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UTILIZING IDEALIZED MESOSCALE MODEL SIMULATIONS TO AID THE PREDICTION OF LAKE-EFFECT SNOWSTORMS

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1. INTRODUCTION

Predicting the development, structure, 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.

The LE storms that frequently result in the greatest impacts are mesoscale 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 several morphologies.

For this study, historically separated classifications of shore-parallel and mid-lake bands are consolidated into a single morphological regime called shoreline bands. Across the range of shoreline band events, over-lake mesoscale low pressure and lower-tropospheric convergence occurs as a result of a linkage and balance between dynamical and surface diabatic forcing. Even though band intensity and position relative to the shoreline may differ depending on the primary forcing, the resulting LE morphology is often a single, coherent shoreline band capable of significant snowfall.

An additional reason for consolidating shore-parallel and mid-lake bands into the shoreline band category was the use of LE cases identified by past studies. Not all previous studies have used the traditional LE classifications or have provided enough information to effectively discriminate between shore-parallel and mid-lake bands. 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.

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 a LE snowstorm. Several investigations have shown that morphology is frequently related to the intensity (e.g., vertical motions, snowfall rate) of a LE mesoscale system. Specifically, Laird et al. (2003a,b) showed that SB events are generally the strongest, WC events often exhibit moderate to weak intensities, and MV events are frequently the weakest.

Despite 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 over-lake fetch (L) to lake-effect snowstorm morphology. Using idealized mesoscale model simulations, Laird et al. (2003a,b) quantified the relationship between U/L and LE morphology. 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).

2. DATA & METHODS

This investigation coalesces information obtained from past observational studies of LE snowstorms in the Great Lakes region with archived data sets to appraise the predictability of LE morphology using the quantity U/L. For consistency with most past studies, an event is defined as a 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 3 events, possibly with different morphology classifications.

Past observational studies of LE snowstorms used satellite and/or radar data, among other data sets, 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),

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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 (1988-1993) 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.

National Weather Service (NWS) 1200 UTC soundings launched at Green Bay, WI (GRB), Sault St. Marie, MI (SSM/Y62), and Buffalo, NY (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 and fetch distance (L). For consistency, the 850 hPa wind speed and direction from NWS soundings were used to determine the ambient wind speed and over-lake fetch distance through the approximate areal center of each lake.

3. RESULTS

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.

Figure 1 presents an overview of the observed LE events and Table 1 provides a detailed comparison of U/L hindcasts of the observed events with the U/L criteria of Laird et al. (2003b). Figure 1a shows the U/L values for each LE event reported in the scientific literature. 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 1b 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 on Fig. 1b) 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 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 value determined from 27 events.

Some useful measures for evaluating the quality of the U/L hindcasts are the probability of detection (POD), false alarm rate (FAR) and bias. The POD is a ratio of the number of correct hindcasts of a 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. 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.

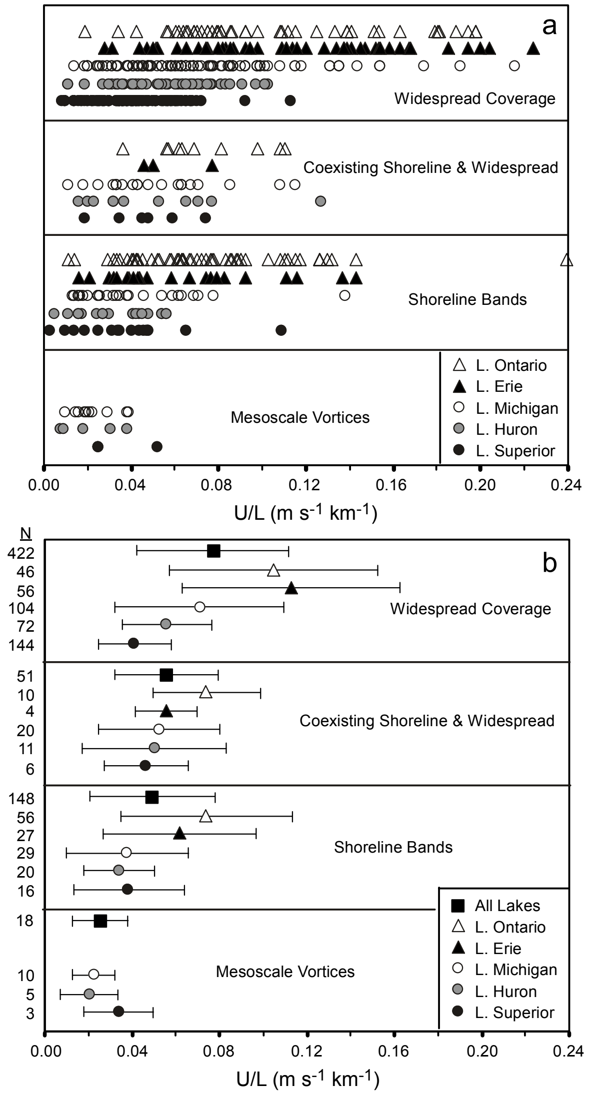

Figure. 1 Individual U/L values (a) and mean and first standard deviation of U/L (b) are shown for 639 LE events reported in the scientific literature with morphologies of MV, SB, WC, and SBWC. N represents the number of events over each lake. See Table 1 for mean values of U/L.

Table 1 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 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 frequent, over the western Great Lakes.

Figure 2 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 (and 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 regions for Lakes 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 readily apparent from the idealized simulations of Laird et al. (2003a).

The U/L criteria for Lakes Michigan, Erie, and Ontario show a larger region for WC 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

Table 1. Evaluation of U/L hindcasts for lake-effect cases from the scientific literature. Shown for each lake-effect morphology and lake are number of cases, minimum U/L, maximum U/L, mean U/L, probability of detection (POD), false alarm rate (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. 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	.0678	2.979
	Erie	27	0.016	0.143	0.062	0.871	.0500	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 & Widespread	Superior	6	0.019	0.074	0.0467	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**

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 1).

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.

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 surface diabatically-forced land-breeze SB events during weak ambient wind conditions (e.g., Passarelli and Braham 1981, Hjelmfelt 1990).

4. SUMMARY

Although mesoscale model simulations have shown the capability of providing detailed forecasts of lake-effect systems (e.g., Ballentine et al. 1998), simpler and 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 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 (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 because of 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. 1, 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 model simulations. Despite this limitation, Fig. 2 may prove to be a useful component in providing an indication of the relative intensity of a 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.

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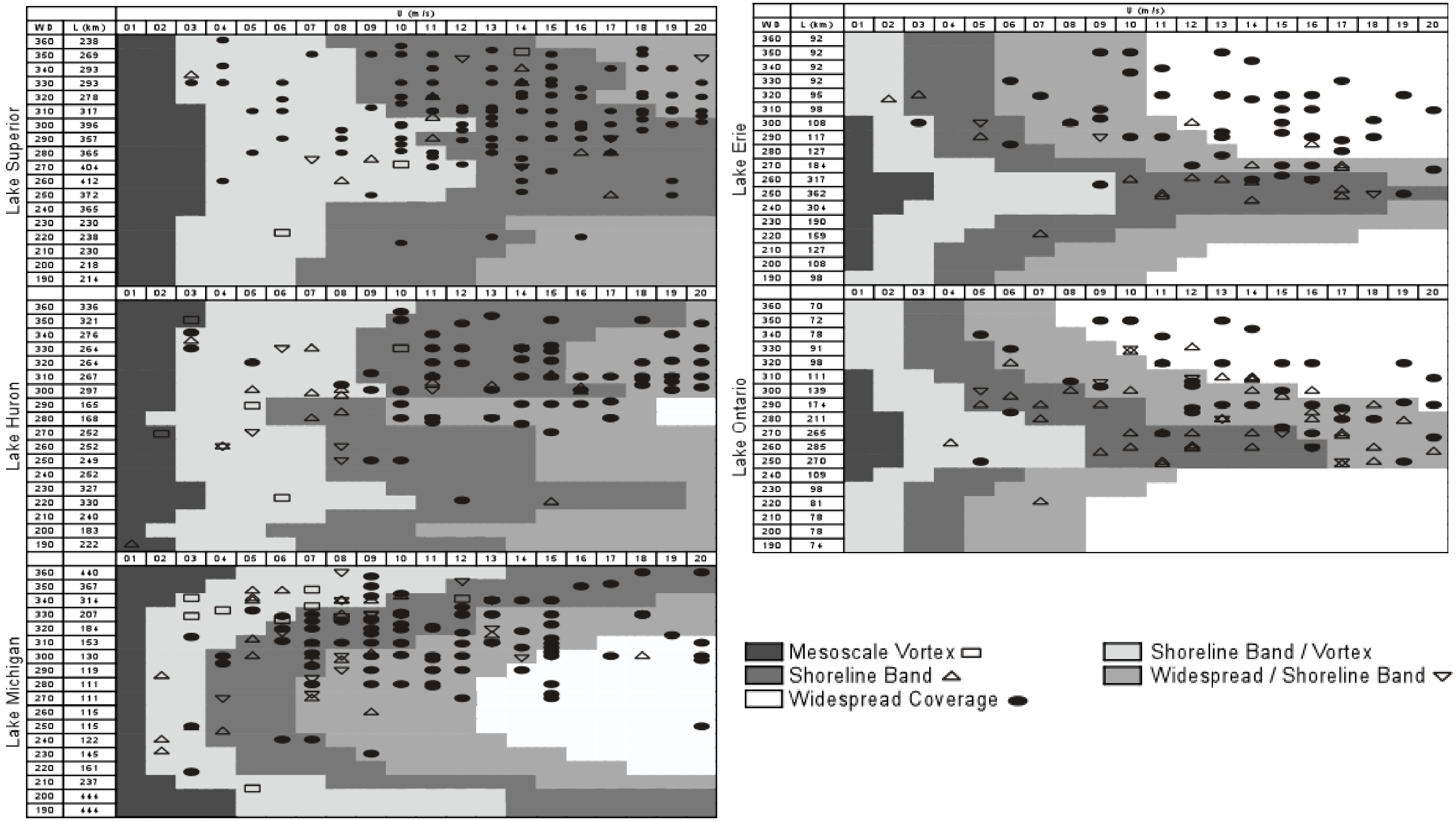

Figure. 2 Morphological regions as a function of maximum fetch (L) and wind speed (U) for each Great Lake. Regions are based on the criteria suggested by Laird et al. (2003b) for mesoscale vortices ($0 < U/L \leq 0.01$ m s^{-1} km^{-1}), coexisting shoreline band and vortex ($0.01 < U/L \leq 0.02$ m 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.

5. REFERENCES

Agee, E. M., and S. R. Gilbert, 1989: An aircraft investigation of mesoscale convection over Lake Michigan during the 10 January 1984 cold air outbreak. *J. Atmos. Sci.*, **46**, 1877-1897.

Ballentine, R. J., 1982: Numerical simulation of land-breeze-induced snowbands along the western shore of Lake Michigan. *Mon. Wea. Rev.*, 110, 1544–1553.

—, A. J. Stamm, E. E. Chermack, G. P. Byrd, and D. Schleede, 1998: Mesoscale model simulation of the 4–5 January 1995 lake-effect snowstorm. *Wea. Forecasting*, **13**, 893–920.

Braham, R. R., Jr., 1983: The Midwest snow storm of 8-11 December 1977. *Mon. Wea. Rev.*, **111**, 253-272.

—, and R. D. Kelly, 1982: Lake-effect snow storms on Lake Michigan, USA. Cloud Dynamics, E. Agee and T. Asai, Eds., D. Reidel, 87-101.

Burrows, W. R., 1991: Objective guidance for 0–24-hour and 24–48-hour mesoscale forecasts of lake-effect snow using CART. *Wea. Forecasting*, **6**, 357–378.

Byrd, G. P., R. A. Anstett, J. E. Heim, and D. M. Usinski, 1991: Mobile sounding observations of lake-effect snowbands in western and central New York. *Mon. Wea. Rev.*, **119**, 2323–2332.

Elsner, J. B., J. R. Mecikalski, and A. A. Tsonis, 1989: A shore-parallel cloud band over Lake Michigan. *Mon. Wea. Rev.*, **117**, 2822-2823.

Ferguson, E. W., 1971: Satellite view of a lake effect snowstorm. *Mon. Wea. Rev.*, **99**, 947-948.

Forbes, G. S., and J. M. Merritt, 1984: Mesoscale vortices over the Great Lakes in wintertime. *Mon. Wea. Rev.*, **112**, 377-381.

Hjelmfelt, M. R., 1990: Numerical study of the influence of environmental conditions on lake-effect snowstorms on Lake Michigan. *Mon. Wea. Rev.*, **118**, 138-150.

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

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

—, 1984: Horizontal roll and boundary-layer interrelationships observed over Lake Michigan. *J. Atmos. Sci.*, **41**, 1816-1826.

Kristovich, D. A. R., 1993: Mean circulations of boundary-layer rolls in lake-effect snow storms. *Bound.-Layer Meteor.*, **63**, 293-315.

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

—, and N. F. Laird, 1998: Observations of widespread lake-effect cloudiness: Influences of lake surface temperature and upwind conditions. *Wea. Forecasting*, **13**, 811-821.

Laird, N. F., 1999: Observation of coexisting mesoscale lake-effect vortices over the western Great Lakes. *Mon. Wea. Rev.*, **127**, 1137–1141.

—, L. J. Miller, and D. A. R. Kristovich, 2001: Synthetic dual-Doppler analysis of a winter mesoscale vortex. *Mon. Wea. Rev.*, **129**, 312-331.

—, D. A. R. Kristovich, and J. E. Walsh, 2003a: Idealized model simulations examining the mesoscale structure of winter lake-effect circulations. *Mon. Wea. Rev.*, **131**, 206–221.

—, J. E. Walsh, and D. A. R. Kristovich, 2003b: Model simulations examining the relationship of lake-effect morphology to lake shape, wind direction, and wind speed. *Mon. Wea. Rev.*, **131**, 2102-2111.

Niziol, T. A., 1982: A record-setting lake effect snowstorm at Buffalo, NY. *Natl. Wea. Dig.*, 7, 19-24.

—, 1987: Operational forecasting of lake effect snowfall in western and central New York. *Wea. Forecasting*, **2**, 310–321.

—, W. R. Snyder, and J. S. Waldstreicher, 1995: Winter weather forecasting throughout the eastern United States. Part IV: lake effect snow. *Wea. Forecasting*, **10**, 61-77.

Passarelli, R. E., Jr., and R. R. Braham, Jr., 1981: The role of the winter land breeze in the formation of Great Lake snow storms. *Bull. Amer. Meteor. Soc.*, **62**, 482-491.

Peace, R. L., and R. B. Sykes, 1966: Mesoscale study of a lake-effect snowstorm. *Mon. Wea. Rev.*, **94**, 495–507.

Pease, S. R., W. A. Lyons, C. S. Keen, and M. R. Hjelmfelt, 1988: Mesoscale spiral vortex embedded within a Lake Michigan snow squall band: High resolution satellite observations and numerical model simulations. *Mon. Wea. Rev.*, **116**, 1374-1380.

Rothrock, H. J., 1969: An aid in forecasting significant lake snows. NWS Tech. Memo WBTM CR-30, NWS Central Region, Kansas City, 12 pp.

Schmidlin, T. W., 1993: Impacts of severe winter weather during December 1989 in the Lake Erie snowbelt. *J. Climate*, **6**, 759-767.

— and J. Kosarik, 1999: A record Ohio snowfall during 9 – 14 November 1996. *Bull. Amer. Meteor. Soc.*, **80**, 1107-1116.

Schoenberger, L. M., 1986a: Mesoscale features of the Michigan land breeze using PAM II temperature data. *Wea. Forecasting*, **1**, 127-135.

—, 1986b: Mesoscale features of a midlake snow band. Preprints, 23rd Conf. on Radar Meteorology, Snowmass, CO, Amer. Meteor. Soc., p. JP206 - JP209.

Sousounis, P. J., G. E. Mann, G. S. Young, R. B. Wagenmaker, B. D. Hoggatt, and W. J. Badini, 1999: Forecasting during the Lake-ICE/SNOWBANDS field experiments. *Wea. Forecasting*, **14**, 955–975.

Sykes, R. B., 1966: The blizzard of 1966 in central New York State—Legend in its time. *Weatherwise*, **19**, 240–247.

Wagenmaker, R. W., J. F. Weaver, and B. Connell, 1997: A satellite and sounding perspective of a sixty-three inch lake effect snow event. *Natl. Wea. Dig.*, **21**, 30–42.

Winstead, N. S., R. M. Schaaf, and P. D. Mourad, 2001: Synthetic aperture radar observations of the surface signatures of cold-season bands over the Great Lakes. *Wea. Forecasting*, **16**, 315-328.