NOTES AND CORRESPONDENCE

Diurnal Variations in Lake-Effect Precipitation near the Western Great Lakes

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ABSTRACT

Lake-effect snowstorms are important parts of the climate of the U.S. Upper Midwest, with significant economic and societal impacts on communities close to the Great Lakes. Some impacts, particularly those on air and ground transportation, depend critically on the time of day that lake-effect precipitation occurs. This study utilizes hourly precipitation data collected near Lakes Superior and Michigan to determine the diurnal behavior of lake-effect precipitation frequency. Precipitation data from approximately 200 lake-effect days during 1988–93, identified by a previous study based on visible satellite data, are examined. A distinct morning maximum and afternoon/evening minimum in lake-effect precipitation frequency was observed, with the largest variations at sites within the snowbelt regions. The relative importance of several factors known to influence lake-effect precipitation development was examined to gain insight into the physical mechanisms controlling the diurnal evolution of lake-effect precipitation.

1. Introduction

The Great Lakes have important impacts on the regional climate system of the Upper Midwestern United States. Modification of cold-season air masses by the lakes results in warmer temperatures, altered wind patterns, increased cloudiness and, in some locations, a substantial increase in wintertime snowfall (e.g., Eichenlaub 1979; Braham and Dungey 1984; Scott and Huff 1996). The majority of these climatological modifications occur during short periods of intense positive surface heat fluxes (Laird and Kristovich 2002), often resulting in significant lake-effect snowstorms (Niziol et al. 1995). Previous studies have noted important economic and societal impacts derived from such storms (i.e., Schmidlin et al. 1992; Schmidlin 1993; Schmidlin and Kosarik 1999; Kunkel et al. 2002). Impacts with negative implications include building and vegetation damage, power outages, injuries, and disruptions of air and ground transportation. The magnitude of impacts on transportation and snow removal procedures, in particular, depends critically on the time of day during which lake-effect snow occurs. Few investigations have been conducted quantifying the diurnal evolution of lake-effect snowstorms.

This study seeks to determine the diurnal behavior of lake-effect precipitation occurrence near Lakes Superior and Michigan through analysis of observations taken during approximately 200 lake-effect days. These lake-effect days, identified by Kristovich and Steve (1995) utilizing visible satellite observations, occurred over a 5-yr time period. Hourly precipitation observations at nine sites are used to determine the diurnal evolution of lake-effect precipitation occurrence. Additional weather observations at three of these sites are used to evaluate several factors previously shown to be important to lake-effect development.

2. Background

While much is known about the physical processes leading to lake-effect precipitation, few studies in the scientific literature have reported on the diurnal evolution of such storms. Passarelli and Braham (1981), for example, postulated that snowfall rates during Lake Michigan lake-effect storms would be greater in the early-morning hours because of climatologically larger lake–air temperature differences at that time. Indeed, several case studies of lake-effect snowbands associated with land breezes found that the bands developed in the near-dawn hours (e.g., Schoenberger 1986; Grim et al. 2004). However, these studies cannot be generalized to all lake-effect situations, particularly since a majority of lake-effect storms on the Great Lakes are not associated with land breezes (Kristovich and Steve 1995).

Two recent studies sought to determine the diurnal

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evolution of precipitation rate in the Great Lakes region. Ruhf and Cutrim (2003) examined hourly precipitation observations at a site 55 km east of Lake Michigan over a 20-yr time period. During the winter months (December through February), they found a peak in precipitation accumulation near 0600 eastern standard time (EST) and a secondary peak in the evening hours. The absence of a near-dawn peak during summer months as well as the concurrent climatological maximum in lake–air temperature difference led them to conclude that lake-effect processes were responsible for the morning precipitation maximum. An alternative result was reported by Miner and Fritsch (1997), who examined the diurnal evolution of autumn lake-effect rain events near Lake Erie. Radar and surface observations indicated that lake-effect precipitation was more intense during the afternoon and early-evening hours. Miner and Fritsch (1997) hypothesized that destabilization of the overland air mass upwind of the lake through afternoon radiational heating may have contributed to over-lake precipitation development. The present study seeks to determine the diurnal variation of lake-effect precipitation occurrence by examination of 221 lake-effect days near Lake Superior and 199 lake-effect days near Lake Michigan.

3. Data and methods

Nine sites in the National Oceanic and Atmospheric Administration (NOAA) Cooperative Observation Network were chosen to determine the diurnal evolution of precipitation occurring on lake-effect days (Figs. 1 and 2). Six sites east of Lake Michigan and one south of Lake Superior are within regions typically affected by lake-effect snows ("snowbelt" locations; e.g., Eichenlaub 1979; Braham and Dungey 1984; Scott and Huff 1996). This study utilizes observations from multiple sites to account for the spatial and temporal variability in the location of individual lake-effect storms. For comparison, two additional sites were chosen in regions typically upwind of Lake Michigan. Note that all times in the present study have been converted to EST.

Precipitation observations were collected using Universal weighing bucket gauges at Marquette, Grand Rapids, and Muskegon, Michigan, and Milwaukee, Wisconsin (Fig. 1), and Fischer–Porter recording rain gauges elsewhere (Fig. 2). Observations from both types of instruments were recorded hourly and have undergone the standard data quality checks for the National Climatic Data Center (NCDC) DSI-3240 dataset (NCDC 2003a). All sites included in the dataset within 50 km of the lakes' shores, and with less than 20% missing data in the months of interest, were used. At some locations using Fischer–Porter gauges, precipitation accumulations over periods of more than 1 h were reported. All such cases were removed from the lake-effect precipitation analyses. Finally, the diurnal evolution of non-lake-effect precipitation occurrence was examined to determine if there were inconsistencies or data reporting errors. Precipitation on non-lake-effect days lacked a systematic diurnal pattern, yet still exhibited similar precipitation frequencies between sites using the same types of observational equipment.

It should be noted that about 70% of the precipitation observations on lake-effect days were at minimum detectable values. Much of the lake-effect precipitation during these months falls as light snow, which is typically underestimated (Goodison et al. 1981; Doesken and Judson 1996). Sites using Fischer–Porter gauges (with minimum detectable precipitation amounts of 2.5 mm) recorded fewer precipitation observations than those using Universal weighing buckets (0.25-mm minimum detectable amounts). Plots of precipitation frequency are shown in this note rather than precipitation amount, since mean or total precipitation amounts are strongly influenced by infrequent, intense events. Analyses of precipitation amount and frequency showed very similar diurnal variations.

To determine the diurnal evolution of lake-effect precipitation occurrence, it is necessary to differentiate lake-effect days from those with precipitation caused by other processes (such as frontal convergence or isentropic lift). For this purpose, we utilize the classifications developed by Kristovich and Steve (1995) based on daytime visible satellite imagery over five cold seasons (defined as September–March 1988–93) to identify dates with distinctive lake-effect cloud patterns. They classified cloud patterns as lake effect if "the clouds appeared to originate over a lake, at least one upwind shore was visible, and the clouds were of the same size scale as the lake." For this study, days classified as lake effect, regardless of convective organization, were examined. As an independent check to validate this classification for Lakes Superior and Michigan, surface observations were compared between lake-effect and non-lake-effect days. It was found that mean temperatures were 5.0°C colder and wind speeds 1.0 m s^{-1} stronger on lake-effect days than on non-lake-effect days. Conditions on these lake-effect days would therefore be more conducive for the upward heat and moisture transport from the lake surfaces essential to lake-effect development.

It is important to note that a lake-effect day, for purposes of this study, is defined as a 24-h period (midnight to midnight EST) during which cloud patterns seen in visible satellite imagery were classified by Kristovich and Steve (1995) as having only lake-effect signatures. Since visible satellite images were used, overnight changes in the organization of clouds could not be detected. For example, if lake-effect clouds only occurred during nighttime hours, that day would not have been classified as a lake-effect day.

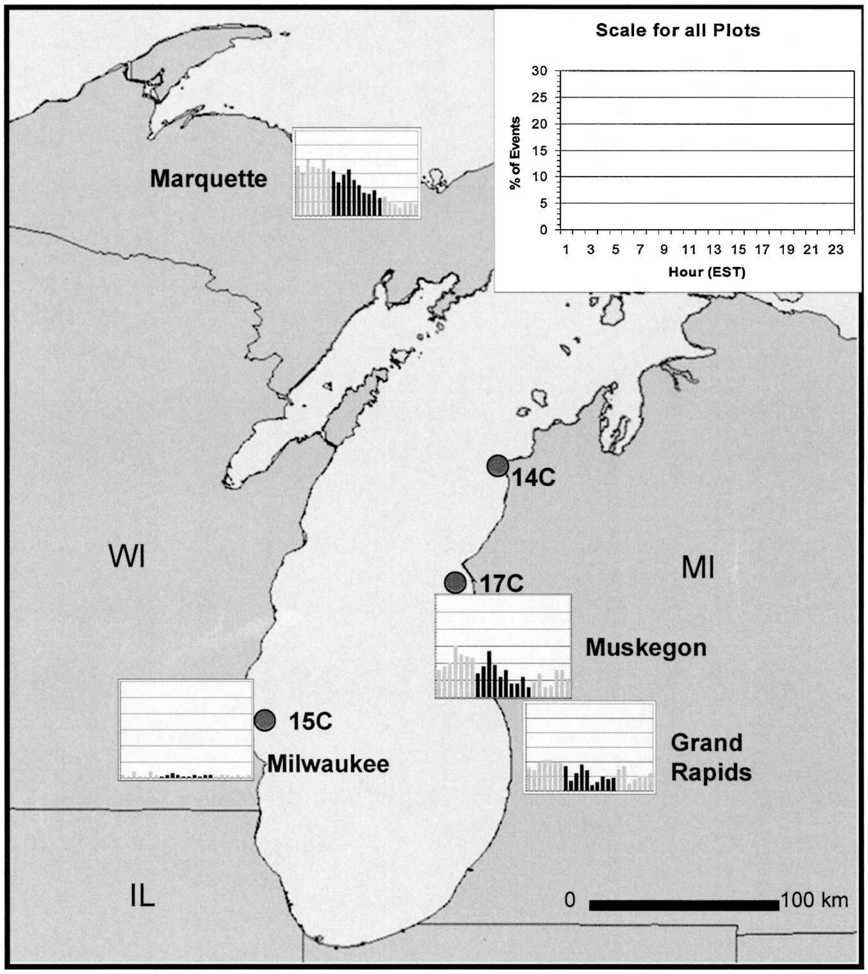

FIG. 1. The frequency of precipitation by hour on lake-effect days from Oct–Mar during the years 1988–93 at several Great Lakes stations utilizing Universal weighing bucket gauges. The hour of the day in EST is along the abscissa, and the percentage of measurable precipitation days occurring during that hour is along the ordinate. Black frequency bars represent approximate daylight hours from which Kristovich and Steve (1995) classified cloud patterns over the Great Lakes. Locations of U.S. Coast Guard stations 14C, 15C, and 17C are indicated.

4. Diurnal variation in lake-effect precipitation

Figures 1 and 2 show the percent of lake-effect days during 1988–93 when precipitation was observed for each hour. Daytime hours, when visible satellite data were available for the classification of lake-effect cloud patterns by Kristovich and Steve (1995), are highlighted as black columns on each graph. These hours can most reliably be attributed to lake-effect processes. The further in time from the period of visible satellite data availability, the greater the probability that different processes influenced precipitation occurrence.

As expected, Figs. 1 and 2 show that precipitation frequency on lake-effect days was highest at locations east of Lake Michigan and south of Lake Superior. Sites with highest mean precipitation frequencies were within regions with greatest mean annual snowfall amounts (Eichenlaub 1979; Scott and Huff 1996).

At all locations within the snowbelt regions (south of Lake Superior and east of Lake Michigan), precipitation occurrence exhibited a distinct diurnal pattern. Maxima precipitation frequencies generally occurred between about 0300 and 1000 EST. Times of minima precipitation frequencies were quite variable from site to site, but tended to occur after 1500 EST. Note that the overall tendency for decreasing precipitation frequency from morning to afternoon is evident whether examining only the daylight hours (black bars) or all hours. The difference in precipitation frequency between the maxima and minima varied greatly from station to station. Sites within the lake-effect snowbelts

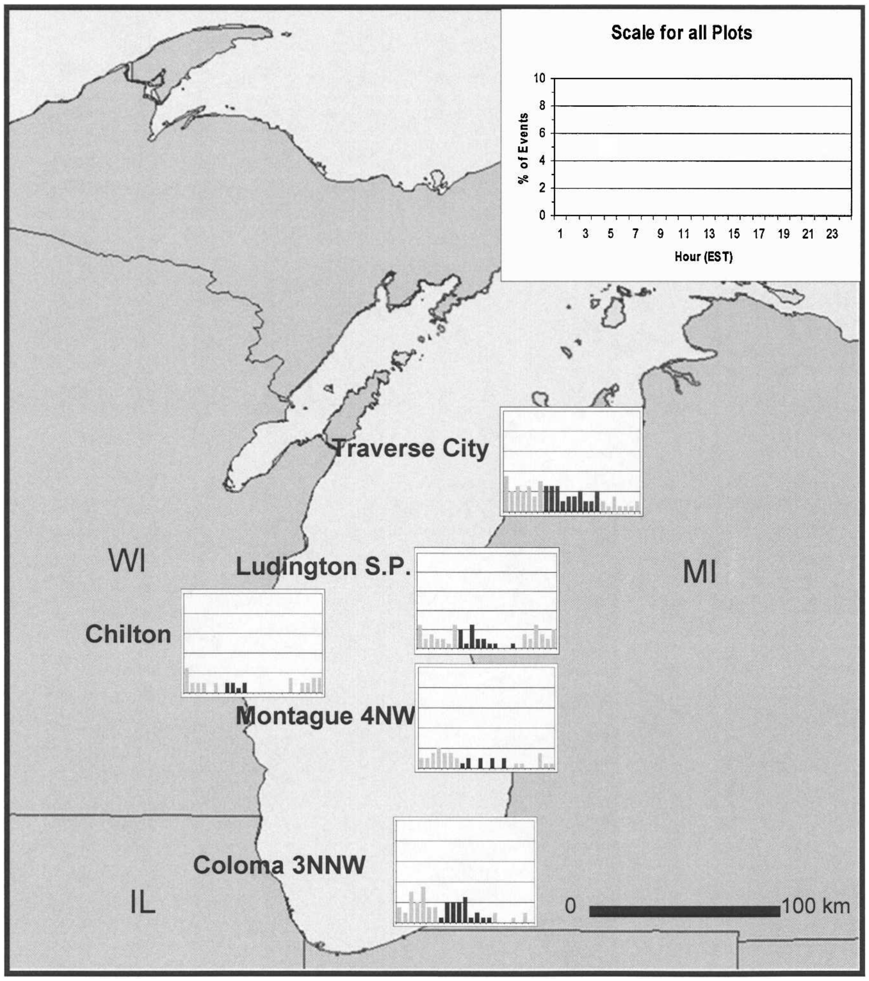

FIG. 2. Same as Fig. 1, except for sites utilizing Fischer–Porter recording rain gauges.

exhibited much larger diurnal variations than those outside of the snowbelts.

For comparison, diurnal variations in precipitation frequency for both lake-effect and non-lake-effect days at two sites (upwind and downwind of Lake Michigan) are shown in Fig. 3. Lake-effect precipitation is relatively rare west of Lake Michigan. As a consequence, precipitation on non-lake-effect days at Milwaukee, Wisconsin, occurred considerably more often than on lake-effect days. Conversely, at Muskegon, Michigan, near the eastern shore of Lake Michigan, morning precipitation on lake-effect days occurred nearly as frequently as on non-lake-effect days. There was little systematic diurnal variation in precipitation occurrence on non-lake-effect days at either site. Therefore, the morning peak in precipitation occurrence seen for lake-effect days is interpreted as due to local processes not active during non-lake-effect days. This result is consistent with the findings of Ruhf and Cutrim (2003) that the observed morning peak in precipitation at the snowbelt site they examined was due to lake-effect processes.

Interestingly, observations from lake-effect days for some sites, particularly Marquette, Michigan, indicated a discontinuity between the initial hourly observation (left-hand sides of graphs shown in Figs. 1 and 2) and the last hourly observations (right-hand sides). This feature appears to be an artifact of the definition of lake-effect day. Kristovich and Steve (1995) used visible satellite imagery to classify the cloudiness for each day over a 5-yr period. It is therefore often not possible to determine during which hour each lake-effect event started or ended. Since most lake-effect events classified by this previous study lasted one day, there is no reason to expect good agreement between initial and final precipitation frequencies.

To explore whether the morning maximum is due to the definition of lake-effect day, as defined here, all lake-effect cases lasting more than one consecutive day at Muskegon and Marquette were examined. There were a total of 17 and 8 multiple-day lake-effect events over Lakes Superior and Michigan, respectively, lasting 2–4 days. As an example, the time series of precipita-

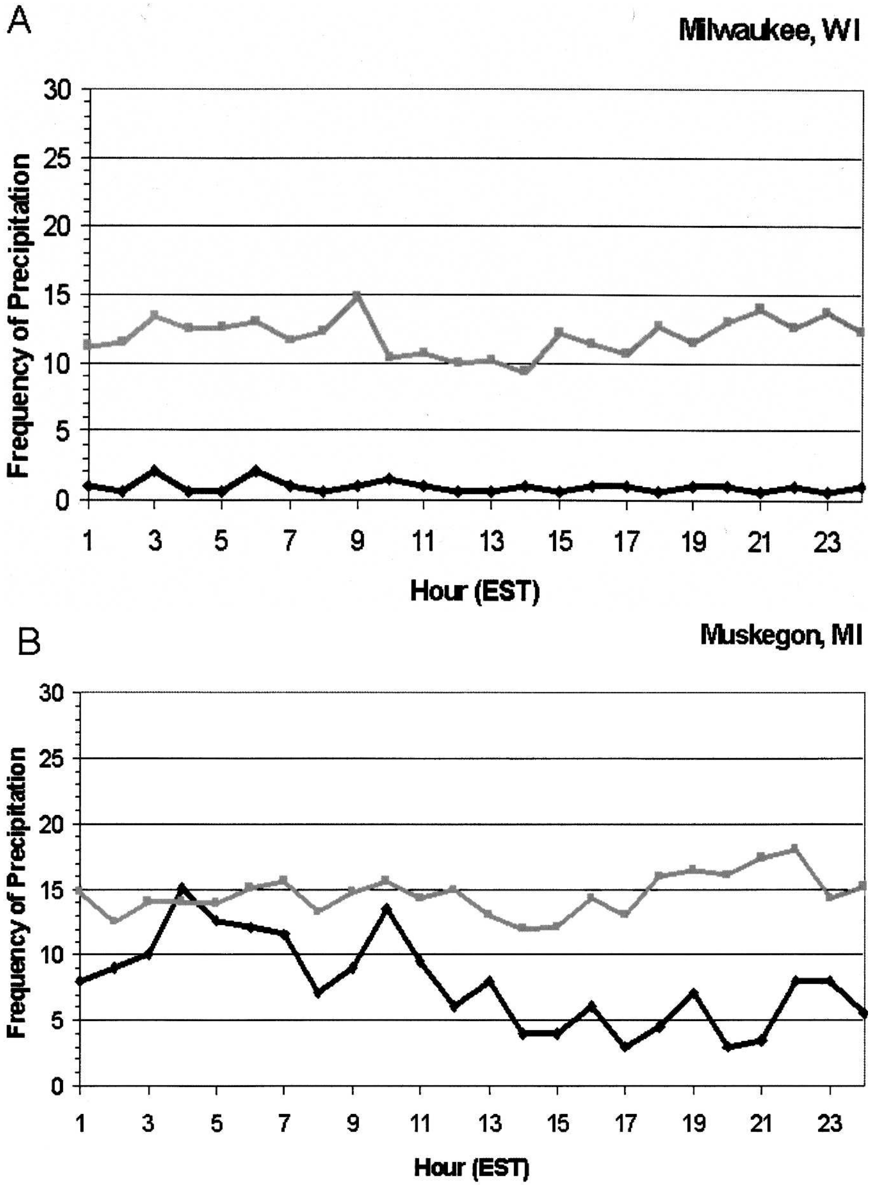

FIG. 3. Precipitation frequency (percent) for Oct–Mar 1988–93 at (a) Milwaukee, WI, and (b) Muskegon, MI, for lake-effect (black lines) and non-lake-effect days (gray lines).

tion amounts from one 3-day event is given in Fig. 4. It was found that there was a great deal of variation in hours of precipitation occurrence in the multiple-day lake-effect events, but that precipitation tended to be observed more often in the morning hours. This is similar to the findings of all lake-effect events shown in Figs. 1 and 2.

5. Discussion of possible contributing factors

To gain insight into the observed diurnal evolution of lake-effect precipitation occurrence, environmental factors previously shown to contribute to the occurrence of lake-effect storms are examined. Previous studies have emphasized the importance of a number of environmental factors on lake-effect precipitation development. Factors that may be anticipated to influence the diurnal behavior of lake-effect precipitation include magnitudes of surface sensible and latent heat fluxes (e.g., Niziol 1987; Kristovich and Laird 1998); atmospheric static stability over the lake (e.g., Rothrock 1969), including height of the lowest inversion (e.g., Niziol et al. 1995); and local uplift due to synoptic and mesoscale atmospheric circulations (e.g., Niziol et al. 1995). Other synoptic and mesoscale factors influencing the local and regional intensity of lake-effect snows in-

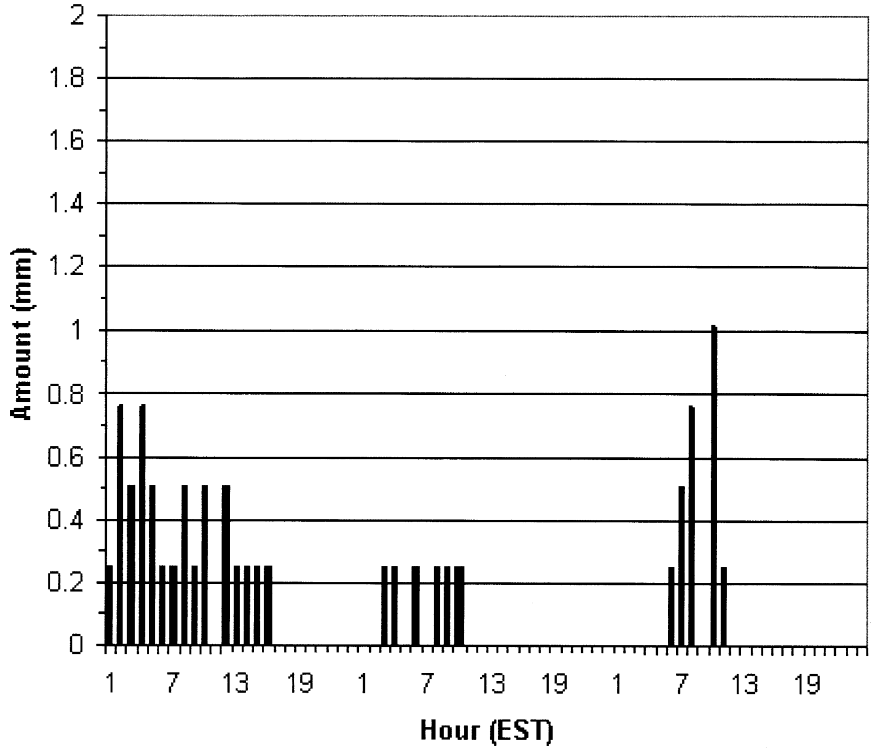

FIG. 4. Precipitation amounts observed at Marquette, MI, during the 10–12 Mar 1992 lake-effect event.

clude differences in surface friction between land and lake, in-cloud air temperatures, lake surface temperature and ice cover variations, radiative processes, lake-effect convective organization, and near-shore topography (e.g., Hjelmfelt 1992; Ballentine et al. 1998; Laird and Kristovich 2004). For convenience, findings from the present study are compared with those of Hjelmfelt (1990), who examined the relative importance of surface sensible heat fluxes, static stability, and low-level moisture content upwind of the lakes on lake-effect intensity. The findings of Hjelmfelt (1990) are generally consistent with those of most subsequent observational and numerical modeling studies.

Operational datasets do not permit a full determination of mechanisms responsible for the diurnal evolution of lake-effect precipitation. However, the relative importance of some of these mechanisms can be examined using available data. For example, vertical sensible and latent heat fluxes, key to the development of lake-effect convection, can be estimated using observations from first-order surface sites near Lake Michigan (Muskegon and Traverse City, Michigan, and Milwaukee, Wisconsin). The importance of other environmental factors, such as atmospheric stability, while not observed directly, may also be inferred.

Lake–air sensible and latent heat fluxes were derived using hourly Surface Airway Observations of air temperature, dewpoint, and wind speed at Milwaukee, Traverse City, and Muskegon (from NCDC dataset DSI-3280; NCDC 2003b) and daily mean lake surface temperatures observed at nearby Coast Guard stations (installations 14C, 15C, and 17C in Fig. 1a). Fluxes were calculated using methods described in Kristovich and Laird (1998). Lack of over-lake atmospheric data may result in local differences between calculated fluxes and actual over-lake fluxes, as discussed in more detail in this previous paper. Nevertheless, in general, the temporal fluctuations in fluxes should be well captured.

Figure 5 shows the mean diurnal sensible and latent heat fluxes calculated from observations on lake-effect days. It was found that the diurnal variation in surface sensible heat flux closely mirrored that of lake-effect precipitation occurrence. Sensible heat flux tended to be greater in the morning hours (0600 to 1000 EST) than in the afternoon hours (after 1300 EST). As expected, the greatest diurnal variations in sensible heat fluxes occurred at Milwaukee, which is typically upwind of Lake Michigan on lake-effect days. Daily changes in lake–air temperature difference, which maximized in the near-dawn hours, largely controlled the sensible heat flux variations. However, mean surface winds were, on average, about 1 m s^{-1} stronger in the afternoon hours, which moderated sensible heat flux variations.

The relationship between lake-effect precipitation occurrence and sensible heat flux is physically reason-

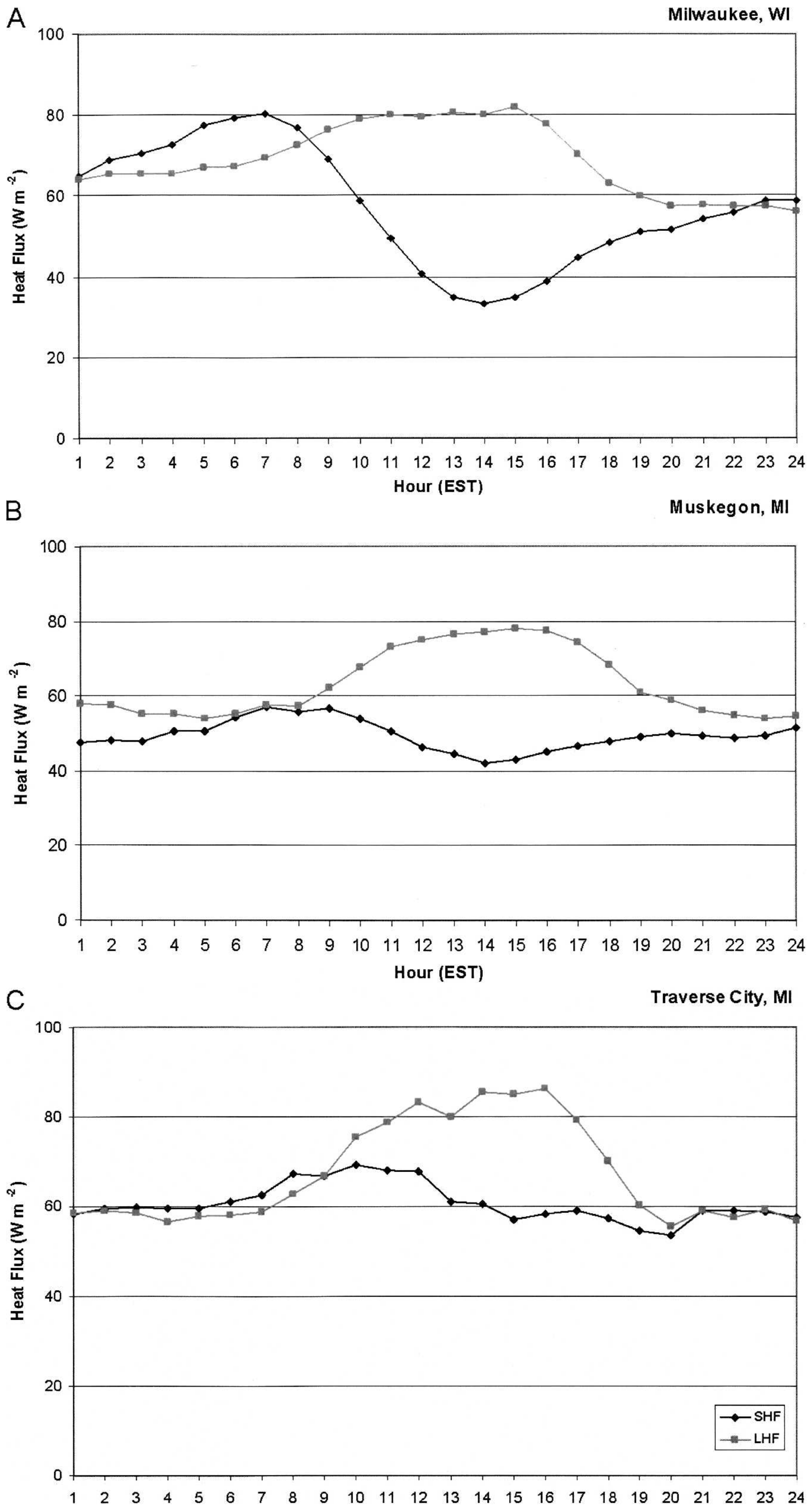

FIG. 5. Mean sensible (solid black) and latent (solid gray) heat fluxes by hour for lake-effect days at (a) Milwaukee, WI, (b) Muskegon, MI, and (c) Traverse City, MI.

able and found by several previous numerical modeling studies (e.g., Hjelmfelt 1990). Increased sensible heat flux would result in more energetic buoyant mixing in the lake-effect convective boundary layer (e.g., Braham and Kristovich 1996). In turn, increased buoyant convection would contribute to deepening the convective boundary layer, thus increasing the likelihood that precipitation would be generated.

The latent heat flux maximum occurred in the afternoon hours, coinciding with the minima in frequency of lake-effect precipitation occurrence. This latent heat flux maximum is due to both increases in wind speeds and dewpoint depression, consistent with downward transport of drier air from aloft. Several studies have pointed out that decreasing atmospheric moisture content (increasing dewpoint depression) upwind of the lake would result in decreasing precipitation amounts (e.g., Lavoie 1972; Hjelmfelt 1990). This drier air would require correspondingly greater amounts of moisture flux from the lake surface to achieve saturation, thus inhibiting lake-effect precipitation during the afternoon.

Another factor found by several studies to be important to lake-effect development is atmospheric static stability. Since sounding data are only available at a limited number of stations twice per day, it was not possible to document mesoscale variations in low-level atmospheric stability in the vicinity of Lakes Superior and Michigan. However, it would be anticipated that upwind stability is generally less in the afternoon hours than in the morning because of absorption of solar insolation at the surface. Several studies have found that lake-effect processes can be intensified if upwind static stability is decreased (e.g., Hjelmfelt 1990; Kristovich and Laird 1998). However, decreasing static stability during the afternoon in the current study corresponds with a minimum in lake-effect precipitation, suggesting that variations in upwind stability did not play as large a role in the diurnal evolution of lake-effect precipitation occurrence as other factors, such as surface sensible heat fluxes.

Frontal, trough, or cyclone passages can lead to or enhance lake-effect precipitation through mesoscale uplift or subsequent cold-air advection. Three-hourly surface charts from NCDC for the period of interest were utilized to examine the temporal distribution of such passages. Approximate times of surface boundaries followed by increased cold-air advection and lake-effect clouds were noted as they crossed the midpoint of Lake Michigan. It was found that times of frontal, trough, or cyclone passages across this region exhibited a small minimum between 1200 and 1500 EST and a maximum between 1500 and 1800 EST (Fig. 6). This minor variation in times of these passages may not represent those of the actual passages due to difficulties in determining frontal positions over the lakes, particularly when the lakes modify the frontal structure and speed (e.g., Dreher et al. 2004). For this reason, and because the passages do not exhibit variations that are similar to precipitation frequency observations, it is concluded that mesoscale uplift due to such boundaries was unlikely to systematically influence the diurnal trends of lake-effect precipitation.

It is important to note that many other factors have been identified as contributing to the occurrence and intensity of lake-effect snowfall. Among these factors are frictional convergence due to differences in surface roughness between land and lake, in-cloud air temperatures, lake surface temperature and ice cover variations, radiative processes, and near-shore topography.

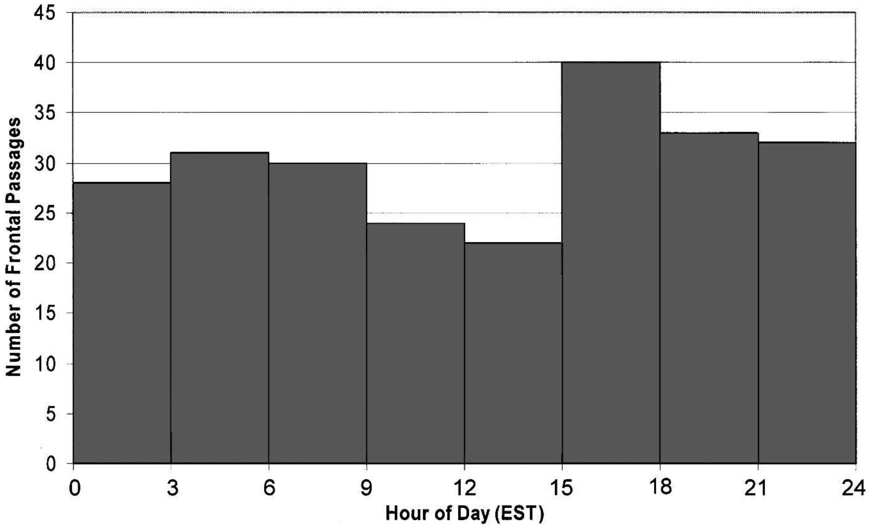

FIG. 6. The number of frontal, trough, and cyclone passages across the midpoint of Lake Michigan preceding cold-air advection and lake-effect days as a function of hour for Oct–Mar 1988–93.

Of these factors, only a few might be expected to exhibit significant diurnal variations. Given the impacts of the timing of winter precipitation on weather forecasting and snow removal activities, future detailed observational and numerical modeling studies should be conducted to fully determine the physical processes that contribute to the observed diurnal evolution of lake-effect precipitation occurrence.

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