Lake Michigan Lake Breezes: Climatology, Local Forcing, and Synoptic Environment

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ABSTRACT

A method was developed to identify the occurrence of lake-breeze events along the eastern, western, and both shores of Lake Michigan during a 15-yr period (1982–96). Comparison with detailed observations from May through September of 1996–97 showed that the method reasonably identified Lake Michigan lake-breeze events. The method also demonstrated the important ability to distinguish non-lake-breeze events; a problem experienced by previously developed lake-breeze criteria. Analyses of the 15-yr climatological data indicated that lake breezes tended to occur more frequently along the eastern shore of Lake Michigan than along the western shore. On average, a maximum number of lake-breeze events occurred during August at each location. This maximum is most closely associated with weaker monthly average wind speeds. Even though the air–lake temperature difference ΔT provides the local forcing for the development of the lake-breeze circulation, large temperature differences are not required. Nearly 70% of all events occurred with a daytime maximum $\Delta T \leq 12°C$. The evaluation of a lake-breeze index ε used in past studies and many forecasting applications showed indices computed using offshore or shore-perpendicular wind speeds (U or $|U|$, respectively) at inland sites resolved $\geq$95% of identified events based on critical ε values of 2–6. When wind speed, irrespective of wind direction, was used to calculate ε, the success of the critical indices decreased by as much as 26%. Results also showed that the lake-breeze index has a considerable tendency to overestimate the number of events. Although the possibility was suggested by previous investigations, the critical value of ε may not be appreciably affected by changes in location along the shoreline. In addition, noteworthy differences in the position of synoptic-scale sea level pressure and wind fields with respect to Lake Michigan were found to occur during eastern, western, and both-shore lake-breeze events.

1. Introduction

Great Lakes lake-breeze circulations, which occur most often during the spring and summer months, can have large economic, societal, and climatic impacts on coastal regions. The impact of the Great Lakes on regional climate conditions has been investigated using both observations (e.g., Kopec 1967; Scott and Huff 1996) and numerical models (e.g., Bates et al. 1993; Lofgren 1997). Although lake breezes are mesoscale weather phenomena, they can significantly modify the summer climatic conditions in the Great Lakes coastal regions by frequently providing cooler temperatures several tens of kilometers inland from lake shorelines. Scott and Huff (1996) found that the presence of Lake Michigan imposed a net cooling of summer mean temperature as large as 2°C within 80 km of the shoreline. Individual lake-breeze events can also play an instrumental role in providing cool temperatures to relieve metropolitan areas in coastal regions, such as Chicago,

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Illinois, and Milwaukee, Wisconsin, during intense heat waves (Kunkel et al. 1996). Even with a limited inland penetration of only 2–3 km, the lake breeze can reduce the daily maximum temperature for a significant fraction of these urban populations.

To assess the potential impacts of lake breezes on coastal areas during summer, it is necessary to obtain a complete climate description of the frequency of lake-breeze occurrence and to identify the synoptic-scale conditions that are favorable for their development. In addition, the results of this description can be used to examine the monthly and interannual frequency of the thermally forced mesoscale lake-breeze circulation. Our focus is on lake breezes that penetrate inland at least 4 km, thereby affecting more coastal areas. The current study takes advantage of historical surface observations at several locations along the Lake Michigan shoreline to identify past eastern- and western-shore lake-breeze events from 1982–96 for the months of May–September. Previous Lake Michigan lake-breeze climatological studies have relied on high-spatial-resolution surface networks to provide observations during relatively short time periods (i.e., $\leq$6 yr). Lyons (1972) used 307 days during 10 summer months of 1966–68 to determine lake-breeze frequencies for the Chicago, Illinois, and Grand Haven, Michigan, areas. Ryznar and Touma (1981) determined lake-breeze frequencies along the southeastern shore of Lake Michigan for March–November of 1973–78.

Several methods have been developed to forecast and to identify sea breezes and lake breezes. Hall (1954) was perhaps the first to suggest simple forecasting criteria for the lake breeze near Chicago, Illinois. These criteria included the presence of nearly clear sky, light winds, and a center of high pressure in the region. Biggs and Graves (1962) applied dimensional analysis and similarity theory to develop a technique for distinguishing between lake-breeze and non-lake-breeze days along the shore of western Lake Erie. Their ‘‘lake-breeze index’’ is defined as a ratio of the inertial and buoyancy forces, where the inertial force is given by the wind speed and the buoyancy force is given by the difference between the inland-air and lake-surface temperatures. Lyons (1972) later modified their lake-breeze index, using the geostrophic wind speed, to provide a forecasting technique for lake breezes in Chicago, Illinois. Recently, Borne et al. (1998) applied six different filters to meteorological measurements to create a dataset of sea-breeze days along the Swedish west coast.

These previous methods were primarily developed as forecasting tools. They typically overpredict the number of events, are difficult to apply to climatological datasets, and utilize a large suite of data variables, which does not allow for an independent examination of atmospheric conditions that occur during lake-breeze events. We developed a method to identify past occurrences of lake breezes on the eastern and western shores of Lake Michigan. Our approach was designed to distinguish lake-breeze events reliably from climatological surface data using a minimum number of variables. This goal was desirable to allow for an independent examination of the lake-breeze index (Biggs and Graves 1962) and key variables measured during lake-breeze occurrences.

Our lake-breeze method and data used are described in section 2. Results from an analysis comparing outcomes from our lake-breeze method with observed lake-breeze events during the summers of 1996–97 are presented in section 3. The frequency and variability of lake-breeze occurrences on the western, eastern, and both shorelines of Lake Michigan based on 1982–96 data are given in section 4. In section 5, we examine the local forcing parameters (e.g., air–lake temperature difference) measured for lake-breeze events during the 15-yr time period and discuss the utility of a lake-breeze index. The synoptic environments associated with lake-breeze occurrences on the eastern, western, and both shores of Lake Michigan are examined in section 6. A summary of our Lake Michigan lake-breeze results is presented in section 7.

2. Data and method

This investigation used a variety of data sources to examine Lake Michigan lake breezes. Hourly surface observations, visible satellite imagery, and radar data were used to survey 1996–97 lake-breeze events. These observed events were then used to scrutinize the validity of a method developed to identify lake-breeze passages objectively using historical hourly surface data. After the method was used to identify past lake-breeze events from 1982 to 1996, composite synoptic analyses were developed using the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP–NCAR) reanalysis.

a. 1996 and 1997 summer observations

Observed Lake Michigan lake-breeze events along the eastern and western shores during the summers of 1996–97 were used to develop our lake breeze method and to evaluate its validity. Our focus was on lake breezes that had considerable inland penetration because of the ability to identify them using routinely collected observations and their greater impact on larger areas of the coastal region. The database used to identify 1996–97 lake-breeze events consisted of hourly observations at surface stations located in the Lake Michigan coastal region (see locations of open circles in Fig. 1), Geostationary Operational Environmental Satellite (GOES) visible satellite imagery, and National Weather Service (NWS) Weather Surveillance Radar-1988 Doppler (WSR-88D) data. Daily time series of temperature, wind speed, and wind direction were reviewed for each coastal station. The surface station data were examined for several distinct elements associated with the passage of

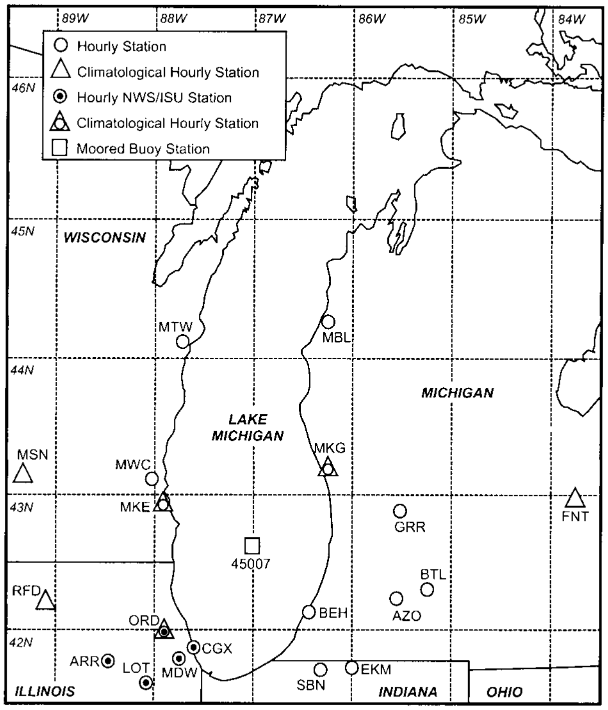


FIG. 1. Map of Lake Michigan region showing the location of NOAA moored buoy 45007 (open square), the six climatological hourly reporting sites (open triangle), surface stations used during 1996–97 for NWS–ISU COMET study (partially filled circle), and hourly surface stations used to determine 1996–97 east, west, and both-shore lake-breeze events (open circle).

a lake breeze. These included (a) a slight fall or general leveling off of temperature after the passage of the lake breeze, (b) an abrupt wind direction change from offshore to onshore at the time of passage, and (c) a short duration or steady increase in wind speed following the lake breeze passage. Each of these characteristics has been well documented for the passage of both lake (e.g., Keen and Lyons 1978; Lyons and Olsson 1973) and sea breezes (e.g., Simpson 1994; Laird et al. 1995). The 1996–97 GOES visible imagery was examined for clearing of cumulus clouds associated with the inland penetration of the lake breeze (e.g., Strong 1972; Purdom 1990; Rabin et al. 1990; Segal et al. 1997). In addition, WSR-88D reflectivity data were examined during numerous events for evidence of an identifiable boundary (i.e., thin line) associated with the lake-breeze front (e.g., Wilson et al. 1994).

A lake-breeze event was designated as having occurred along a particular shoreline when at least three surface stations on one side of Lake Michigan observed the passage of a lake breeze. It was necessary for at least one of the three stations to be located within 5 km of the shore. These criteria and the distance between surface stations limited our observed lake breezes during 1996–97 to events that generally penetrated more than 20 km inland and/or extended along more than 100 km of the shoreline. The GOES visible imagery was then used to confirm lake-breeze events and to determine when a lake breeze was unlikely to have occurred because of the presence of significant overcast conditions. Days having significant overcast conditions associated with a synoptic feature (i.e., low pressure center, frontal boundary) in the region were not included in the 1996–97 observed lake-breeze dataset.

In addition to the satellite, surface, and radar data, information from daily logs of the Chicago, Illinois, lake breeze completed by personnel at the Romeoville, Illinois, NWS Forecast Office were used to supplement the 1996–97 database. The daily lake-breeze logs were completed as part of an NWS and Iowa State University (ISU) Cooperative Program for Operational Meteorology, Education, and Training (COMET) study. These records focused on only the portion of Lake Michigan shoreline in the vicinity of Chicago, Illinois. Both lake breezes that penetrated far inland (e.g., >80 km) and moved onshore but remained near the lake shoreline (e.g., <2 km) were reported. Although lake breezes that remained near the coastline were recorded for Chicago during the summers of 1996–97, they were not included in our observed lake-breeze dataset because of the possible difficulty of identifying the occurrence of near-shore events on climatological timescales with hourly surface stations having low spatial resolution in the Great Lakes coastal regions. For example, because of their proximity to the lakeshore, stations at Milwaukee, Wisconsin (MKE), and Muskegon, Michigan (MKG), may identify lake breezes that penetrate inland at least 4 km. However, coastal stations positioned similar to Chicago O'Hare Airport, Illinois (ORD), can only detect lake breezes that penetrate at least 20–25 km inland.

b. 1982–96 climatological surface observations

The 1982–96 Lake Michigan lake-breeze ''climatology,'' here used to mean a description of frequency of occurrence, was completed using hourly surface observations from three meteorological stations near the lakeshore, three inland stations at a distance greater than 110 km from the shore, and lake surface water temperature measurements from a moored buoy station positioned in south-central Lake Michigan (see Fig. 1). The three shoreline stations include: MKG, located about 4 km from the eastern shore, MKE, about 4 km from the western shore, and ORD, located nearly 22 km from the southwestern shore. These sites were chosen based on their complete long records of observations and their proximity to the Lake Michigan shoreline. The three inland stations included: Rockford, Illinois (RFD; ~105 km inland), Madison, Wisconsin (MSN; ~130 km inland), and Flint, Michigan (FNT; ~190 km from Lake Michigan). These inland stations were chosen for their long records of observations and the lack of lake-breeze influence in their observations. Lake water temperatures used for this investigation were collected at 0.6 m below the surface by the National Oceanographic and Atmospheric Administration (NOAA) No. 45007 moored buoy. The historical buoy data are not available prior to 1981, thereby limiting the duration of our analyses.

c. *Lake-breeze methodology*

Our method to determine the occurrence of a lake breeze was designed to use a minimum set of parameters that would adequately describe properties observed at the surface during the evolution of lake breezes and conditions favorable for their development. Based on methods used during previous investigations (e.g., Ryznar and Touma 1981; Borne et al. 1998), knowledge of lake and sea breezes (e.g., Simpson 1994), and the examination of the 1996–97 Lake Michigan lake-breeze data, the following criteria were used to identify lake-breeze occurrences from 1982 to 1996 at the coastal climatological sites (MKE, ORD, and MKG).

1) A change in average wind direction from offshore or calm conditions in the morning (0500–0700 LST) to onshore during the afternoon (1600–1800 LST). Onshore and offshore flows were defined using a north–south (0°–180°) coastline orientation for MKE and MKG. For ORD, the perpendicular shoreline flow was defined using a coastline orientation of 330°–150°.
2) A positive difference in temperature between the daily maximum at an inland station and the lake surface measured at the same hour, that is, $(\Delta T)_{\max} > 0°\mathrm{C}$.
3) An average air temperature in the morning (0500–0700 LST) lower than during the afternoon (1600–1800 LST).
4) An average wind speed in the morning (0500–0700 LST) less than 5.5 m s^{-1}.

Criteria (1) and (2) were designed to identify the passage of a lake breeze, and criteria (3) and (4) were found to effectively exclude other atmospheric events, such as synoptic fronts, that may have several characteristics similar to lake breezes in hourly collected surface datasets (e.g., surface wind direction change).

Our criteria were applied to hourly surface observations from May through September during 1982–96 to distinguish days when lake breezes occurred along the eastern shore (ES), western shore (WS), and both shores (BS) of Lake Michigan. A lake breeze on both shores was identified when the criteria were simultaneously met for both MKG and MKE. Our approach is somewhat limited in representing all lake breezes that occur along the Lake Michigan shoreline because of the small number of climatological stations available and their distances from the shoreline. For example, some lake breezes remain near the shoreline (i.e., < 4 km inland) and may not be detected at surface observation sites. In addition, the development of a nighttime ES land breeze may cause our criteria to identify a lake breeze for the following day. This would occur when an offshore land breeze develops in a light gradient westerly flow. As the boundary layer reestablishes after sunrise, turbulent mixing would transport westerly momentum downward resulting a wind shift from offshore to onshore. Although this situation does not inhibit the development of a lake breeze, it would tend to enhance slightly our estimates of ES frequencies. Events of these kinds are difficult to identify when examining a single climatological station. Therefore, our method identifies only lake breezes that penetrate inland at least 4 km at MKG and MKE or approximately 22–25 km at ORD during opposing offshore or calm conditions.

d. *Synoptic analyses*

An examination of the synoptic environments associated with lake-breeze occurrences on the ES, WS, and BS of Lake Michigan used daily mean large-scale circulation fields, including sea level pressure and wind, obtained from the NCEP–NCAR reanalysis (Kalnay et al. 1996) for the study period of 1982–96. The surface (10-m height) wind data are provided on T62 ($\sim$1.9° in midlatitudes) resolution, and other fields (e.g., sea level pressure) are on 2.5° latitude by 2.5° longitude grids. For consistency, all fields were mapped into the 2.5° grid mesh.

3. 1996–97 Lake Michigan lake breezes and validity of the lake-breeze method

a. *Summer 1996–97 lake breezes*

A detailed examination of observational data for the summers of 1996–97 provided a catalog of days when a Lake Michigan lake breeze occurred. The development of this lake-breeze catalog was critical to determine the accuracy of our method. Figure 2 shows the average frequency of observed lake-breeze events along the ES, WS, and BS for May–September from 1996 and 1997. On average, ES and WS lake breezes occurred during 35% and 21% of the days, respectively, and BS events occurred on 17% of the days. Of interest, the 1996–97 data show ES lake breezes occurred about 14% more frequently than WS lake breezes. This difference may be accounted for by WS lake breezes that develop and remain stationary within several kilometers of the lakeshore or slightly offshore during time periods with westerly ambient flow (e.g., Strong 1967; Arritt 1993). This would result in very few inland surface sites observing the passage of the lake breeze. To examine this hypothesis, we temporarily included *all* lake breezes observed during the 1996–97 NWS–ISU COMET project irrespective of the inland penetration distance (open squares on Fig. 2). When these days were included, we found the average observed WS lake-breeze frequency increased from 21% to 41%. The frequency of BS events increased to 23% because of an increase of limited inland penetrating WS events that occurred during ob-

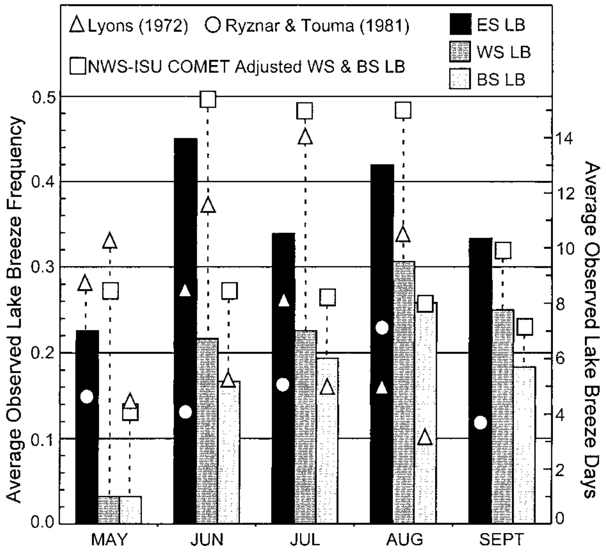
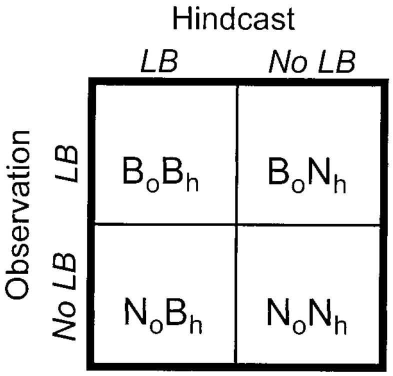


FIG. 2. 1996–97 average observed eastern (ES), western (WS), and both-shore (BS) lake-breeze frequencies and number of events for May–Sep. Also shown are reported lake-breeze frequencies for the ES, WS, and BS from Lyons (1972) (open triangle) and the ES from Ryznar and Touma (1981) (open circle). The open squares represent the 1996–97 WS and BS lake-breeze frequencies adjusted to include reports of near-shore lake breezes from the NWS–ISU COMET study.



		Hindcast	
		LB	No LB
Observation	LB	B_oB_h	B_oN_h
	No LB	N_oB_h	N_oN_h

FIG. 3. A matrix of lake-breeze observations and hindcasts. The variables "B" and "N" refer to an observation that contains a lake breeze (LB) or no LB, respectively, and the subscripts "o" and "h" refer to observations and hindcasts, respectively.

served ES events. These results suggest that WS lake breezes may not penetrate as far inland as ES lake breezes for Lake Michigan and that climatological surface data, particularly for Chicago, may underestimate the occurrence of WS and BS lake breezes.

For comparison, also shown on Fig. 2 are the average monthly lake-breeze frequencies from Lyons (1972) (open triangles) for ES, BS, and Chicago, Illinois, and from Ryznar and Touma (1981) (open circles) for the ES. Both Lyons (1972) and Ryznar and Touma (1981) examined data collected by high-spatial-resolution surface station networks located within 15 km of the Lake Michigan shore. The average frequency of ES lake breezes reported by Ryznar and Touma (1981) (16%) is lower than that determined for 1996–97 and that reported by Lyons (1972). Lyons (1972) showed lake breezes occurred an average of 13% more frequently along the Chicago, Illinois, shore (37%) than along the ES (24%) of Lake Michigan. This is consistent with our findings when the ES and adjusted WS (i.e., including all NWS–ISU COMET observations) lake-breeze frequencies were considered. Because of the limited number of years examined, it is difficult to determine whether the difference between our 1996–97 observed lake-breeze frequencies and those of Lyons (1972) and Ryznar and Touma (1981) are statistically significant or are a result of interannual variability in the number of Lake Michigan lake-breeze events.

b. Validity of lake-breeze method

Table 1 summarizes the results when a lake-breeze or non-lake-breeze event was identified using our method and compared with the observed occurrence of an event on the ES, WS, and BS. For this comparison, hourly surface data from the MKG, MKE, and ORD climatological stations were used. The 1996–97 NWS–ISU data were not included. Some useful measures for evaluating the accuracy of the lake-breeze method can be illustrated concisely if the hindcasts and observations are placed into a matrix as shown in Figure 3, where the variables "B" and "N" refer to an observation that contains a lake breeze (LB) or no LB, respectively, and the subscripts "o" and "h" refer to observations and hindcasts, respectively. Correct hindcasts thus lie in cells B_oB_h (i.e., an LB was identified and it occurred) and N_oN_h (i.e., an LB was not identified and none occurred). Definitions of the measures used to evaluate the accuracy of the method for events when a lake breeze was observed are shown below. These measures were also used to evaluate the accuracy of the method in identifying non-lake-breeze events (see Table 1).

Probability of detection (POD) of lake-breeze events:

$$\text{POD Lake breeze} = \frac{\text{Number of correct hindcasts of LB occurrence}}{\text{Total number of observed LB}} = \frac{B_oB_h}{B_oB_h + B_oN_b}$$

False alarm rate (FAR) of lake-breeze events:

$$\text{FAR Lake breeze} = \frac{\text{Number of incorrect hindcasts of LB occurrence}}{\text{Total number of hindcasts of LB occurrence}} = \frac{N_oB_h}{B_oB_h + N_oB_h}$$

TABLE 1. Values associated with the matrix shown in Fig. 3 and measures used to evaluate the accuracy of the lake-breeze method for different locations during the summers of 1996–97.

	MKG (ES)	MKE (WS)	ORD	MKG–MKE (BS)
B_oB_f	74	46	33	23
B_oN_f	33	17	30	28
N_oB_f	22	33	26	17
N_oN_f	170	204	211	231
POD LB	0.69	0.73	0.52	0.45
POD no LB	0.89	0.86	0.89	0.93
FAR LB	0.23	0.42	0.44	0.43
FAR no LB	0.16	0.08	0.12	0.11
Bias LB	0.90	1.25	0.94	0.78
Bias no LB	1.06	0.93	1.02	1.04

Bias of lake-breeze events:

$$\text{Bias Lake breeze} = \frac{\text{Total number of LB occurrences identified}}{\text{Total number of LB occurrences observed}} = \frac{B_oB_h + N_oB_h}{B_oB_h + B_oN_h}$$

The POD ranges from 0 to 1, where 1 indicates that hindcasts identified every lake breeze. Note that neither correct hindcasts of LB nonoccurrence (i.e., events in cell N_oN_h of Fig. 3) nor incorrect hindcasts of LB occurrence (i.e., N_oB_h) affect the POD. The FAR ranges from 0 to 1, where 0 indicates that incorrect hindcasts of lake breezes were not made, and is unaffected by observations in which no LB is forecast (i.e., B_oN_h and N_oN_h). The bias ranges from 0 to infinity with an ideal value of 1. It is important to note that these measures should not be used separately but must be applied jointly. For example, POD = 1 could be obtained by *always* hindcasting that a lake breeze will occur, while FAR = 0 could be obtained by *never* hindcasting a lake breeze. Likewise, although it is usually desired for the bias to equal unity, the bias alone does not necessarily indicate whether the hindcasts are correct. For example, a bias of 1 could be obtained if all of the identified lake breezes are incorrect (i.e., $B_oB_h = 0$), with $N_oB_h = B_oN_h$.

The POD values for non-lake-breeze events indicate the lake-breeze method was ≥86% accurate for all locations. In addition, FAR and bias values for non-lake-breeze events were ≤0.16 and near unity, respectively. These measures suggest that our method will characterize very few non-lake-breeze events as lake-breeze events, an important issue when developing a climatological database to examine the key parameters of lake breezes. The POD values show that the method distinguished 69%, 73%, 52%, and 45% of observed 1996–97 lake breezes for MKG, MKE, ORD, and BS, respectively. The results for ORD are not surprising, given the inland distance of the station from the Lake Michigan shoreline (∼22 km inland) and our earlier finding that WS lake breezes in the vicinity of Chicago can often be restricted to several kilometers inland of the shoreline. This result is consistent with the statement by Lyons (1972) and Lyons and Olsson (1973) that the Chicago lake breeze penetrates inland >15 km on only about 30%–40% of lake-breeze days. The inland penetration of the Chicago lake-breeze is likely influenced by several factors, such as predominant offshore winds (e.g., Arritt 1993), increased surface roughness due to the urban area, and thermal modification of the boundary layer in response to the urban heat island (e.g., Arya 1988).

Although the lake breeze frequencies at MKG and MKE seem to be underestimated on average by ∼30%, this value was reasonably consistent within the 5-month periods during 1996 and 1997. This suggests that the month-to-month variations present in our estimated frequencies may be representative of the actual seasonal variability of lake-breeze occurrences from May through September. We may expect that atmospheric conditions leading to the occurrence of a lake breeze along the entire Lake Michigan shoreline, BS, could be easily captured by an objective method because of the likely strength of the circulations. However, only 45% of all BS events during 1996–97 were detected using our method, even though 93% of all BS non-lake-breeze events were correctly identified. One explanation may be the failure of identifying an ES or WS lake breeze during BS events because of the constraint of our criteria (a), a change from morning calm or offshore winds to afternoon onshore winds. This situation may occur when the center of high pressure is shifted slightly east or west relative to Lake Michigan resulting in morning onshore flow along one of the shorelines (see section 6).

Comparison with the Lake Michigan 1996–97 observed records has shown that our objective method can reasonably identify lake-breeze events. An examination of the method's validity for identifying lake-breeze events at several climatological stations showed a higher rate of success at MKG and MKE than at ORD or for BS events. The comparison also demonstrates the notable ability of our method to distinguish non-lake-breeze events, a problem experienced by previously developed methods (i.e., Biggs and Graves 1962; Lyons 1972).

4. Lake-breeze climatology

Previous Lake Michigan lake-breeze climatological studies have relied on high-spatial-resolution surface networks to provide observations during relatively short time periods (i.e., ≤6 yr). Our method takes advantage of historical surface observations at several locations along the Lake Michigan shoreline to identify past lake-breeze events from 1982 to 1996. In this section, we use the large set of identified lake-breeze events to pre-

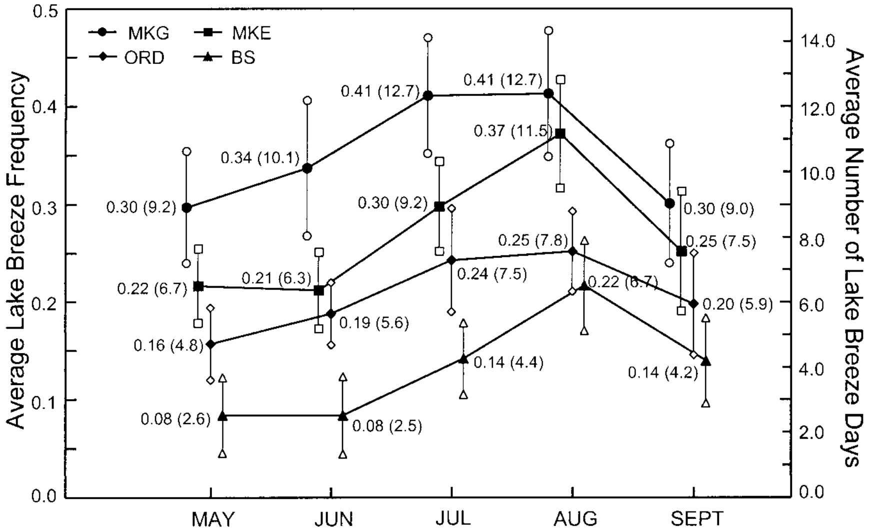


FIG. 4. Average monthly lake-breeze frequency and number of lake-breeze days for 1982–96. Results are shown for Milwaukee, WI (MKE), Muskegon, MI (MKG), Chicago, IL (ORD), and both shore (BS). Open shapes denote 95% confidence interval. Lake-breeze frequency and number of lake-breeze days (in parentheses) are shown for each data point.

sent information pertaining to the monthly and interannual variability of Lake Michigan lake breezes.

a. Monthly frequency

The May–September 15-yr average lake-breeze frequency and 95% confidence interval are shown for MKG, MKE, ORD, and BS of Lake Michigan in Fig. 4. Lake-breeze events tended to occur most frequently at MKG, with fewer lake breezes occurring at MKE and ORD. Figure 4 shows that June and July are the only months when the difference in average frequency is statistically significant between MKE and MKG. When MKE and ORD are compared, the difference is only statistically significant in August. Table 2 shows that, on average, 3.5 more lake-breeze events occur at MKG than MKE during June and July, and the difference is ≤2.5 events for May, August, and September. Although MKG and MKE experience more than nine and six lake-breeze events each month, respectively, only 20%–50% actually occur on the same day and result in a Lake Michigan BS lake-breeze event. This result suggests that environmental conditions favorable for lake breeze development on both shores occur less frequently than conditions necessary for lake breezes on the ES or WS.

In general for each site and BS, there is an increase of about 1.3 days per month in the number of lake-breeze events from May through August, then a 24% to 37% decrease into September. This is consistent with an August maximum in the number of ES lake breezes found by Ryznar and Touma (1981). Interestingly, Lyons (1972) found maxima in May and July for ES and WS lake breezes, respectively. These differences could be indicative of interannual variability in the number of lake-breeze events for a particular month and potential shifts in the timing of the maximum each year for a station.

Some of the monthly variations in lake-breeze occurrence can be understood by examining average monthly wind speeds and the difference between maximum inland-air and lake temperatures—important factors for the development of lake breezes. Figure 5 shows the 1982–96 average monthly lake temperature for buoy 45007 and wind speed, wind direction, and maximum air temperature at MSN, RFD, and FNT for May–September. Based on the average $(\Delta T)_{\max}$ alone, May and June would be expected to have the greatest occurrences of lake breezes, with average temperature differences of nearly 16°C. However, stronger offshore flow for the WS of Lake Michigan in May, June, and September may result in lake-breeze circulations being located offshore or suppressed (e.g., Strong 1967; Lyons 1972; Arritt 1993), and stronger onshore flow for the ES during these months may inhibit the development of lake breezes or produce weak circulations superimposed on the ambient flow (e.g., Estoque 1962; Arritt 1993; Atkins and Wakimoto 1997). Although July and August have $(\Delta T)_{\max}$ values of about 10° and 5.5°C, respectively, the lower average wind speeds are less likely to inhibit the development of lake breezes and their inland penetration. Temperature differences are an important factor for lake-breeze development, but their relation to seasonal lake-breeze frequency is not readily apparent and should be examined further. However, our analysis suggests that seasonal variations in wind speed have a first-order inverse relation to the May–September average lake-breeze frequencies.

TABLE 2. Lake-breeze frequency (Freq), number of lake-breeze events, and days included in analyses for Milwaukee, WI (MKE), Muskegon, MI (MKG), both shores (BS), and Chicago, IL (ORD). Here, CI is confidence interval.

Location and year	May freq	May LB days	May days	Jun freq	Jun LB days	Jun days	Jul freq	Jul LB days	Jul days	Aug freq	Aug LB days	Aug days	Sep freq	Sep LB days	Sep days
MKE															
1982	0.23	7	31	0.20	6	30	0.32	10	31	0.32	10	31	0.30	9	30
1983	0.13	4	31	0.17	5	30	0.52	16	31	0.42	13	31	0.17	5	30
1984	0.23	7	31	0.20	6	30	0.26	8	31	0.58	18	31	0.13	4	30
1985	0.19	6	31	0.20	6	30	0.29	9	31	0.26	8	31	0.13	4	30
1986	0.13	4	31	0.10	3	30	0.26	8	31	0.29	9	31	0.10	3	30
1987	0.10	3	31	0.17	5	30	0.26	8	31	0.23	7	31	0.20	6	30
1988	0.23	7	31	0.17	5	30	0.42	13	31	0.32	10	31	0.17	5	30
1989	0.32	10	31	0.27	8	30	0.36	11	31	0.39	12	31	0.50	15	30
1990	0.19	6	31	0.23	7	30	0.19	6	31	0.39	12	31	0.30	9	30
1991	0.23	7	31	0.30	9	30	0.26	8	31	0.39	12	31	0.30	9	30
1992	0.32	10	31	0.33	10	30	0.26	8	31	0.48	15	31	0.30	9	30
1993	0.23	7	31	0.13	4	30	0.29	9	31	0.52	16	31	0.17	5	30
1994	0.32	10	31	0.33	10	30	0.26	8	31	0.36	11	31	0.30	9	30
1995	0.23	7	31	0.23	7	30	0.32	10	31	0.26	8	31	0.33	10	30
1996	0.18	5	28	0.15	4	27	0.21	6	29	0.39	12	31	0.38	11	29
Average	0.22	6.7		0.21	6.3		0.30	9.2		0.37	11.5		0.25	7.5	
95% CI	0.04	1.2		0.04	1.2		0.05	1.4		0.06	1.7		0.06	1.8	
MKG															
1982	0.32	10	31	0.33	10	30	0.42	13	31	0.42	13	31	0.40	12	30
1983	0.23	7	31	0.53	16	30	0.29	9	31	0.52	16	31	0.33	10	30
1984	0.16	5	31	0.20	6	30	0.39	12	31	0.52	16	31	0.17	5	30
1985	0.23	7	31	0.33	10	30	0.45	14	31	0.29	9	31	0.20	6	30
1986	0.13	4	31	0.37	11	30	0.36	11	31	0.52	16	31	0.20	6	30
1987	0.32	10	31	0.33	10	30	0.45	14	31	0.29	9	31	0.43	13	30
1988	0.39	12	31	0.33	10	30	0.65	20	31	0.19	6	31	0.30	9	30
1989	0.32	10	31	0.47	14	30	0.58	18	31	0.58	18	31	0.40	12	30
1990	0.26	8	31	0.20	6	30	0.39	12	31	0.42	13	31	0.33	10	30
1991	0.29	9	31	0.43	13	30	0.39	12	31	0.32	10	31	0.23	7	30
1992	0.55	17	31	0.43	13	30	0.48	15	31	0.39	12	31	0.23	7	30
1993	0.26	8	31	0.10	3	30	0.26	8	31	0.52	16	31	0.10	3	30
1994	0.42	13	31	0.30	9	30	0.32	10	31	0.36	11	31	0.33	10	30
1995	0.32	10	31	0.50	15	30	0.45	14	31	0.32	10	31	0.50	15	30
1996	0.27	8	30	0.19	5	26	0.29	9	31	0.55	16	29	0.35	10	29
Average	0.30	9.2		0.34	10.1		0.41	12.7		0.41	12.7		0.30	9.0	
95% CI	0.06	1.8		0.07	2.1		0.06	1.8		0.06	2.0		0.06	1.8	
Both															
1982	0.10	3	31	0.07	2	30	0.19	6	31	0.23	7	31	0.17	5	30
1983	0.03	1	31	0.03	1	30	0.16	5	31	0.23	7	31	0.10	3	30
1984	0.03	1	31	0.03	1	30	0.10	3	31	0.29	9	31	0.03	1	30
1985	0.10	3	31	0.07	2	30	0.10	3	31	0.13	4	31	0.10	3	30
1986	0.00	0	31	0.07	2	30	0.07	2	31	0.19	6	31	0.10	3	30
1987	0.03	1	31	0.10	3	30	0.13	4	31	0.10	3	31	0.17	5	30
1988	0.10	3	31	0.03	1	30	0.29	9	31	0.10	3	31	0.07	2	30
1989	0.10	3	31	0.10	3	30	0.23	7	31	0.29	9	31	0.30	9	30
1990	0.07	2	31	0.03	1	30	0.10	3	31	0.29	9	31	0.20	6	30
1991	0.07	2	31	0.23	7	30	0.16	5	31	0.16	5	31	0.10	3	30
1992	0.29	9	31	0.20	6	30	0.19	6	31	0.29	9	31	0.10	3	30
1993	0.03	1	31	0.00	0	30	0.10	3	31	0.29	9	31	0.07	2	30
1994	0.16	5	31	0.17	5	30	0.16	5	31	0.23	7	31	0.13	4	30
1995	0.10	3	31	0.13	4	30	0.13	4	31	0.10	3	31	0.30	9	30
1996	0.07	2	28	0.00	0	26	0.03	1	29	0.35	10	29	0.17	5	29
Average	0.08	2.6		0.08	2.5		0.14	4.4		0.22	6.7		0.14	4.2	
95% CI	0.04	1.2		0.04	1.2		0.04	1.1		0.05	1.4		0.04	1.3	

TABLE 2. (*Continued*)

Location and year	May freq	May LB days	May days	Jun freq	Jun LB days	Jun days	Jul freq	Jul LB days	Jul days	Aug freq	Aug LB days	Aug days	Sep freq	Sep LB days	Sep days
ORD															
1982	0.19	6	31	0.20	6	30	0.23	7	31	0.32	10	31	0.10	3	30
1983	0.10	3	31	0.20	6	30	0.26	8	31	0.39	12	31	0.23	7	30
1984	0.16	5	31	0.17	5	30	0.23	7	31	0.29	9	31	0.20	6	30
1985	0.13	4	31	0.10	3	30	0.19	6	31	0.26	8	31	0.03	1	30
1986	0.10	3	31	0.13	4	30	0.29	9	31	0.26	8	31	0.13	4	30
1987	0.07	2	31	0.20	6	30	0.16	5	31	0.13	4	31	0.20	6	30
1988	0.16	5	31	0.20	6	30	0.42	13	31	0.10	3	31	0.23	7	30
1989	0.32	10	31	0.20	6	30	0.45	14	31	0.29	9	31	0.43	13	30
1990	0.16	5	31	0.13	4	30	0.23	7	31	0.26	8	31	0.17	5	30
1991	0.07	2	31	0.20	6	30	0.32	10	31	0.29	9	31	0.13	4	30
1992	0.23	7	31	0.33	10	30	0.23	7	31	0.29	9	31	0.17	5	30
1993	0.16	5	31	0.20	6	30	0.10	3	31	0.23	7	31	0.27	8	30
1994	0.13	4	31	0.17	5	30	0.16	5	31	0.19	6	31	0.27	8	30
1995	0.19	6	31	0.27	8	30	0.23	7	31	0.19	6	31	0.13	4	30
1996	0.20	5	25	0.13	3	24	0.16	5	31	0.29	9	31	0.28	8	29
Average	0.16	4.8		0.19	5.6		0.24	7.5		0.25	7.8		0.20	5.9	
95% CI	0.04	1.1		0.03	1.0		0.05	1.7		0.04	1.3		0.05	1.6	

b. *Interannual frequency*

A listing of the average monthly lake-breeze frequency for May–September during 1982–96 at MKG, MKE, and ORD and for BS is shown in Table 2. The interannual variability of lake breezes for each station and BS is large during the 15-yr period. For example, MKE and MKG exhibit decreases in August lake-breeze frequency from 0.52 to 0.36 between 1993 and 1994. Figure 6 shows the interannual variability of September lake-breeze frequency. Although the fluctuations at all sites are large, there are extended time periods (e.g., 3–5 yr) when the lake-breeze frequency is noticeably above or below the average values shown in Fig. 6 and Table 2. For example, during 1983–88 (1989–92), MKE experienced an extended time period when the frequency of lake-breeze occurrences was below (above) average. Although not shown, similar extended time periods were observed in other months and are present for MKG, ORD, and BS frequencies. This finding suggests that interannual fluctuations in the frequency of the Lake Michigan lake breeze, a mesoscale circulation, may be responsive to regional-scale atmospheric changes (e.g., winds and air temperature) and their influence on environmental conditions (e.g., lake water temperatures).

5. Local forcing and the lake-breeze index

Observational and modeling investigations have generally described the influence of local atmospheric conditions on the development of lake-breeze circulations during specific events or under idealized atmospheric conditions. In addition, the validity of theoretical and empirical indices derived to forecast the occurrence of Great Lakes lake breezes has typically been examined using short time periods (e.g., one summer) at specific locations. The 15-yr lake-breeze database provides a large set of events that has been used to quantify the typical local atmospheric conditions thought to have the greatest influence on lake-breeze development and to examine the utility of lake-breeze indices (e.g., Biggs and Graves 1962) to predict Lake Michigan lake-breeze events.

a. *Atmospheric conditions important for lake-breeze development*

The parameters examined during each lake-breeze event include: (a) maximum daily air–lake temperature differences determined using data from inland surface stations and NOAA buoy 45007, (b) average daytime (1000–1600 LST) wind speed, (c) average daytime shore-perpendicular wind speed, and (d) total opaque cloud cover. The total opaque cloud cover indicates the amount of celestial dome covered by clouds or obscuring phenomena through which the sky or higher cloud layers could not be seen.

Figure 7a shows that nearly 70% of all lake-breeze events occurred with a $(\Delta T)_{\max} \leq 12°\mathrm{C}$ and that values of $(\Delta T)_{\max} > 20°\mathrm{C}$ were infrequently (~15%) recorded. All of the lake-breeze events with a $(\Delta T)_{\max} > 20°\mathrm{C}$ occurred during May and early June when the average monthly values are still greater than 16°C (see Fig. 5). The finding that large values of $(\Delta T)_{\max}$ are not required for lake breezes is consistent with the modeling results from Segal and Pielke (1985) and Arritt (1987). Arritt (1987) found that, once the water is cold relative to the air above, stable stratification acts to suppress turbulent heat fluxes, insulating the air from the cold water (i.e., the ‘‘coldness’’ is not efficiently conducted up into the air). Thus, beyond a certain $(\Delta T)_{\max}$ the lake breeze is

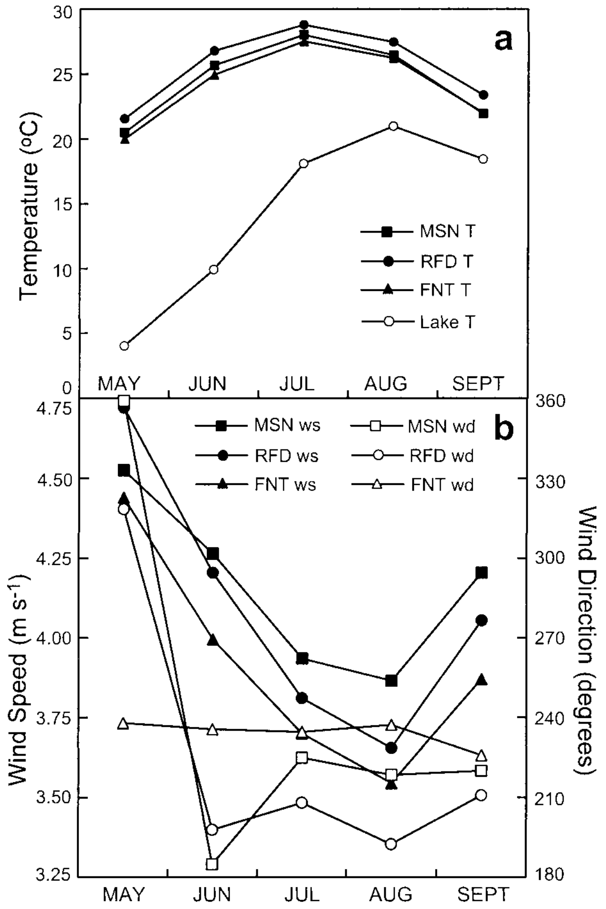


FIG. 5. (a) Average monthly maximum temperature (°C) for Madison, WI (MSN), Rockford, IL (RFD), and Flint, MI (FNT). Also shown is average monthly Lake Michigan surface water temperature measured by NOAA buoy 45007. Average values were determined using data from 1982 to 1996. (b) Average monthly wind speed (m s^{-1}) and direction (degrees from north) for MSN, RFD, and FNT.

nearly insensitive to the water temperature because further cooling of the water does not significantly cool the air temperatures above the lake.

Figures 7b,c show the frequency of the average daytime wind speed and shore-perpendicular wind speed, respectively. During nearly 95% of all lake-breeze events, the average daytime wind speed observed at an inland station was ≤ 5 m s^{-1}. The largest number of events occurred with inland wind speeds of 2–4 m s^{-1}, and nearly 75% of all lake-breeze events occurred during conditions when shore-perpendicular wind speeds were $\leq |2$ m $s^{-1}|$. Using numerical model simulations, Arritt (1993) showed that wind speeds in this regime lead to the most intense sea breezes when the flow was offshore and still allowed sea breezes to develop during events with onshore flow of this magnitude.

The influence of cloud cover was taken into account by Lyons (1972) when refining a lake-breeze prediction method for Chicago, Illinois. He found that the accuracy of his method was increased when it was assumed that no lake breeze would form on days having greater than 40% sunshine reduction from extensive nonconvective middle and high clouds. Figure 8 shows the frequency of total opaque cloud cover observed at MSN and FNT for WS and ES lake breezes, respectively, BS days, and on days when a lake breeze did not occur. The cloud cover was examined during the hour when the maximum daily inland temperature was reported. For lake-breeze days, MSN and FNT generally reported clear sky or partly cloudy conditions. Nearly 70%–80% of the days had cloud cover $\leq 5/10$. As may be expected, there was a lower frequency of clear skies ($\sim 50\% \leq 5/10$) and a higher frequency of overcast conditions ($\sim 30\% \geq 8/10$) on days with no lake breeze.

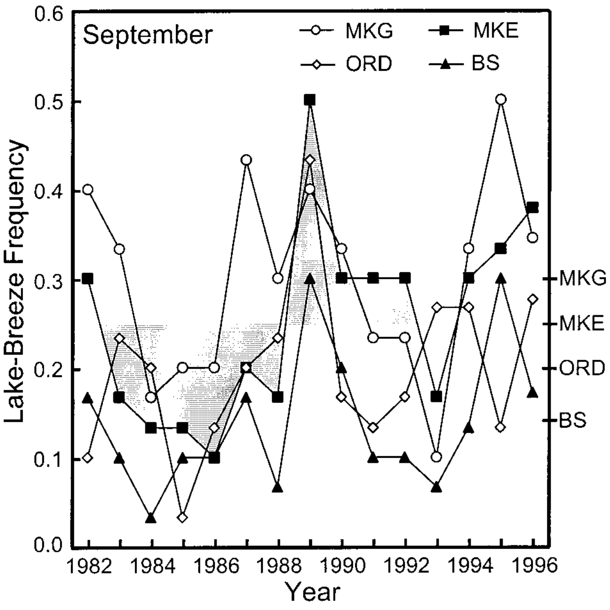


FIG. 6. Sep lake-breeze frequency for Milwaukee, WI (MKE), Muskegon, MI (MKG), Chicago, IL (ORD), and both shores (BS) from 1982 to 1996. The average Sep frequency for each curve is shown on the right vertical axis. Shaded regions represent example of extended time periods when MKE frequency is above or below average.

b. Lake-breeze index

The prediction of a lake breeze for a specific location (e.g., Chicago, Illinois) has garnered much attention, and several simple empirical criteria and forecasting procedures have been developed to address this issue (e.g., Biggs and Graves 1962; Hall 1954). Empirical criteria have often been developed using data from a limited number of years (≤ 3 yr) and their validity has typically been examined using only a small independent data sample (~ 1 yr). Biggs and Graves (1962) and Lyons (1972) used the following empirical relationship to forecast lake-breeze occurrences on the western shores of Lakes Erie and Michigan:

$$\varepsilon = \frac{V^2}{C_p(\Delta T)_{\max}},$$

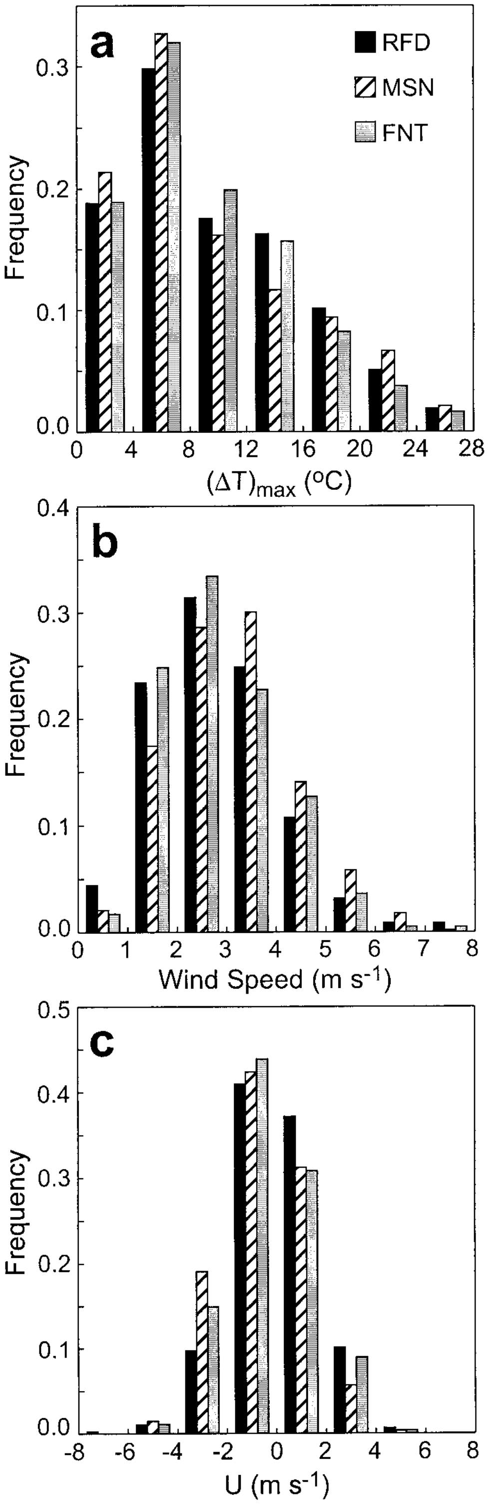


FIG. 7. Observed frequency of (a) maximum air–lake temperature difference $(\Delta T)_{\max}$, (°C), (b) average daytime (1000–1600 LST) wind speed (m s^{-1}), and (c) average daytime shore-perpendicular wind speed U (m s^{-1}) during lake-breeze events for Rockford, IL (RFD), Madison, WI (MSN), and Flint, MI (FNT).

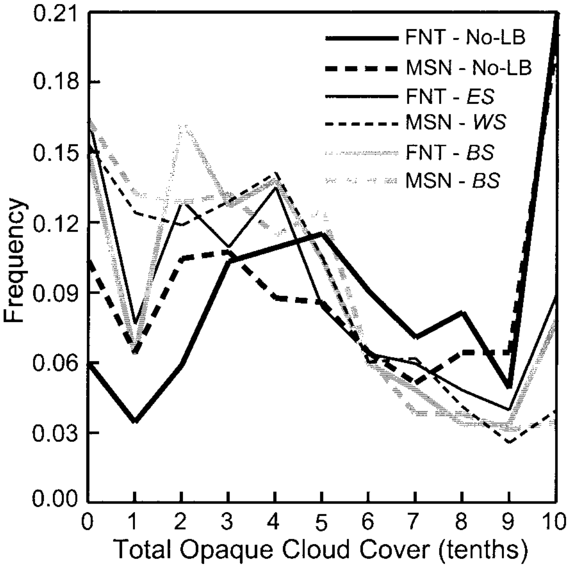


FIG. 8. Frequency of total opaque cloud cover (tenths) for east-shore non-lake-breeze days (FNT-No-LB), west-shore non-lake-breeze days (MSN-No-LB), east-shore lake-breeze days (FNT-ES), and west-shore lake-breeze days (MSN-WS). Also shown is frequency of cloud cover for both-shore (BS) lake-breeze days at Flint, MI, inland from ES (FNT-BS) and Madison, WI, inland from WS (MSN-BS).

where V is the average surface wind speed (m s^{-1}) irrespective of direction at an inland station, $(\Delta T)_{\max}$ is the maximum inland-air and lake surface water temperature difference (K), C_p is the specific heat of dry air at constant pressure (1.003 J K^{-1} gm^{-1}), and ε is an empirically derived constant called the lake-breeze index. We retain the mixture of cgs and SI units in C_p so the index can be compared with prior studies. Biggs and Graves (1962) and Lyons (1972) found that when the index was below the critical values of 3.0 and 10.0, respectively, greater than 90% hindcast accuracy in predicting lake-breeze events was achieved. However, Biggs and Graves (1962) and Lyons (1972) found 65% and 58% of the error, respectively, was associated with the failure of an expected lake breeze to occur, indicating the methods tended to overestimate the number of lake breezes. Even when Lyons (1972) refined the index by including cloud cover information, 36% of the error still remained from overprediction of lake breezes. Lyons (1972) suggested that opaque cloud cover is not necessary to limit the formation of a lake breeze. For this investigation, the data were not available to examine nonopaque cloud information, and our analysis of opaque cloud cover (see Fig. 8) did not suggest a well-defined threshold to identify non-lake-breeze events. Therefore, the definition of the lake-breeze index presented by Biggs and Graves (1962) was used for our analyses.

An examination of the utility of ε for the ES, WS, and southwestern shoreline (i.e., ORD, or Chicago, Illinois) of Lake Michigan using data from the three inland sta-

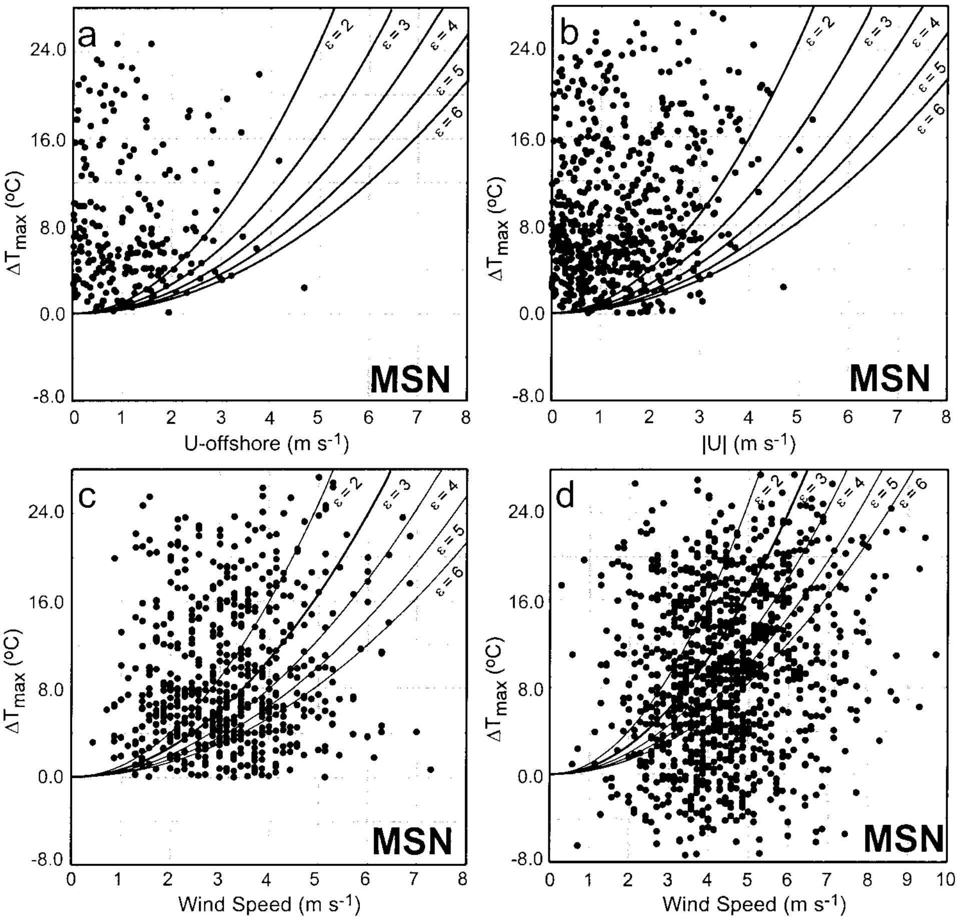


FIG. 9. Lake-breeze index ε calculated using data from Madison, WI (MSN), and NOAA buoy 45007. Index for lake-breeze days was determined using maximum air–lake temperature difference $(\Delta T)_{\max}$ (°C) and (a) shore-perpendicular wind component U during offshore gradient flow (m s^{-1}), (b) $|U|$ for both offshore and onshore gradient flow (m s^{-1}), and (c) wind speed (m s^{-1}). (d) Index for non-lake-breeze days was calculated using $(\Delta T)_{\max}$ (°C) and MSN wind speed (m s^{-1}). Shown on each panel are curves for critical values of $\varepsilon = 2, 3, 4, 5$, and 6.

tions (i.e., MSN, RFD, and FNT) was performed. Figures 9a–d show some of our results when comparing critical lake-breeze indices with data collected at MSN during 1982–96 WS lake-breeze and non-lake-breeze events. Critical values of $\varepsilon = 2, 3, 4, 5$, and 6 were used for comparison with the data. Figures 9a–c show values of ε determined using $(\Delta T)_{\max}$ and the shore-perpendicular wind component U for offshore gradient flow, $|U|$ for both onshore and offshore gradient flow, and wind speed, respectively. If the lake-breeze indices were accurate in their prediction of lake-breeze events, all calculated values of ε would have been located to the left of the critical ε curves shown in Figs. 9a–c. Table 3 shows the percentage of events that are constrained by different critical

TABLE 3. Percentage of 1982–96 lake-breeze events identified using critical values of lake-breeze index ε. Calculated values of ε for Madison, WI (MSN), using U, $|U|$, and wind speed. Also shown is percentage of non-lake-breeze days identified as lake-breeze events for 1982–96. The $|U|$ results for Rockford, IL (RFD), and Flint MI (FNT), are shown.

Critical lake-breeze index ε	MSN ε U offshore wind speed (%)	MSN ε $\lvert U\rvert$ shore-perpendicular wind speed (%)	MSN ε total wind speed (%)	MSN ε $\lvert U\rvert$ non-lake-breeze (%)	RFD ε $\lvert U\rvert$ shore-perpendicular wind speed (%)	FNT ε $\lvert U\rvert$ shore-perpendicular wind speed (%)
2	95	95	69	44	95	93
3	99	97	80	60	97	96
4	99	97	86	68	98	97
5	99	98	90	73	98	98
6	99	98	91	75	99	98

values of ε. When using either U or $|U|$ to calculate ε, 95% of WS lake-breeze events were resolved based on a critical ε value of 2. However, when wind speed, irrespective of wind direction, was used to calculate ε, the success of the indices noticeably decreased. For example, a decrease of 26% was experienced for a critical value of $\varepsilon = 2$, and a reduction of about 18% resulted for a threshold of $\varepsilon = 3$.

Figure 9d shows ε calculated from $(\Delta T)_{\max}$ and wind speed for non-lake-breeze events. This figure clearly demonstrates the finding by previous studies that the lake-breeze index has a considerable tendency to overestimate the number of lake-breeze events. Table 3 shows that 60% of non-lake-breeze events were characterized as lake-breeze days for $\varepsilon = 3$, the critical value determined by Biggs and Graves (1962). Although our lake-breeze method described in section 2 partially contributed to this error by underestimating the number of lake-breeze events from 1982–96 and placing them in the non-lake-breeze category, Biggs and Graves (1962) showed that both frontal passages and days with onshore gradient flow may be distinguished as lake-breeze events for $\varepsilon = 3$. Based on our analyses of ε values calculated using wind speed, a critical threshold of $\varepsilon = 3$ would tend to underestimate the actual number of lake-breeze events by about 20% and to identify nearly 60% of non-lake-breeze days as lake breezes. Similar results (not shown) were found when data from RFD and FNT, the two other inland sites, were examined and compared with critical values of lake-breeze indices.

Biggs and Graves (1962) and Lyons (1972) stated that the critical value of their lake-breeze index would likely need to be modified for different locations, thus making the index problematic when conducting regional lake-breeze investigations. However, Walsh (1974) showed that a theoretically derived criterion to distinguish lake-breeze from non-lake-breeze events agreed with the criterion ($\varepsilon = 3.0$) of Biggs and Graves (1962) to within 1°C when $(\Delta T)_{\max}$ was estimated for $|U| \leq 10$ m s^{-1}. This finding provided theoretical support for the observed linear empirical relationship between V^2 and the critical $(\Delta T)_{\max}$. The approaches used by Biggs and Graves (1962) and Walsh (1974) suggest that there is no physical basis for variations in the critical value of ε at different locations except due to changes in topography or coastline shape. The data from three inland sites were compared to investigate the likely significance that changes in location (i.e., topography and coastline shape) may have on the critical value of the lake-breeze index. Figure 10 shows ε determined using observed $(\Delta T)_{\max}$ and $|U|$ for MSN, RFD, and FNT. The relationships developed using critical values of ε from 2 to 6 correctly identify nearly the same percentage of lake-breeze events irrespective of location (see Table 3). This confirms the theoretical finding of Walsh (1974) and demonstrates that ε may not be significantly affected by changes in location as suggested by both Biggs and Graves (1962) and Lyons (1972). Although this result

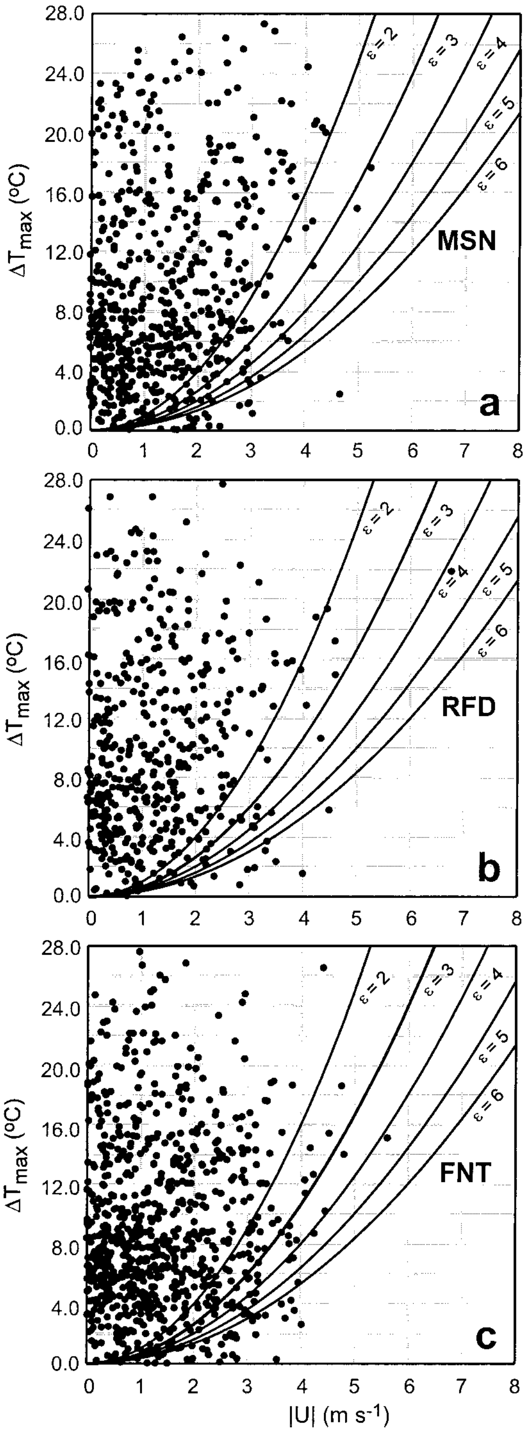


FIG. 10. Lake-breeze indices ε calculated using data from (a) Madison, WI (MSN), (b) Rockford, IL (RFD), (c) Flint, MI (FNT), and NOAA buoy 45007. Values of index were calculated from maximum air–lake temperature difference $(\Delta T)_{\max}$ (°C) and shore-perpendicular wind component $|U|$ for both offshore and onshore gradient flow (m s^{-1}). Shown on each panel are curves for critical values of $\varepsilon = 2$, 3, 4, 5, and 6.

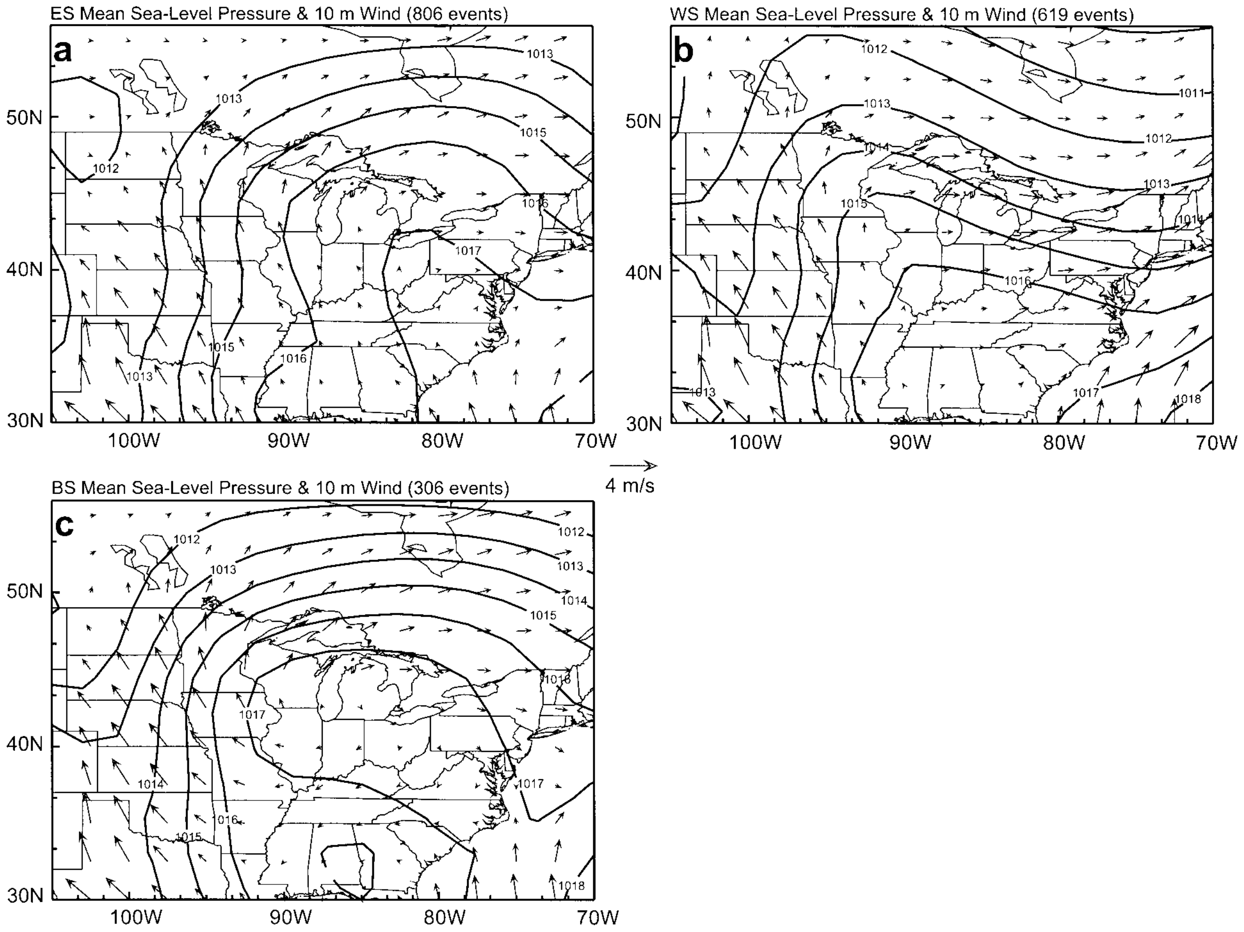


FIG. 11. Mean sea level pressure (hPa) and 10-m wind fields for 1982–96 (a) east-shore (ES), (b) west-shore (WS), and (c) both-shores (BS) lake-breeze events. Length for 4 m s^{-1} wind vector is shown. Also shown in parentheses are number of days used to establish the mean fields.

is encouraging, further examination of ε for other locations in the Great Lakes (e.g., Cleveland, Ohio; Gary, Indiana) and smaller lakes (e.g., Lake St. Clair, Lake Champlain) is necessary to corroborate this finding.

6. Synoptic environment

The relationship between synoptic-scale conditions (e.g., sea level pressure field) and Great Lakes mesoscale lake-breeze circulations has not received much attention despite its importance to summer weather (e.g., King 1996) and air pollution episodes (e.g., Lyons et al. 1995; Dye et al. 1995; Hastie et al. 1999) in the region. Hall (1954) was among the first to describe the relationship between synoptic-scale conditions and the development of a Lake Michigan lake breeze. He showed that an area of high pressure with its center or ridge line near the southwestern shoreline of Lake Michigan was a favorable sea level pressure pattern for the development of a Chicago, Illinois, lake breeze. Additionally important to the development of a lake breeze is the existence of a lake-scale (i.e., mesoscale) region of high pressure. With daytime Great Lakes surface waters typically colder than the overlying air during May–September (see Fig. 5), a mesoscale region of high pressure over Lake Michigan has been shown to occur (e.g., Strong 1972). Data to examine the characteristics of the likely mesoscale high pressure region in the vicinity of Lake Michigan was not available for this investigation. The analyses and discussion in this section present several "typical" synoptic-scale fields associated with Lake Michigan lake breezes.

Figures 11a–c show composite sea level pressure and wind fields that occur over the eastern United States during ES, WS, and BS lake-breeze events. The ES, WS, and BS composite synoptic fields are based on conditions during 806, 619, and 306 lake-breeze events from 1982 through 1996, respectively. The composite fields in Fig. 11a suggest that an ES lake breeze is likely to occur during time periods with a ridge of high pressure oriented in a northwest direction across eastern Ohio and Michigan (<300 km to the east of Lake Michigan) and weak (<2 m s^{-1}) southeasterly surface winds. The synoptic conditions favorable for a WS lake breeze are similar to those described by Hall (1954) and are shown in Fig. 11b with a ridge of high pressure located over Illinois, Iowa, Wisconsin, and Minnesota, resulting in weak (≤ 2 m s^{-1}) westerly winds across Lake Michigan. Based on our composite fields in Fig. 11c, simultaneous lake breezes along the ES and WS of Lake Michigan occur when a region of high pressure is centered over the lake, leading to nearly calm wind conditions throughout the region. Each of these synoptic environments allows lake breezes to develop and to penetrate inland under weak offshore flow or calm conditions.

7. Summary and conclusions

A method was developed in the current study to identify the occurrence of lake-breeze events along the eastern, western, and both shores of Lake Michigan during a 15-yr period (1982–96). The method utilized known characteristic properties observed at the surface associated with lake- or sea breezes. When compared with Lake Michigan lake-breeze observations from May through September of 1996–97, the method was found to identify lake-breeze events reasonably. A higher rate of success was found for MKG and MKE than at ORD or for BS events. In addition, our method has the added ability to distinguish non-lake-breeze events, a problem experienced by previously developed lake-breeze criteria (i.e., Biggs and Graves 1962; Lyons 1972).

The 15-yr climatological analyses indicated that lake breezes tended to occur more frequently along the eastern shore of Lake Michigan than along the western shore. In addition, there was a gradual increase in the number of lake-breeze events from May through August, then a slight decrease into September. This trend seems to be most closely associated with the change in average surface wind speeds in the region during the 5-month period, with the largest number of lake breezes occurring during the weakest wind period of August. Examination of the interannual variability suggests that fluctuations in the frequency of the Lake Michigan lake breeze, a mesoscale circulation, may be responsive to regional-scale atmospheric changes.

The average daytime wind speed observed at an inland station was ≤ 5 m s^{-1} during nearly 95% of all lake-breeze events. The largest number of events occurred with inland wind speeds of 2–4 m s^{-1}, and nearly 75% of all lake-breeze events occurred during conditions when shore-perpendicular wind speeds were $\leq |2$ m s$^{-1}|$. Although the air–lake temperature difference provides the local forcing for the development of the lake-breeze circulation, large temperature differences are not required and do not alone enhance the frequency of lake breezes.

Several variations of a lake-breeze index ε (e.g., Biggs and Graves 1962) were evaluated using identified lake-breeze events from 1982 to 1996. Indices computed using U or $|U|$ were found to provide the best prediction of lake-breeze events. The different values of ε calculated using either U or $|U|$ resolved $\geq$95% of identified lake-breeze events based on critical ε values of 2–6. When wind speed, irrespective of wind direction, was used to calculate ε, the success of the critical indices was reduced. Our finding confirms those by previous studies that showed the lake-breeze index has a significant tendency to overestimate the number of lake-breeze events. Based on our analyses of values calculated using wind speed, a critical threshold of $\varepsilon = 3$ would tend to underestimate the actual number of lake-breeze events by about 20% and identify nearly 60% of non-lake-breeze days as lake breezes. Additional results confirm the theoretical finding of Walsh (1974) and demonstrate that ε may not be significantly affected by changes in location as suggested by both Biggs and Graves (1962) and Lyons (1972).

Synoptic-scale composite fields show the ES lake breeze is likely to occur during time periods with a ridge of high pressure oriented northwestward across eastern Ohio and Michigan and weak southeasterly surface winds. Also, WS lake breezes tend to occur when a ridge of high pressure is located west of Lake Michigan, resulting in westerly winds of ≤ 2 m s^{-1} across the lake. Simultaneous lake breezes along the ES and WS of Lake Michigan occur when a region of high pressure is centered over the lake, leading to nearly calm wind conditions throughout the region.

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