1987; Burrows 1991; Niziol et al. 1995; Sousounis et al. 1999). These storms can often produce significant snow accumulations within very short time periods, which may negatively impact transportation systems, limit business operations, cause significant property damage, and result in injuries and deaths due to accidents and exertion (Schmidlin 1993; Schmidlin and Kosarik 1999). The difficulty in predicting the development and evolution of LE snowstorms rests with the numerous parameters that influence the LE system (e.g., Hjelmfelt 1990; Laird et al. 2003a) and the complex atmospheric circulations that exist and interact across various spatial and temporal scales. For example, Mann et al. (2002) showed that individual LE snowstorms on the meso β scale (20–200 km; Orlanski 1975) could be influenced by coexisting meso-α-scale (200–2000 km) collective lake disturbances that develop over the Great Lakes region (Weiss and Sousounis 1999).

The LE storms that frequently result in the greatest impacts are meso-β-scale systems typically associated with an individual lake. These systems are often characterized by a distinct morphology that may include widespread coverage, typically comprised of wind-parallel horizontal roll convection (e.g., Kristovich 1993; Kristovich and Laird 1998), shoreline bands (e.g., Passarelli and Braham 1981; Ballentine et al. 1998), mesoscale vortices (e.g., Forbes and Merritt 1984; Laird 1999), or an amalgamation of two morphologies (e.g., Schoenberger 1986b).

For this study, historically separated classifications of shore-parallel and midlake bands are consolidated into a single morphological regime called *shoreline bands.*

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Across the range of shoreline band events, overlake mesoscale low pressure and lower-tropospheric convergence occurs as a result of a linkage between dynamical and surface diabatic forcings. For example, strong winds oriented along the major lake axis during a cold-air outbreak result in dynamically forced large surface heat fluxes, formation of an overlake mesoscale low pressure center, generation of a land-breeze circulation superimposed on the large-scale flow, and subsequent development of an overlake convergence zone and midlake snowband that can often produce heavy snow far inland (e.g., Braham and Kelly 1982; Niziol et al. 1995). Alternatively, calm winds in combination with a large lake–land temperature difference leads to strong diabatic forcing through establishing large horizontal gradients in surface heating, generation of an overlake mesoscale low pressure center, formation of a land breeze, and subsequent development of a shore-parallel snowband (e.g., Passarelli and Braham 1981). Even though band intensity and position relative to the shoreline may differ depending on the primary forcing (i.e., dynamical or diabatic), the resulting LE morphology is often a single, coherent meso-β-scale shoreline band (Laird et al. 2003b). While the former case is most often associated with heavy snowfall, both processes have been observed to be capable of producing significant snow (e.g., Braham 1983; Ballentine et al. 1998).

Since the current study partially relies on information obtained from previous LE investigations, an additional rationale behind consolidation into our shoreline band morphology was that not all previous studies have used the traditional LE classifications, specifically midlake or shore-parallel bands, or provided enough information to effectively discriminate between these two similar classifications. For example, Kristovich and Steve (1995) used a single grouping for ‘‘bands parallel to the long axis of each lake.’’ Hereafter MV, SB, WC, and SBWC will be used to refer to mesoscale vortices, shoreline bands, widespread coverage, and coexisting shoreline band and widespread coverage, respectively.

Hjelmfelt (1990), using simulations of LE over Lake Michigan, and Laird et al. (2003a,b), using idealized simulations of LE over a circular or elliptical lake, have shown that morphology is frequently related to the intensity (e.g., vertical motions, snowfall rate) of an LE meso-β-scale system. Laird et al. (2003a,b) showed that SB events are generally associated with the largest vertical motions, WC events exhibit moderate to weak vertical motions, and MV frequently contain the weakest vertical motions (summarized in Fig. 1). These relationships have also been formed using a knowledge base from observations (e.g., Braham and Kelly 1982) and many years of operational experience (e.g., Niziol et al. 1995). Given that the snowstorm intensity is often the most problematic quantity to predict and measure, knowledge of the LE morphology can be an important element in identifying the potential intensity of an LE snowstorm. This study focuses on the determination of snowstorm morphology due to 1) the relative ease of identifying LE mesoscale structure from radar and satellite data and 2) the difficulties associated with measuring and quantifying the intensity of an LE event for valid comparison with other LE events.

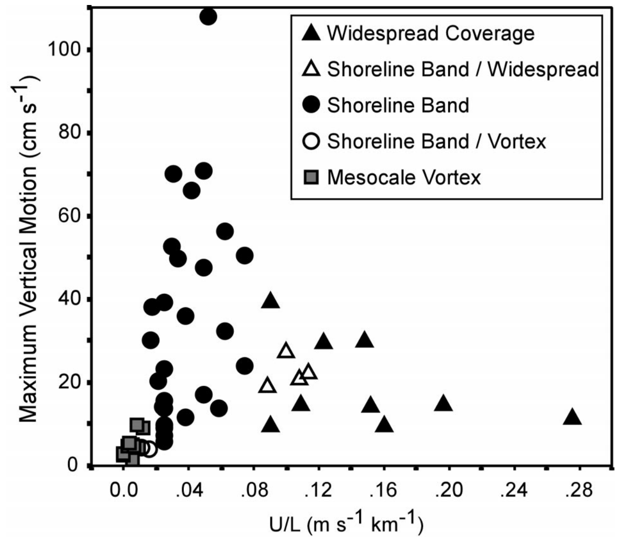

FIG. 1. The 24-h maximum vertical motion vs U/L for idealized mesoscale model simulations of Laird et al. (2003a,b) demonstrating the relationship of LE morphology to a measure of snowstorm intensity.

Regardless of the complexity of the LE system, forecasters in the Great Lakes region have for several decades recognized a general relationship of wind speed (U) and overlake fetch (L) to LE snowstorm morphology. Using idealized mesoscale model simulations of LE conditions over an isolated lake, Laird et al. (2003a,b) found U/L was a useful parameter for determining the meso-β-scale LE morphology and periods of morphological transition. The ratio of U/L is equivalent to the inverse advective residence time of an air parcel over a lake. The relationship with LE morphology was found to be independent of the difference between the upwind surface air and lake surface temperatures (ΔT) for events with $\Delta T > 5°C$.

Laird et al. (2003a,b) developed several criteria in U/L parameter space to identify different LE morphologies. The criteria were based on 35 model simulations conducted by Laird et al. (2003a) for LE conditions over a circular lake and refined by Laird et al. (2003b) using 21 simulations with an elliptical lake. Figure 1 shows the distribution of mesoscale morphology from these simulations within U/L parameter space. Lake-effect conditions with low U/L values ($\leq$0.02 m s^{-1} km^{-1}) resulted in an MV or a combined morphology with vortex and SB. Conditions leading to intermediate values of U/L (0.02 to ~0.09 m s^{-1} km^{-1}) tended to result in the development of an SB and land-breeze convergence zone. A relatively wide morphological transition zone between SB and WC was found to exist near U/L =

0.09 m s^{-1} km^{-1}, and U/L values greater than approximately 0.11 m s^{-1} km^{-1} produced WC within a region over and downwind of the lake. Additionally, Laird et al. (2003a,b) found that transitions from one LE morphology to another in U/L parameter space were continuous, and within U/L transitional zones the structure of a circulation often contained features characteristic of more than one LE morphology. Observations presented by Pitts et al. (1977), Schoenberger (1986b), and Laird (1999) provide examples of events in which multiple LE morphologies (e.g., MV and SB, WC and SB) coexisted over a single lake.

The current investigation uses data from previously published Great Lakes LE observational studies to provide an assessment of the prognostic utility of the ratio of wind speed to maximum fetch distance (U/L) criteria suggested by Laird et al. (2003a,b). Section 2 presents the data and methods used. Section 3 provides results from analyses of 1) information from past studies of LE MV, SB, WC, and SBWC events and 2) a climatological database of LE events identified by Kristovich and Steve (1995) and observations of lake ice cover. Conclusions and a summary of the investigation are provided in section 4.

2. Data and methods

This investigation coalesces information obtained from past observational studies of LE snowstorms in the Great Lakes region with archived datasets to appraise the predictability of LE morphology using the quantity U/L. For consistency with most past studies, an *event* is defined as an LE snowstorm on a particular date over a single lake. For example, several LE events, each over a different lake, could occur on the same date within the Great Lakes region. A 3-day LE snowstorm over a single lake would consist of three events, possibly with different morphology classifications.

Past observational studies of LE snowstorms used satellite and/or radar data, among other datasets, to examine their respective LE event(s) and provide a classification of the LE morphology. Studies that described MV events include Forbes and Merritt (1984), Pease et al. (1988), Laird (1999), Laird et al. (2001), and Laird et al. (2003a). These studies described 18 MV events that occurred over Lakes Superior, Huron, and Michigan. Studies of SB events include Sykes (1966), Peace and Sykes (1966), Ferguson (1971), Holroyd (1971), Passarelli and Braham (1981), Braham and Kelly (1982), Ballentine (1982), Niziol (1982), Braham (1983), Schoenberger (1986a,b), Elsner et al. (1989), Byrd et al. (1991), Burrows (1991), Wagenmaker et al. (1997), Ballentine et al. (1998), and Laird et al. (2003a). Information was collected from these studies for 31 SB events occurring within the entire Great Lakes region. Information from 20 WC events over Lakes Superior, Michigan, and Ontario was obtained from Holroyd (1971), Kelly (1982), Braham and Kelly (1982), Kelly (1984), Pease et al. (1988), Agee and Gilbert (1989), Byrd et al. (1991), Kristovich (1993), Kristovich and Laird (1998), Winstead et al. (2001), and Laird et al. (2003a).

The 5-year database developed by Kristovich and Steve (1995, hereafter referred to as KS95) offered the largest number of identified LE events. KS95 used five winters (October–March) of visible satellite images (1988–93) to document the frequency of LE cloud bands over each of the Great Lakes. They classified LE events as widespread cloud coverage (i.e., usually consisting of cellular and/or horizontal roll convection), single or double SB, or SBWC. Although MV events were not identified by KS95, information was collected for 117 SB, 402 WC, and 51 SBWC events with each type occurring over each of the Great Lakes. Since visible satellite data were useful only for a 6-h time period on each date included in KS95, any diurnal changes in LE morphology could not be determined. Therefore, a KS95 event is defined as an LE snowstorm over a single lake on a particular date between 1431 and 1931 UTC.

National Weather Service (NWS) 1200 UTC soundings launched at Green Bay, Wisconsin (GRB), Sault St. Marie, Michigan (SSM/Y62), and Buffalo, New York (BUF), just prior to or during each LE event were used to provide wind information for Lake Michigan, Lakes Superior and Huron, and Lakes Erie and Ontario, respectively. Twenty-one events did not have soundings available and were not included in this study. This reduced the total number of events from 660 to 639. The U/L criteria suggested by Laird et al. (2003a,b) incorporated the ambient wind speed (U, m s^{-1}) not influenced by frictional drag. For consistency, the 850-hPa wind speed and direction from NWS soundings were used to provide the ambient wind conditions. A comparison of 850-hPa winds at our chosen sounding locations with winds at other regional sounding sites removed from the lake shores (e.g., Flint, Michigan; Albany, New York; Pittsburgh, Pennsylvania) suggested the 850-hPa ambient wind conditions over each Great Lake were well represented by soundings at GRB, SSM/Y62, and BUF. On average, wind direction and speed varied between sites by approximately 10° and 3.0 m s^{-1}, respectively.

The overlake fetches for a lake were determined using the distances from the upwind to downwind shore for each wind direction, with the overlake path through the approximate areal center of each lake. This approach allowed each directional fetch to represent the approximate maximum fetch, a measure consistent with the definition of L used by Laird et al. (2003a,b). The fetch distances are changed only slightly, with a different choice of the center point over any of the lakes resulting in a minimal impact on U/L values and hindcasts of LE morphology. For example, a shift in the center point of $\pm$10 km in the north–south (east–west) direction over Lake Erie during conditions with 850-hPa winds of 10 m s^{-1} from 250° (i.e., long-axis fetch) would alter the original U/L of

0.028 m s^{-1} km^{-1} by $\pm$0.002 m s^{-1} km^{-1} ($\pm$0.001). In addition, determination of the overlake fetch is sensitive to the uncertainty in estimating the ambient wind direction. An error in the overlake wind direction of $\pm 10°$ would result in an average change in the fetch distance for Lake Superior, Lake Huron, and Lakes Michigan, Erie, and Ontario of 9%, 14%, and 16%, respectively, and a similar change in U/L.

The overlake fetch distance can be strongly influenced by the presence of ice cover on the lake. Lake ice coverage has large seasonal and interannual variability (e.g., Richards 1964; Assel and Quinn 1979; Assel et al. 1995) and has the potential of significantly impacting LE snowstorms (e.g., Niziol 1987; Niziol et al. 1995). Although the relationship between substantial lake ice cover on the Great Lakes and the reduction of heat and moisture fluxes from the lake surface has not been quantified, ice cover acts to effectively reduce the open-water area of a lake (i.e., L) and can therefore impact values of U/L. Digital ice charts from the Great Lakes Environmental Research Laboratory (GLERL) (Assel et al. 2002) and the KS95 database were used to examine the impact that ice coverage may have on the prediction of LE morphology. Using the 850-hPa wind direction and GLERL ice charts, an adjusted maximum fetch distance, L, was determined for each event in the KS95 database.

The digital ice charts for the period of 1988–93 typically segmented regions of significant ice cover concentrations using values of 50%, 80%, and 95%. For our investigation, overlake areas with $<$80% ice cover concentration were considered to be equivalent to open, ice-free water, and areas with $>$80% concentration were considered to represent the effective shoreline of a lake and were used to determine an adjusted L for the corresponding LE event. Since the reduction of heat and moisture fluxes from the lake surface have not been quantified for lake-effect conditions when significant ice cover exists, the use of 80% ice cover concentration as a threshold value for this study should be considered an initial indication of the impact of ice cover on LE systems. This approach may provide an overestimate of the ice cover impact on determining LE morphology from U/L when adjusted L values are used since surface heat transfer to the atmosphere still exists over regions with high concentration ($>$80%) and solid (100%) ice cover (e.g., Assel 1999).

Surprisingly, 11 KS95 LE events were found to have occurred under conditions when the underlying lake had significant ice coverage ($\geq$80% ice cover concentration) over the *entire* lake. Three events occurred over Lake Superior during the months of March 1989, February 1991, and March 1991, and the remaining eight events occurred over Lake Erie during February 1989 when ice coverage was $\geq$95%. Based on our treatment, the maximum fetch distance was reduced to 0 for the 11 events, causing U/L values to become undefined. Therefore these events were discarded from our analyses. An examination of the LE morphology for these events showed that widespread coverage occurred on 8 of the 11 cases, which seems to support the findings of Laird et al. (2003a,b) that widespread coverage predominates at the higher values of the U/L parameter space. Sections 3b and 4 will further discuss the impacts of lake ice cover on LE events and their morphology.

3. Analyses and results

Results from two analyses are presented that used observational data from prior Great Lakes LE studies to assess the U/L criteria developed from idealized model simulations. Hindcasts of each morphology over each lake were performed with U and L values determined from 850-hPa wind data. Hindcasts of 639 LE events were examined using the U/L criteria suggested by Laird et al. (2003b) for vortices ($0 < U/L \leq 0.01$ m s^{-1} km^{-1}), coexisting shoreline band and vortex ($0.01 < U/L \leq 0.02$ m s^{-1} km^{-1}), shoreline bands ($0.02 < U/L \leq 0.06$ m s^{-1} km^{-1}), coexisting shoreline band and widespread coverage ($0.06 < U/L \leq 0.11$ m s^{-1} km^{-1}), and widespread coverage ($U/L > 0.11$ m s^{-1} km^{-1}). For this study a U/L hindcast within a morphological transition region was considered correct if the observed event contained either of the individual or coexisting morphologies.

a. Analysis of U/L for observed LE events

Figure 2 and Table 1 present an overview of the observed LE events, and Table 2 provides a detailed comparison of U/L hindcasts of the observed events with the U/L criteria of Laird et al. (2003b). Figure 2a shows the U/L values for each LE event reported in the scientific literature, including events composing the KS95 study. Values are identified by LE morphology and specific Great Lake. The data points for SB, WC, and SBWC are widely distributed across a range of U/L values, and MV events are limited to low values of U/L. The scattered distributions of SB, WC, and SBWC U/L values demonstrate the complexity and mesoscale variation of observed LE events and the potential difficulty in using U/L to forecast LE morphology.

Figure 2b presents the mean and first standard deviation of U/L for all events classified by specific lake and mesoscale LE morphology. Although MV events have not been reported over the eastern Great Lakes, a comparison of the mean U/L values over each lake shows consistent increases from MV to SB events and SB to WC events. The mean U/L values for all lakes within a particular type of LE morphology (i.e., ''All Lakes''—black squares in Fig. 2b) display the same increase from MV through WC. The U/L values for the SBWC events over a single lake are generally located in the U/L transition region between SB and WC LE morphologies. This result is qualitatively consistent with the modeling results of Laird et al. (2003a,b) that

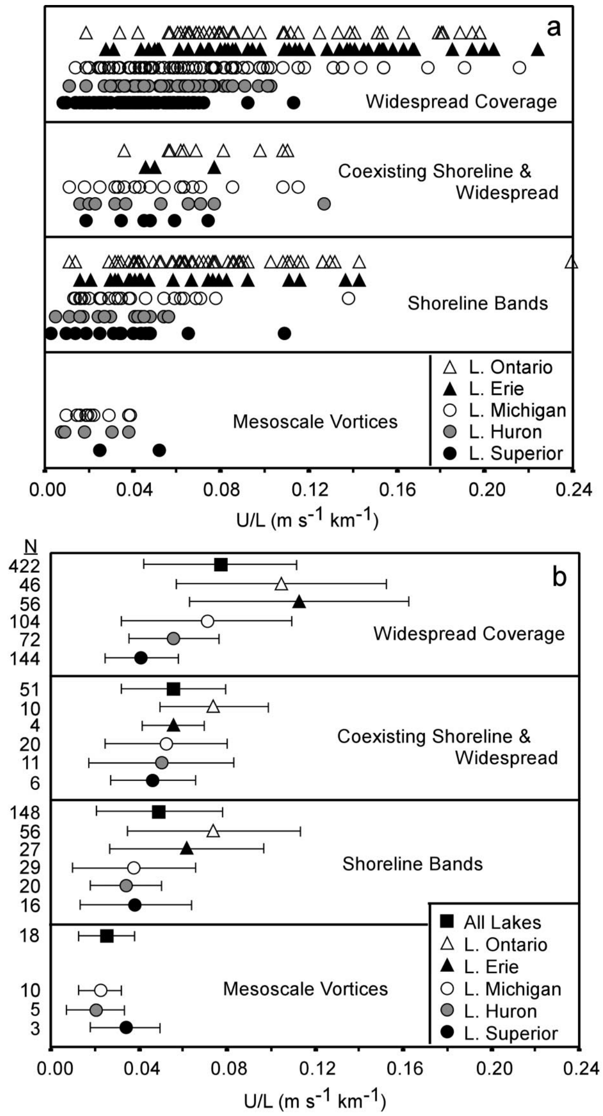

FIG. 2. (a) Individual *U*/*L* values and (b) mean and first standard deviation of *U*/*L* are shown for 639 LE events reported in the scientific literature with morphologies of mesoscale vortex, shoreline band, widespread coverage, and coexisting shoreline band and widespread coverage. Here, *N* represents the number of events over each lake. See Table 2 for mean values of *U*/*L*.

showed the transitions from one morphology to another in *U*/*L* parameter space are continuous and the morphology of a mesoscale circulation may contain an amalgamation of structural features. Exceptions occurred for Lake Superior, where the mean *U*/*L* value of 6 SBWC events is slightly greater than the WC mean *U*/*L* value determined from 140 events, and Lake Erie, where the mean *U*/*L* value of 4 SBWC events is less than the SB mean *U*/*L* value determined from 27 events.

The independent-samples *t*-test procedure (assuming a population normal distribution of *U*/*L* values) was used to statistically compare the mean *U*/*L* values for two LE morphological groups. Table 1 shows the results of the comparison of MV with SB, SB with WC, and MV with WC events over each lake (mean *U*/*L* values are shown in Fig. 2 and Table 2). A low significance value for the *t* test (typically <0.05) indicates that there was a statistically significant difference between the two group means. The bold face numbers in Table 1 denote the comparisons of *U*/*L* means for two morphologies that were statistically significant at the 95% confidence level. The findings that several of the comparisons of mean *U*/*L* values were statistically significant and the relatively consistent increase of *U*/*L* means of each lake and the all-lakes value with a change from MV to SB and SB to WC suggests that the quantity *U*/*L* contains information important to the fundamental dynamics responsible for the different meso-β-scale LE circulations in the Great Lakes. It is important to note, however, that even though the difference in *U*/*L* means between different LE morphologies was statistically significant in most cases, there was a large amount of variability in the *U*/*L* values for each morphology (Fig. 2), and the mean *U*/*L* values varied less between morphologies than the *U*/*L* criteria suggested by Laird et al. (2003b).

TABLE 1. Statistical comparisons of mean *U*/*L* values for mesoscale vortex and shoreline band events (MV–SB), shoreline band and widespread coverage events (SB–WC), and mesoscale vortex and widespread coverage events (MV–WC). Numbers represent the significance value of the independent-samples *t* test of equality of means. Bold face denotes that comparison of means was statistically significant (<0.05) at the 95% confidence level. MV events were not observed over Lakes Erie and Ontario.

Lake	MV–SB	SB–WC	MV–WC
Superior	0.764	0.560	0.445
Huron	0.102	**0.000**	**0.000**
Michigan	**0.017**	**0.000**	**0.000**
Erie	—	**0.000**	—
Ontario	—	**0.001**	—
All Lakes	**0.000**	**0.002**	**0.000**

Some useful measures for evaluating the quality of the *U*/*L* hindcasts of LE morphology in relation to the *U*/*L* criteria resulting from the idealized model simulations of Laird et al. (2003b) are the probability of detection (POD), false alarm rate (FAR), and bias. The POD is a ratio of the number of correct hindcasts of an LE morphology to the total number of observed events of the same LE morphology. The POD ranges from 0 to 1, where a value equal to 1 would indicate that hindcasts correctly identified the morphology for each LE event. Note that neither correct hindcasts of another LE morphology nor incorrect hindcasts of LE morphology affect the POD. The FAR is a ratio of the number of incorrect LE morphology hindcasts to the total number of hindcasts of the same morphology. The FAR ranges from 0 to 1, where 0 indicates that incorrect hindcasts of LE morphology were not made. The bias is a ratio of the total number of hindcasts of a particular LE morphology to the total number of observed events of the same morphology. Ideally, the bias would equal unity.

TABLE 2. Evaluation of *U/L* hindcasts for LE cases from literature. Shown for each LE morphology and lake are number of cases, minimum *U/L*, maximum *U/L*, mean *U/L*, POD, FAR, and bias. POD, FAR, and bias were determined using *U/L* criteria from Laird et al. (2003b). Mean values for each morphology are also included (All Lakes).

Lake-effect morphology	Lake	No. of cases	Min *U/L*	Max *U/L*	Mean *U/L*	POD (L03b)	FAR (L03b)	Bias (L03b)
Vortices	Superior	3	0.025	0.052	0.034	0.000	1.000	6.333
	Huron	5	0.008	0.038	0.021	0.600	0.769	2.600
	Michigan	10	0.010	0.039	0.023	0.500	0.783	2.300
	Erie	—	—	—	—	—	—	—
	Ontario	—	—	—	—	—	—	—
	All Lakes	18	—	—	0.026	0.367	0.851	3.744
Shoreline	Superior	16	0.003	0.109	0.039	0.909	0.878	7.455
	Huron	20	0.005	0.056	0.034	0.936	0.721	3.355
	Michigan	29	0.013	0.138	0.038	0.959	0.678	2.979
	Erie	27	0.016	0.143	0.062	0.871	0.500	1.742
	Ontario	56	0.011	0.239	0.074	0.849	0.341	1.288
	All Lakes	148	—	—	0.049	0.905	0.624	3.364
Coexisting shoreline and widespread	Superior	6	0.019	0.074	0.047	0.167	0.955	3.833
	Huron	11	0.016	0.127	0.050	0.273	0.917	3.273
	Michigan	20	0.011	0.115	0.053	0.350	0.870	2.700
	Erie	4	0.046	0.077	0.056	0.250	0.963	6.750
	Ontario	10	0.036	0.110	0.074	0.500	0.922	6.400
	All Lakes	51	—	—	0.056	0.308	0.925	4.591
Widespread	Superior	144	0.008	0.113	0.041	0.140	0.087	0.153
	Huron	72	0.011	0.103	0.056	0.446	0.000	0.000
	Michigan	104	0.014	0.216	0.071	0.516	0.086	0.565
	Erie	56	0.028	0.224	0.113	0.831	0.183	1.017
	Ontario	46	0.019	0.198	0.105	0.857	0.422	1.482
	All Lakes	422	—	—	0.077	0.558	0.156	0.643

It is important to recognize that these measures should not be used separately but must be applied jointly to provide an indication of the quality of the hindcasts and *U*/*L* criteria.

Table 2 shows the POD values determined for the different LE morphologies over each lake and the all-lakes average POD values for MV, SB, SBWC, and WC events. The POD values for MV events indicate that the *U*/*L* criterion ($U/L < 0.02$ m s^{-1} km^{-1}) was about 37% accurate when all vortex events were considered. The *U*/*L* method identified 0%, 60%, and 50% of the 3 Lake Superior, 5 Lake Huron, and 10 Lake Michigan LE vortex events, respectively. Additionally, FAR values were large with an all-lakes average of about 85%.

The hindcasts were noticeably improved for LE SB events ($0.01 < U/L \leq 0.11$ m s^{-1} km^{-1}) with POD values for each of the Great Lakes larger than 84%. The all-lakes POD value indicated that just over 90% of all SB events were correctly identified. However, the FAR for SB events was relatively large (~62%), suggesting that numerous events with hindcasts of SB events had a different LE morphology.

The SBWC events were the most difficult to identify with the *U*/*L* criteria (POD ≈ 31% and FAR ≈ 95%). This result is likely due to the increased complexity of the mesoscale dynamics associated with these events, the limited number of events, and the difficulty in defining the SBWC transitional region in *U*/*L* parameter space from the limited number of idealized simulations conducted by Laird et al. (2003a,b).

The WC mean *U*/*L* values ranged from 0.041 to 0.113 with a relatively large distinction in values between the western and eastern Great Lakes. The *U*/*L* criteria for WC events ($U/L > 0.06$ m s^{-1} km^{-1}) showed a high probability to identify WC over Lakes Erie and Ontario with POD values of about 83% and 86%, respectively, with relatively low FAR and bias values. While over Lakes Superior, Huron, and Michigan both POD and FAR values were relatively low because few WC morphology events were hindcasted for these lakes. The cause of the difference in *U*/*L* values between these two regions is unclear, but shows a weakness of the *U*/*L* criteria to identify WC events, the most climatologically frequent, over the western Great Lakes.

Figure 3 shows the LE morphology of observed events and identifies the idealized *U*/*L* parameter space for MV, SB, WC, and mixed-morphology events for each of the Great Lakes as a function of wind direction (i.e., overlake fetch) and wind speed. The morphological regions are based on the *U*/*L* criteria suggested by Laird et al. (2003b). Examination of the observed events for Lakes Superior, Huron, and Michigan shows LE events predominantly occurred with wind directions between west and north. Widespread coverage events tended to occur over Lakes Superior and Huron for wind speeds greater than 10 m s^{-1}, with other types of less frequently occurring LE morphologies (i.e., MV, SB, and mixed-morphology events) at lower wind speeds. The distribution of the *U*/*L* morphological regions for Lake Superior and Huron seem to limit the potential prediction of WC in favor of forecasting SB or mixed-morphology events. This weakness in using the *U*/*L* criteria to predict

WC for large, more circular lakes (large fetch distances for all wind directions) was not apparent from the idealized circular lake simulations of Laird et al. (2003a).

The *U*/*L* criteria for Lakes Michigan, Erie, and Ontario show a larger region for WC and a greater possibility of predicting these events than over Lakes Superior and Huron. This is associated with the difference in lake shape (more elliptical) and a significant decrease in fetch distances over a range of wind directions. The general shift in *U*/*L* morphological regions toward lower wind speeds for Lakes Michigan, Erie, and Ontario captured a slight decrease in the average wind speed that occurs during observed WC events over Lakes Michigan, Erie, and Ontario when compared to WC over Lakes Superior and Huron. In general, this shift of idealized *U*/*L* regions toward lower wind speeds resulted in increased predictability of WC and SBWC morphologies over Lakes Michigan, Erie, and Ontario (Table 2).

Additionally, SB and SBWC events were a larger percentage of LE storms reported for Lakes Erie and Ontario (KS95). The *U*/*L* morphological regions for SB and SBWC extend to higher wind speeds in association with wind directions down the long axis of the lakes, a condition often favorable for intense SB events at the downwind shoreline. Even though POD of SB events for Lakes Erie and Ontario (0.87, 0.85) were lower than for SB events on the western Great Lakes, the FAR and bias were reduced, and SB events that occurred under higher wind speed conditions were better identified for Lakes Erie and Ontario (Fig. 3). Under conditions when dynamical forcing of large surface heat fluxes is the dominant mechanism for intense SB development (e.g., Niziol et al. 1995), the *U*/*L* criteria seems to identify SB events more readily than criteria suggested by previous studies that have emphasized conditions favorable for land-breeze development during weak ambient wind conditions (e.g., Passarelli and Braham 1981; Hjelmfelt 1990).

b. Analysis of U/L for KS95 and lake ice coverage

Increased lake ice coverage tends to inhibit the exchange of heat and moisture from the lake surface to the atmosphere during cold winter periods. Although most of the Great Lakes rarely form a continuous ice cover during the winter (e.g., Assel and Quinn 1979; Assel et al. 1985), extensive nearshore and shallow-water regions in the Great Lakes (e.g., Lake Erie) often become covered by a significant concentration of ice, which affects a decrease in the maximum overlake fetch. The impact that these regions of significant ice coverage have on boundary layer fluxes and circulations or the development and evolution of mesoscale LE snowstorms has not been quantified.

The current investigation uses the GLERL ice cover digital dataset (Assel et al. 2002) in combination with LE morphology information from the KS95 database to account for regions of significant ice cover and assess the impact of ice cover on the use of the *U*/*L* criteria. If significant ice cover was present for a KS95 LE event, an adjusted open-water maximum fetch (*L*) was determined using fetch distances over which there was less than 80% ice concentration and the *U*/*L* value for the event was recalculated. If the lake had no significant ice cover during an event, the *U*/*L* value remained the same. Ice cover was present for 204 LE events of the 570 SB, WC, and SBWC events examined using the KS95 dataset.

Table 3 shows individual lake POD values determined for SB, SBWC, and WC events and average all-lakes values. In general, these results are similar to those found when ice cover was not taken into account (Table 2). The individual lake and all-lakes mean *U*/*L* values increased from SB to SBWC events and from SBWC to WC events. The results showed a high probability to identify SB events over each lake (~91%), with the largest FAR and bias values over the western Great Lakes. The probability of identifying SBWC events showed the largest increase combined with a slight decrease of FAR values. Overall, POD values increased or remained nearly the same for each Great Lake and LE morphology with the inclusion of the GLERL ice cover information. Although accounting for lake ice cover had a relatively small impact on the hindcasts of LE morphology when applying the *U*/*L* criteria, these results suggest that ice coverage can have a measurable influence on LE events. Additionally, these findings suggest that more work is needed to determine the impacts of ice cover on both LE boundary layer structure and the morphology of LE circulations.

4. Summary and conclusions

Although mesoscale model simulations have shown the capability of providing detailed forecasts of lake-effect systems (e.g., Ballentine et al. 1998), simpler more accessible techniques that have proven useful for operational forecasting, such as proxies, rules of thumb, and decision trees (e.g., Niziol 1987; Niziol et al. 1995), are likely to find continued use in a balance between the man–machine mix of the forecast process (Sousounis et al. 1999). Forecasters in the Great Lakes region have for several decades recognized a general relationship of wind speed and fetch to LE morphology. Laird et al. (2003a,b) used a series of idealized mesoscale model simulations to identify and examine this relationship and suggest *U*/*L* criteria that could be used as an aid to forecast LE morphology, a proxy of snowstorm intensity. Information and data from past observational LE studies were used to assess the effectiveness of the suggested *U*/*L* criteria to correctly identify LE morphology.

The results showed that the *U*/*L* criteria, developed from idealized mesoscale model simulations of LE conditions over circular (Laird et al. 2003a) and elliptical

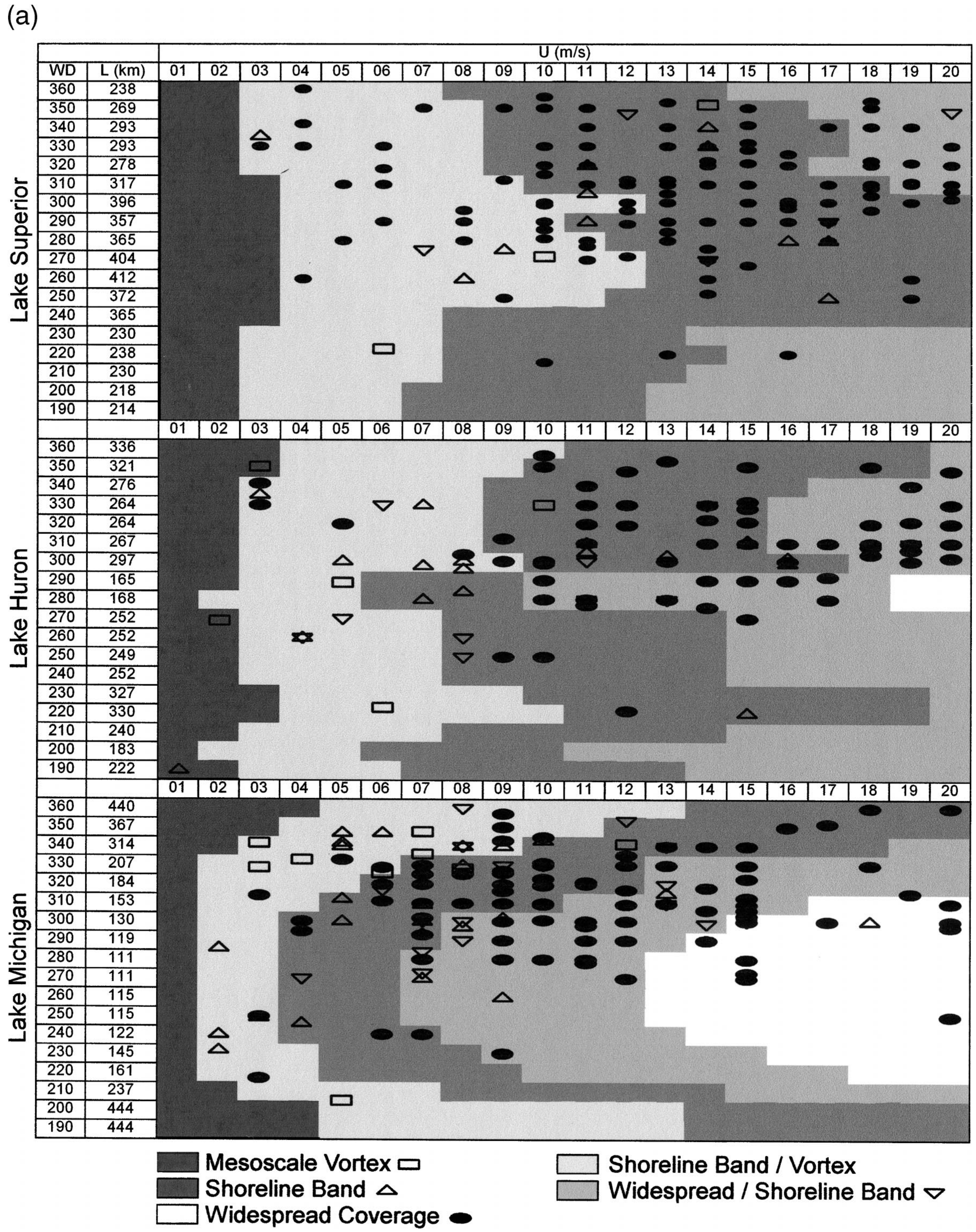

FIG. 3. Morphological regions as a function of maximum fetch (L) and wind speed (U) for each Great Lake. Regions are based on the criteria suggested by Laird et al. (2003b) for mesoscale vortices ($0 < U/L \leq 0.01$ m s^{-1} km^{-1}), coexisting shoreline band and vortex ($0.01 < U/L \leq 0.02$ m s^{-1} km^{-1}), shoreline bands ($0.02 < U/L \leq 0.06$ m s^{-1} km^{-1}), coexisting shoreline band and widespread coverage ($0.06 < U/L \leq 0.11$ m s^{-1} km^{-1}), and widespread coverage ($U/L > 0.11$ m s^{-1} km^{-1}). Observed morphology for events is represented by symbols.

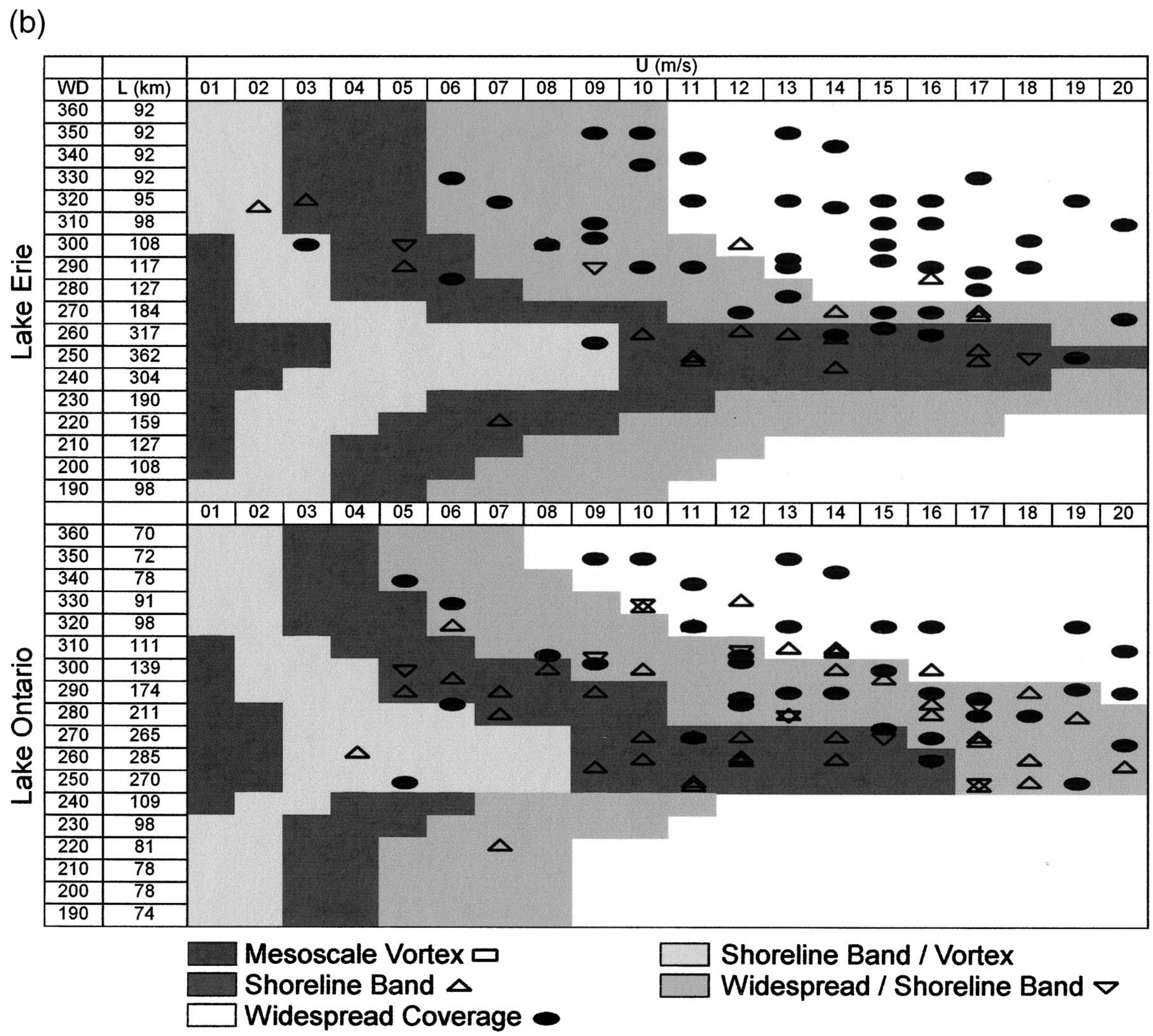

FIG. 3. (*Continued*)

(Laird et al. 2003b) lakes, contain important information related to the mesoscale dynamics of different LE morphologies, but may provide only a limited benefit when being used to predict mesoscale morphology in real LE situations. The *U*/*L* criteria exhibited the greatest probability of detecting LE SB events, but also experienced a relatively large number of false hindcasts of these events. The probability of the *U*/*L* criteria to identify WC events, the most frequently observed in the Great Lakes region, was approximately 56%–62%, with low occurrences of falsely predicting WC events. The results also show that MV and SBWC events have a low probability of being correctly identified by the *U*/*L* criteria. This is likely due to the low frequency of occurrence and enhanced complexity of these mesoscale events.

The examination of the *U*/*L* criteria in this study suggests that *U*/*L* is related to observed LE morphology, although not as directly as previously indicated by idealized model simulations, and could be used to provide a first-order estimate of the LE morphology that would develop for particular LE wind conditions over a specific lake. The results, especially the variability shown in Fig. 2, suggests that a spectrum of LE events within a single morphology exists and that the idealized or ''normal'' LE conditions used by Laird et al. (2003a,b) may not have adequately represented this spectrum with the limited array of nearly 55 model simulations. Despite this limitation, Fig. 3 may prove to be a useful component in providing an indication of the relative intensity of an LE event for specific wind conditions by identifying the likely LE morphology. For example, forecasted LE conditions with a wind direction of 330° and wind speed of 13 m s^{-1} would indicate that SB, SBWC, and WC events are likely to develop over Lakes Superior and Huron, Lake Michigan, and Lakes Erie and Ontario, respectively.

It is generally understood that extensive regions of significant lake ice cover concentrations decrease the upward heat and moisture fluxes from the lake surface, although the relationship has not been quantified. Even

TABLE 3. Evaluation of *U/L* hindcasts with ice coverage for KS95 LE cases. Shown for each LE morphology and lake are number of cases, minimum *U/L*, maximum *U/L*, mean *U/L*, POD, FAR, and bias. POD, FAR, and bias determined using *U/L* criteria from Laird et al. (2003b). Mean values for each morphology are also included (All Lakes). Mesoscale vortex events were not reported by KS95.

Lake-effect morphology	Lake	No. of cases	Min *U/L*	Max *U/L*	Mean *U/L*	POD (L03b)	FAR (L03b)	Bias (L03b)
Shoreline	Superior	15	0.003	0.109	0.044	0.952	0.873	7.523
	Huron	16	0.010	0.070	0.035	0.926	0.734	3.482
	Michigan	20	0.015	0.160	0.044	0.950	0.672	2.900
	Erie	19	0.016	0.143	0.055	0.913	0.533	1.957
	Ontario	43	0.011	0.239	0.074	0.830	0.371	1.321
	All Lakes	113	—	—	0.050	0.914	0.637	3.440
Coexisting shoreline and widespread	Superior	6	0.020	0.081	0.052	0.333	0.952	7.000
	Huron	11	0.019	0.127	0.055	0.364	0.909	4.000
	Michigan	20	0.011	0.133	0.055	0.350	0.860	2.500
	Erie	4	0.046	0.077	0.059	0.500	0.917	6.000
	Ontario	10	0.036	0.110	0.074	0.700	0.848	4.600
	All Lakes	51	—	—	0.059	0.449	0.897	4.820
Widespread	Superior	140	0.008	0.200	0.048	0.274	0.091	0.301
	Huron	71	0.013	0.131	0.062	0.549	0.043	0.573
	Michigan	90	0.015	0.216	0.073	0.536	0.078	0.582
	Erie	52	0.028	0.725	0.133	0.860	0.109	0.947
	Ontario	43	0.019	0.198	0.107	0.868	0.361	1.358
	All Lakes	396	—	—	0.085	0.617	0.136	0.752

under conditions when a solid ice cover forms, vertical heat transfer from the ice–water interface through the overlying ice and snow layers to the atmosphere can occur (Assel 1999). For example, a comparison of the KS95 LE cloud database with GLERL ice charts shows a total of eight winter cases when LE convective clouds (six WC and two SB events) developed over Lake Erie and the underlying surface area of the lake was completely covered with an ice concentration of 95%. Although the results of this investigation showed that accounting for ice cover when using the *U*/*L* criteria only leads to a small improvement of the accuracy of the hindcasts, the impact that different concentrations of lake ice cover have on the modification of LE boundary layer structure, mesoscale morphology, microscale cloud structure, and snowstorm intensity remains an important and challenging unresolved scientific issue and should be quantified for use in mesoscale weather forecast models.

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