Observations of Widespread Lake-Effect Cloudiness: Influences of Lake Surface Temperature and Upwind Conditions

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ABSTRACT

Large spatial and temporal variations were observed in the location of the upwind cloud edge over Lake Michigan during five westerly wind lake-effect events in November 1995 through January 1996. This study examines the impacts of variations of Lake Michigan surface water temperatures (and corresponding surface fluxes) and upwind static stability on the location of the upwind edge of lake-effect clouds, which develop as cold air crosses the lake during the winter. Data used in this study were collected during the 1995/96 National Weather Service Lake-Effect Snow study. Spatial variations in the location of the upwind lake-effect cloud edge are shown to be related to spatial variations in surface heat and moisture fluxes between the lake surface and overlying air. Surface fluxes are influenced by both the distribution of lake surface water temperatures and variations of surface wind speed, air temperature, and relative humidity. Temporal variations of heat and moisture fluxes from the lake surface and low-level static stability upwind of the lake correlate well with changes in locations of the upwind lake-effect cloud edge. In general, increases in total flux over a particular period tended to correspond with westward change in the position of the upwind cloud edge, whereas decreases in total flux corresponded to eastward shifts of the upwind cloud edge. Atmospheric static stability below the upwind inversion was found to be more important than the inversion height in controlling the location of the upwind cloud edge over the lake, with increases in stability corresponding to eastward shifts in its location.

1. Background

Lake-effect snowstorms, associated with cold air outbreaks over the Great Lakes, occur frequently during autumn and winter months (e.g., Holroyd 1971; Passarelli and Braham 1981; Kelly 1986; Niziol 1987; Kristovich and Steve 1995). For purposes of this study, lake-effect events are defined as those where heat and moisture input from the Great Lakes results in the development and growth of an internal, convective boundary layer and accompanying clouds (e.g., Lenschow 1973; Chang and Braham 1991). The magnitudes of heat and moisture fluxes from the surface of the lakes greatly influence the growth rate of the convective boundary layer. These surface fluxes, in turn, are controlled largely by temperature and vapor pressure differences between the surface and overflowing air and low-level wind speeds. Satellite observations reveal the presence of complex spatial variations of wintertime surface water temperatures across each of the Great Lakes (Schwab et al. 1992). This study examines the impacts of variations of Lake Michigan surface water temperatures (and corresponding surface fluxes), surface conditions, and upwind static stability on the location where clouds first form as cold air crossed the lake during five events from November 1995 to January 1996.

Previous studies have utilized aircraft-measured in situ data to investigate the rate of boundary layer, cloud, and snow growth as a function of fetch across Lake Michigan during westerly wind lake-effect events (e.g., Chang and Braham 1991; Kristovich 1993). They observed that convective boundary layers developed rapidly in the vicinity of the western shore and thereafter deepened at a slower rate across the remainder of the lake, usually reaching depths of 1 to 3 km near the downwind shore. These studies of lake-effect boundary layer growth were limited to a single cross section over the lake during a single time interval. Chang and Braham (1991) and Kristovich (1991) observed that clouds developed within 10–40 km from the upwind shore, with snow developing farther downwind. A recent visible satellite image, shown in Fig. 1, provides an example of lake-effect clouds over Lake Michigan. In general, clouds initially develop when boundary layer convection penetrates the condensation level or moisture content is sufficient that mixing processes result in local supersaturations. The upwind cloud edge is an indicator of the location where latent heat release and cloud radiational properties may begin to play a role in boundary layer evolution. Large spatial and temporal variations were observed in the location of upwind cloud edge

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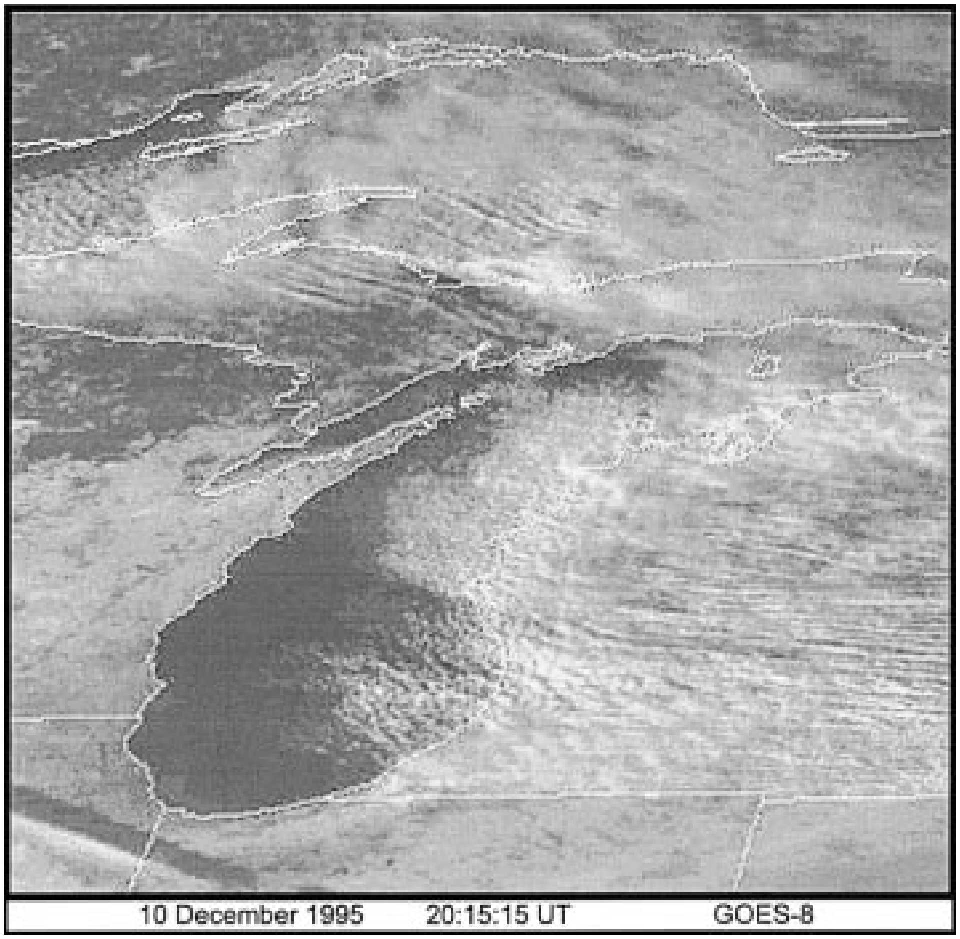

FIG. 1. *GOES-8* visible satellite image of lake-effect clouds over Lake Michigan on 10 December 1995 at 2015 UTC. (Image courtesy of CIRA, Fort Collins, CO.)

over Lake Michigan for five westerly wind lake-effect events in the winter of 1995/96. These variations suggest that cloud development processes and boundary layer evolution differed significantly over the lake during these events.

Many factors are known to affect the growth rate of convective boundary layers, such as surface fluxes, atmospheric stability, near-surface humidity, humidity profile, latent heat release, entrainment, and large-scale subsidence [see, e.g., Moeng and LeMone (1995) for a review of recent boundary layer research]. For lake-effect conditions, recent studies indicate that surface fluxes and upwind stability play important roles in boundary layer growth, circulation patterns, and snowfall rates. For example, Hjelmfelt (1990), using numerical sensitivity tests, found that the evolution of lake-effect boundary layers and mesoscale circulations were most influenced by surface fluxes and upwind atmospheric stability. Byrd et al. (1995) argued that modification of the air upwind of Lake Ontario by Lake Huron significantly influenced lake-effect snowfall patterns in west-central New York State, by influencing upwind stability and humidity profiles and altering surface fluxes. Chang and Braham (1991) found that surface fluxes dominated the heat and moisture budgets of lake-effect boundary layers over Lake Michigan. They also observed a rapid increase in the growth rate of a convective boundary layer over Lake Michigan as the top of the boundary layer penetrated an elevated near-neutral layer. Therefore, it is important to examine both the influences of surface fluxes and upwind stability when trying to understand the initial development of lake-effect boundary layers. The current study utilizes data collected during the National Weather Service (NWS) Lake-Effect Snow (LES) study to examine the influences of variations of surface fluxes and atmospheric stability upwind of Lake Michigan on the distance from the upwind shore that lake-effect boundary layer clouds develop.

2. Methodology

Events included in this study occurred during lake-effect situations with west or northwesterly winds. Five cases (3–4, 8–9, and 21–22 November 1995, 10–11 December 1995, and 19–20 January 1996) provided time periods of lake-effect cloudiness, useful for examining relationships of surface fluxes over Lake Michigan and upwind conditions to the temporal evolution and spatial distribution of widespread lake-effect clouds. Data were collected during the 1995/96 efforts of the NWS LES study. The primary datasets utilized in this investigation were *Geostationary Operational Environmental Satellite-8* (*GOES-8*) visible and infrared (IR) satellite imagery, Lake Michigan surface temperature distributions, NWS soundings, and hourly surface observations around Lake Michigan.

Lake-effect cloud coverage over Lake Michigan was determined from *GOES-8* satellite imagery, obtained from the Cooperative Institute for Research in the Atmosphere (CIRA), Fort Collins, Colorado. A 24-h continuous record of the locations of lake-effect clouds in each of the five cases was determined from IR imagery. High-resolution (1 km) visible imagery (e.g., Fig. 1) was used to supplement the IR imagery (4-km resolution) for daylight periods. Time periods when synoptic- and upper-level clouds were present over Lake Michigan were determined from animations of IR imagery and were excluded from the analysis. This was possible due to the quasi-stationary character of lake-effect cloud fields relative to synoptic- and upper-level clouds. Excluding these time periods gave 12 to 24 h of continuous data for four of the five events. On the remaining case, 8–9 November 1995, high clouds overspread the lake-effect cloudiness, causing the upwind cloud edge analysis to be broken into a 7- and a 5-h segment.

For this study, it was necessary to determine the locations of the upwind cloud edge over Lake Michigan with accuracy. The most reliable method, utilizing our dataset, was to establish an IR threshold temperature to differentiate between lake-effect clouds and the lake surface regardless of time of day. The threshold for each event was determined by comparing the locations of the upwind cloud edge on visible imagery during daylight hours to the spatial distribution of temperature on IR imagery at corresponding times. Since the diurnal variation of lake surface temperature is thought to be small, this threshold was then used to determine the locations of upwind cloud edge during nighttime periods. The resulting analyses, while somewhat subjective, revealed a physically realistic evolution of the upwind lake-effect cloud edge over Lake Michigan for each of the five cases.

Daily lake surface temperature distributions were obtained from the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) CoastWatch program. These were derived from data collected by the Advanced Very High Resolution Radiometer on NOAA polar-orbiting weather satellites (Schwab et al. 1992). Lake surface temperatures are updated daily with information from cloud-free portions of the previous day's satellite imagery. Although this is the best available dataset on spatial distributions of lake surface temperature, it is important to note that these lake surface temperature distributions are a composite from measurements on several days. One may expect a possible 1°–2°C departure from actual lake temperatures, due to the composite nature of these satellite observations during periods when the lake temperature changes rapidly, such as during late autumn (R. A. Assel, GLERL 1997, personal communication). Schwab et al. (1992) compared satellite-derived water temperatures with temperatures measured by NOAA weather buoys in the Great Lakes and found satellite temperatures were an average of 1°C cooler than buoy temperatures with an rms deviation of 1°–1.5°C. This error was not a function of temperature, indicating that spatial variations of surface temperature are accurate within 1.5°C. However, accuracy of lake water temperature estimates have likely improved due to recent advancements in satellite sensors and surface water temperature processing algorithms (G. A. Leshkevich, GLERL 1996, personal communication).

In order to determine relationships of moisture and heat input from the lake to the location of the upwind lake-effect cloud edge, estimates of surface fluxes were derived from water temperatures and meteorological observations taken near the upwind shore of Lake Michigan. For surface flux calculations, Lake Michigan was separated into four regions based on the location of selected observation stations that provided measurements of surface air temperature, humidity, and wind speed (Fig. 2). Estimated average midlake water surface temperatures were determined for each of these regions for each day. Heat and moisture fluxes were estimated every 3 h during each lake-effect event, using

$$H = c_p C_H \rho\, u(\theta_L - \theta) \approx H = c_p C_H \rho\, u(T_L - T) \qquad (1)$$

$$E = C_E \rho\, u(q_L - q) \approx E = C_E u(\rho_{vL} - \rho_v), \qquad (2)$$

where H is sensible heat flux (W m^{-2}); E is vapor flux (g m^{-2} s^{-1}); C_H and C_E are nondimensional bulk transfer coefficients of heat and moisture, respectively (using a constant value of 1.5×10^{-3}); c_p is specific heat at constant pressure for dry air (1004.5 J kg^{-1} K^{-1}); ρ is air density; ρ_v is water vapor density; u is wind speed; θ is potential temperature; T is temperature; and q is specific humidity. The subscript L denotes values associated with the lake surface or near the surface. Since lake-effect boundary layers and clouds develop due to both heat and moisture input, total flux

$$F_T = H + EL_v, \qquad (3)$$

with L_v denoting the latent heat of vaporization, was calculated in order to simplify examination of their relationships.

Bulk transfer relationships were utilized since vertical profile information was not available at each measurement location (Garratt 1992). In utilizing the bulk transfer method, temporal trends in estimated and actual val-

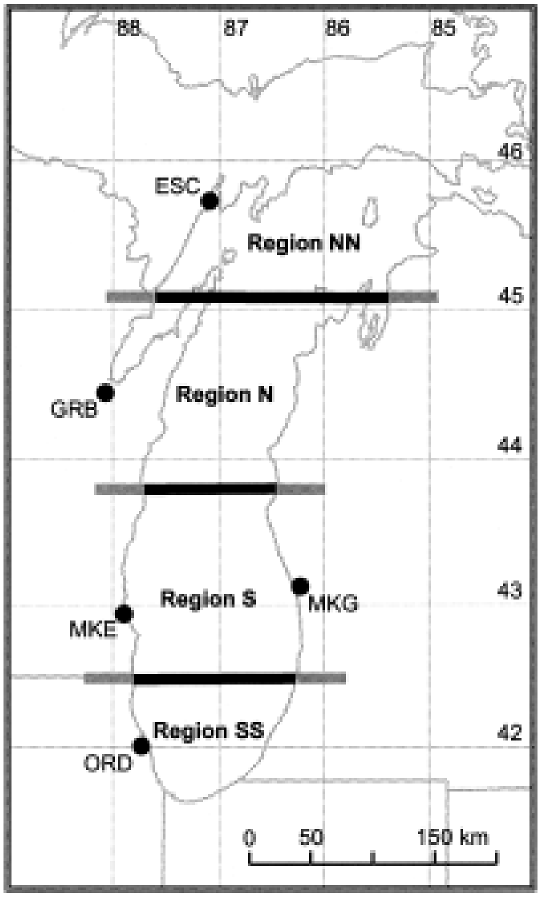

FIG. 2. Locations of surface observations along the western shore (ESC, GRB, MKE, ORD) and regions of Lake Michigan water temperatures utilized for surface flux estimations. In addition, location of Muskegon, MI (MKG), is shown along eastern shore.

ues of F_T over Lake Michigan should be closely related, though specific values may not be numerically equivalent. In addition, the calculated fluxes may not be equivalent to actual fluxes over the lake because the air temperature, humidity, wind speed, and lake surface temperature are not taken at the same location. There are a variety of methods for estimating surface fluxes (e.g., Sykes et al. 1993; Stull 1994). The methods used for this investigation were chosen since they give reasonable values compared to past in situ observations of fluxes over Lake Michigan (e.g., Chang and Braham 1991; Kristovich 1993; Kristovich and Braham 1998) and due to the limited vertical extent (i.e., measured at a single altitude) of the wind and temperature observations.

3. Upwind cloud-edge evolution

Lake-effect cases with west or northwesterly winds during November 1995 to January 1996 were used to examine the roles of surface fluxes and upwind static stability on the location where clouds first develop within lake-effect boundary layers. Several characteristics of the lake-effect boundary layer, such as growth rate, cannot often be directly measured. However, the distance that clouds initially form from the upwind shore over Lake Michigan during lake-effect events is an identifiable stage of the evolution of the internal, convective boundary layer across the lake. This section outlines the evolution of the location of the upwind cloud edge over the lake during westerly wind events that were accompanied by widespread cloudiness and light snow over and downwind of Lake Michigan.

Figures 3a1–e1 show the locations of the upwind cloud edge at 3-h intervals during five lake-effect cases. The upwind edge of the lake-effect clouds during the two early November cases (3–4 and 8–9 November 1995) remained relatively stationary over midlake throughout the events. The locations of the upwind cloud edge during the three latter cases (21–22 November 1995, 10–11 December 1995, and 19–20 January 1996) exhibited large variations over the duration of the events. During the onset of these latter events, clouds developed within 25 km of the western shore. As the 21–22 November and 19–20 January cases progressed, the location over the lake at which clouds developed drifted eastward. Interestingly, the upwind cloud edge over the southern two regions (regions SS and S) of the lake propagated eastward much faster than over the northern two regions (regions N and NN). The movement of the upwind cloud edge during the 10–11 December case was similar to that of the two cases described above, except that near the end of the event (0000–0600 UTC 11 December), the upwind cloud edge developed back toward the western shore in the southern regions.

The 16-h lake-effect event on 21–22 November 1995 (Fig. 3c1) serves as an example of how much the location of the upwind lake-effect cloud edge can vary over Lake Michigan. Clouds developed in the lake-effect boundary layer within about 25 km of the entire western (upwind) shore of Lake Michigan during the first few hours of this event (2000–2200 UTC). For the next 14 h (until about 1200 UTC 22 November), the western edge of the lake-effect clouds moved eastward, particularly over the southern half of Lake Michigan. For northern regions N and NN (north of approximately 44° latitude), lake-effect clouds covered most of the lake (over 90% of the fetch distance across Lake Michigan) for 83% of the case. In southern regions (S and SS), lake-effect clouds covered most of the lake for only 53% of case. This suggests that there were significant variations in boundary layer development from north to south during this case, and this difference became more pronounced later in the lake-effect period. The reasons for the variations in the location of the upwind cloud edge will be discussed in sections 4 and 5.

4. Influence of variations in surface fluxes

The distribution of clouds within the convective boundary layer during westerly wind lake-effect events

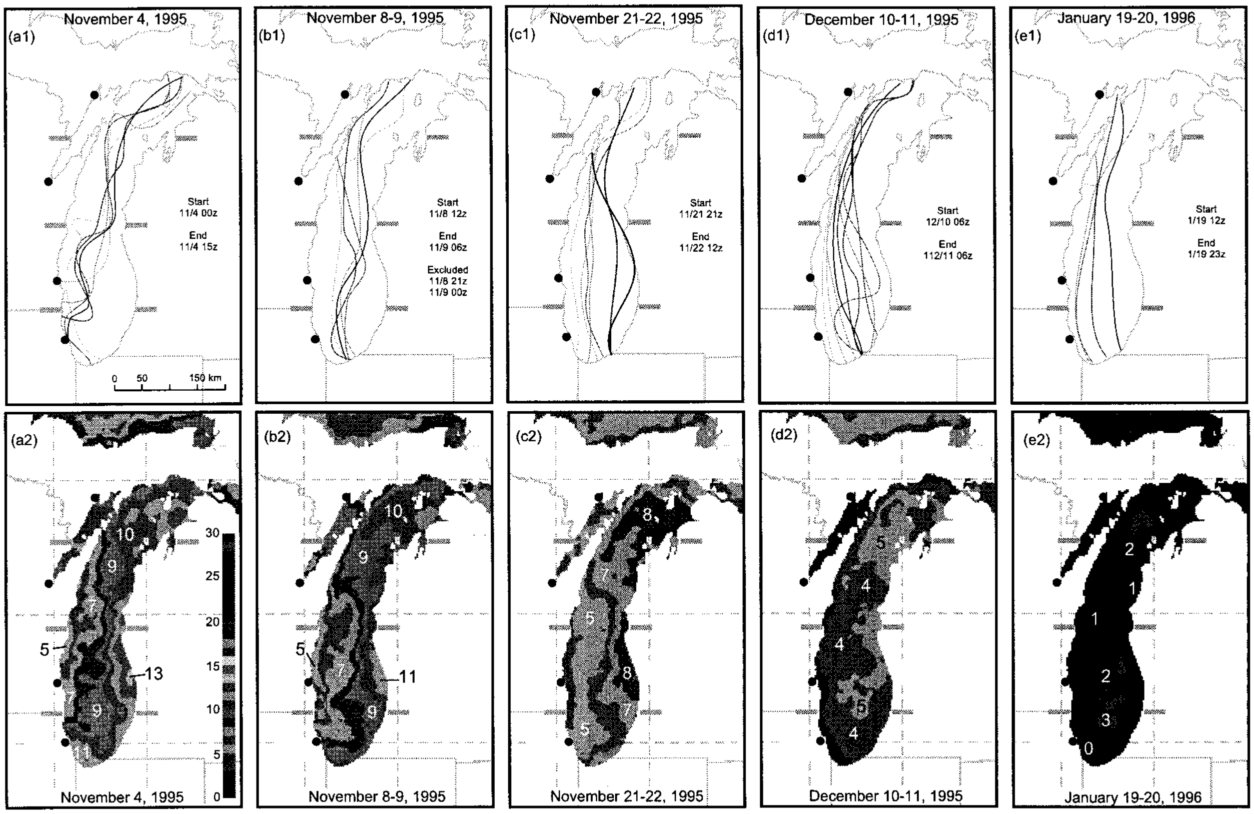

FIG. 3. (a1–e1) Upwind edge of lake-effect clouds at 3-h intervals with start and end times of event shown. Continuous line shading shows progression of cloud edge from earlier (lighter shades) to later (darker shades) time periods. (a2–e2) Daily lake surface temperature distributions for each event. Shading represents differing lake surface temperatures. Values denote lake surface temperatures in degrees Celsius. Boundaries for regions discussed in the text are designated along the eastern and western shores.

can vary considerably during a given time period (Figs. 1 and 3). A visual comparison indicates that there was a strong relationship between the distribution of lake surface temperature and the location of the upwind cloud edge during the later stages of these events (Fig. 3). For example, upwind cloud edges on 21–22 November were farthest from the upwind shoreline in regions S and SS (southern two regions). This cloud-free area corresponded with the locations of colder lake surface temperatures. This association of cloud-free and cold lake water temperature regions was evident for cases with large west-to-east increases of lake surface water temperature of 4°–8°C and south-to-north increases of 2°–3°C (3–4, 8–9, and 21–22 November). In general, relatively uniform wind speeds and only small variations in upwind air temperatures (2°–3°C) and upwind relative humidity were present over the north–south extent of Lake Michigan during these cases.

The December and January cases exhibited weaker east–west gradients and smaller north–south variations in lake surface water temperatures (1°–1.5°C) than the November cases. However, a similar evolution of the upwind cloud edge was observed for these cases, with the upwind cloud edge developing close to the Wisconsin and upper Michigan shore over the two northern regions and farther from the upwind shore over the two southern regions. In these two cases, larger variations in air temperatures (3°–6°C), but not in relative humidity values, were present from north to south upwind of Lake Michigan.

The combined effects of variations in lake surface and atmospheric conditions resulted in changes in the rate of heat and moisture transfer from the surface to the atmosphere. Figure 4 gives F_T values for each region, with gray-shaded time periods having either synoptic or upper-level clouds obscuring lake-effect clouds. As anticipated, F_T values over northern sections of the lake (regions NN and N) tended to be larger than values over southern sections (regions SS and S). At a given time, these values varied from north to south by as much as 375 W m^{-2} (e.g., 0300 UTC 11 December 1995). This added flux might be expected to result in more rapid boundary layer development and cloud formation closer to the upwind shore over the northern regions of Lake Michigan than over the southern regions. A comparison of Figs. 3 and 4 indicates that, generally, decreases (increases) in F_T with time were accompanied by an eastward (westward) movement of the upwind lake-effect cloud edge.

Since total surface fluxes are not routinely available

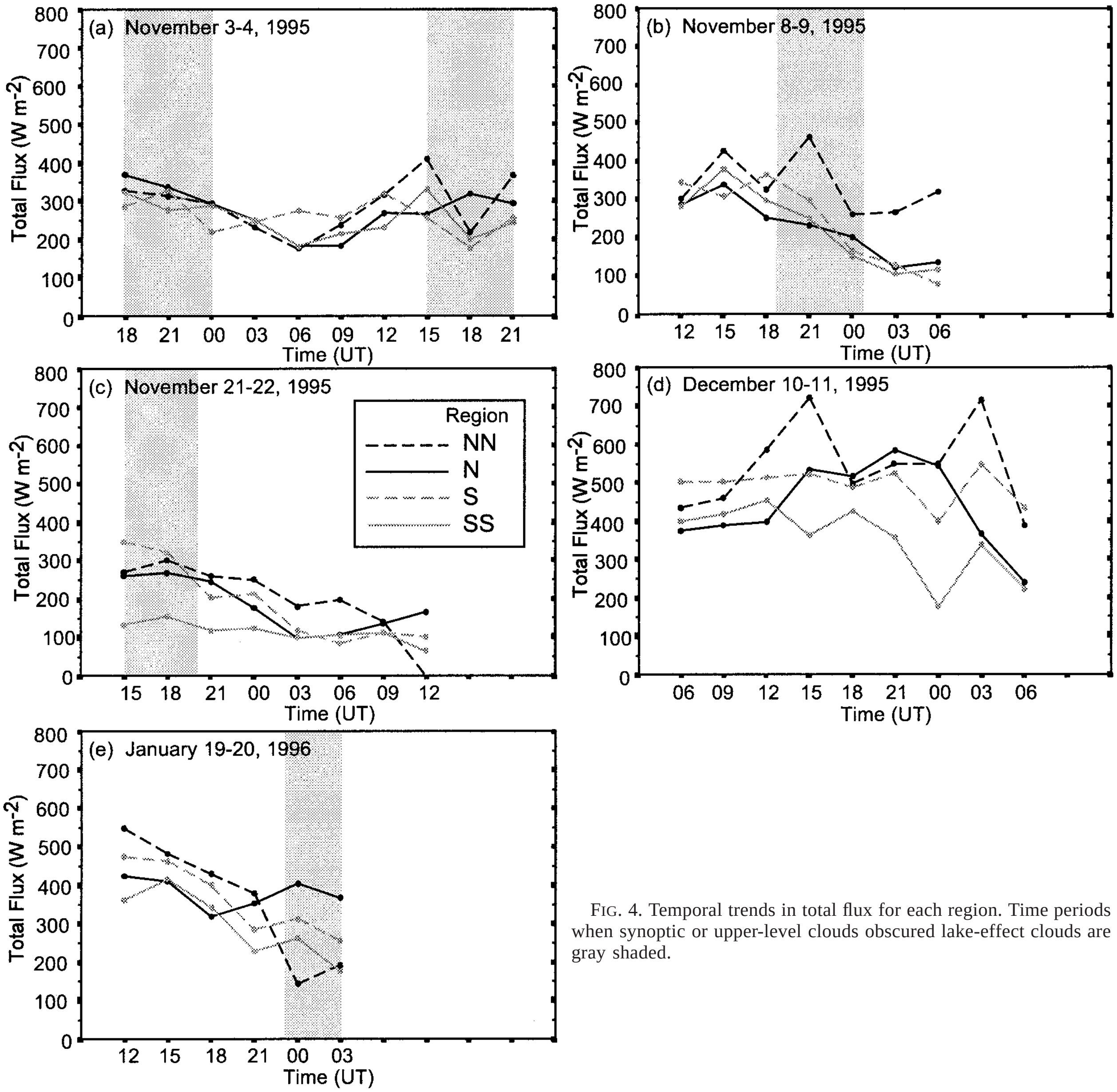

FIG. 4. Temporal trends in total flux for each region. Time periods when synoptic or upper-level clouds obscured lake-effect clouds are gray shaded.

to forecasters, it is instructive to examine the factors that contribute to total surface fluxes and the location of the upwind cloud edge. Equations (1), (2), and (3) reveal that to a first approximation, surface fluxes are controlled by variations in air density, wind speed, lake surface temperature and air temperature, and moisture content (as well as other factors that are not included in bulk methodologies, such as surface wave age or spray). Since lake water temperatures vary slowly with time during December through January, and air density variations are small, then temporal changes in surface fluxes at a given location depend primarily upon changes in air temperature, moisture content, and wind speed. On the five cases studied, wind speeds often varied with time by up to a factor of 2. Air–lake temperature differences and vapor density differences only varied by ±30% and ±6% from mean values, respectively. Since wind speed is a factor in both sensible and latent heat fluxes, and since it was the factor that varied the most with time at any given location, it might be expected that wind speed variations were primarily responsible for changes in surface fluxes.

Using data from all five cases, Fig. 5 shows the relationship of the observed fraction of the lake covered by lake-effect cloudiness to total flux (F_T), air temperature, relative humidity, and wind speed. Each panel contains the linear regression lines for the four regions over Lake Michigan. For each of the four regions, cloud

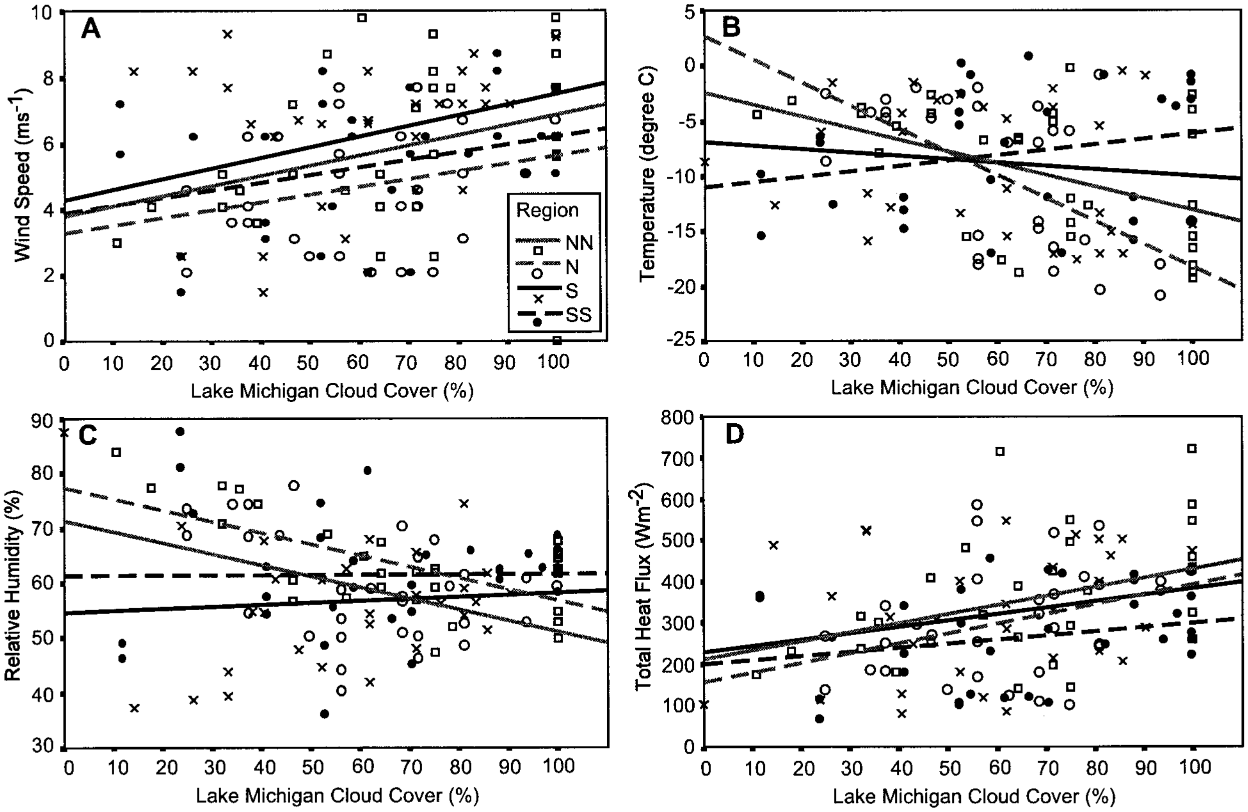

FIG. 5. Scatterplots showing the relationship between the percentage of Lake Michigan covered by lake-effect clouds and total flux, upwind air temperature, upwind relative humidity, and wind speed. A regression line, derived using least squares method, is given for each of the four regions over Lake Michigan studied.

cover over Lake Michigan increased as wind speed increased (Fig. 5a). Generally, lower temperatures resulted in more cloud cover, although the slope of the regression line varied greatly between regions (Fig. 5b). Examination of all of the data revealed relative humidity had little relationship to cloud cover (Fig. 5c). There is a positive correlation between the amount of clouds covering the lake and the total flux for each region, even though there is much scatter in the data (Fig. 5d). The slopes of the regression lines are similar from region to region, suggesting an increase in cloudiness corresponding to about half the distance across the lake for every 50 W m^{-2} of increase in total flux. The overall relationship holds for each of the days studied (not shown). Despite these general relationships, there are time periods where cloud edge movement did not correspond well with temporal changes in total flux.

5. Influence of upwind static stability profile

The stability of the atmosphere upwind of the Great Lakes during a lake-effect event is thought to influence the depth to which convection over the lakes will penetrate (e.g., Hjelmfelt 1990; Chang and Braham 1991; Byrd et al. 1995), thereby playing a role in determining the location from the upwind shore where lake-effect clouds develop. Standard NWS soundings taken at Green Bay, Wisconsin (GRB), were used to examine the evolution of the static stability profile upwind of Lake Michigan and determine the inversion height, taken to be the base of a layer in which temperature increases with altitude. In general, an inversion initially existed below 2.5 km during each event with a nearly neutral layer below. As the events proceeded, the inversion tended to lower and the static stability below the inversion increased. For example, early in the 21–22 November 1995 lake-effect event (0000 UTC 22 November), the sounding showed a low-level lapse rate of 8.2°C/km from the surface to about 850 mb, with a dry and stable capping inversion above (Fig. 6). Near the end of the lake-effect event (1200 UTC 22 November), the inversion had lowered to approximately 900 mb, the layer below became more stable (lapse rate of 5.5°C/km), and a near-surface nocturnal inversion developed.

In order to assess the relationship between lake-effect cloud formation and upwind stability, it is necessary to determine the height at which clouds at the upwind cloud edge formed. It is common to use sounding data to estimate cloud-base height in convective situations. However, since the atmospheric stability and moisture profiles are modified rapidly over the lake, the upwind

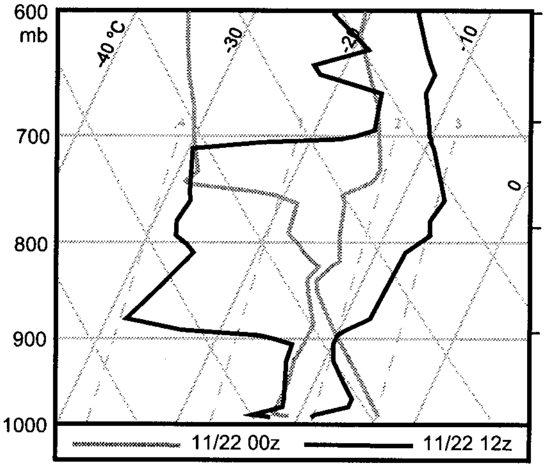

FIG. 6. Green Bay, WI (GRB), soundings at 0000 and 1200 UTC 22 November 1995.

soundings taken at GRB are not likely to provide an accurate estimate of the cloud-base height. Chang and Braham (1991) and Kristovich (1991) found, using in situ aircraft observations, that the height of cloud base remained nearly constant or increased slightly across Lake Michigan in similar lake-effect situations. Therefore, we would expect that the height at which the upwind cloud edge forms would be reasonably estimated by cloud-base heights reported near the downwind shore. In the five cases examined, estimated cloud bases at Muskegon, Michigan (MKG), were found to be below the inversion height upwind of the lake (GRB) most (81%) of the time. This suggests that, in lake-effect cases, the upwind inversion height may not be an important factor in controlling the location of the upwind cloud edge and boundary layer growth to this point. Therefore, it is necessary to consider the evolution of the static stability profile below the low-level inversion in order to examine variations in the location of the upwind cloud edge.

Figure 7 shows the variation of the atmospheric lapse rate and average relative humidity below the inversion throughout each of the five cases. There were sizable increases in the static stability (lapse rate decreases of more than 1.5°C/km) during 21–22 November and 19–20 January. The 10–11 December case suggests a similar pattern. However, a key sounding to examine the static stability evolution over this case was not available. These increases in static stability were accompanied by a steady eastward movement of the upwind cloud edge across Lake Michigan, suggesting that the initial boundary layer growth rate decreased with time. During the 3–4 and 8–9 November events, when the upwind cloud edge remained positioned over midlake, the static stability below the inversion remained nearly neutral with the lapse rate varying 1.5°C/km or less. These data suggest that increases in the below-inversion static stability tend to limit the initial growth rate of the lake-effect boundary layer and delay the formation of clouds over the lake by limiting the vertical distance that buoyant convective plumes can penetrate. Variations in relative humidity did not appear to be well correlated with changes in locations of the upwind cloud edge in these cases, perhaps due to the limited range of humidity values in the cases chosen for this study.

6. Summary and discussion

Lake-effect snowstorms are manifestations of internal convective boundary layer growth as heat and moisture fluxes from relatively warm lake waters modify the lowest levels of cold air passing over the lake. The upwind cloud edge is an indicator of the location where latent heat release and cloud radiational properties may begin to play a role in atmospheric boundary layer evolution. Large variations in the position of the upwind cloud edge are suggestive of variations in the evolution of a convective boundary layer over the lake. This study examines whether variations in the locations of the upwind edge of lake-effect clouds over Lake Michigan can be explained by the most important variables (surface fluxes and upwind static stability) thought to affect boundary layer development rates in lake-effect situations (Hjelmfelt 1990; Chang and Braham 1991; Byrd et al. 1995). This is accomplished by examining the temporal and spatial evolution of the upwind cloud edge, estimates of surface flux rates, and upwind static stability, on five westerly wind lake-effect cases during November 1995 through January 1996.

Results from this investigation suggest that variations in heat and moisture fluxes from the lake surface and low-level static stability upwind of the lake are correlated with changes in locations of the upwind cloud edge. In general, increases in total flux (F_T, including both sensible and latent heat fluxes) over a particular period tended to correspond with westward propagation in the position of the upwind cloud edge, whereas periods with decreases in total flux corresponded to eastward shifts of the upwind edge of the lake-effect clouds. Of the factors used in bulk estimates of total surface fluxes, changes in wind speed dominated, with upwind air temperature and relative humidity playing smaller roles. Lake-effect clouds formed below the low-level inversion height, suggesting that static stability below the upwind inversion is more important than the inversion height in controlling the location of the upwind cloud edge over the lake. There were sizable increases in the static stability (decreased lapse rate) below the upwind inversion height in cases where the upwind edge of the clouds steadily moved eastward across Lake Michigan. While both factors (surface fluxes and upwind static stability) are clearly related to the locations of the upwind cloud edge over the lake, it was not possible to determine the relative importance of each factor using these data.

Spatial variations in the location of the upwind lake-

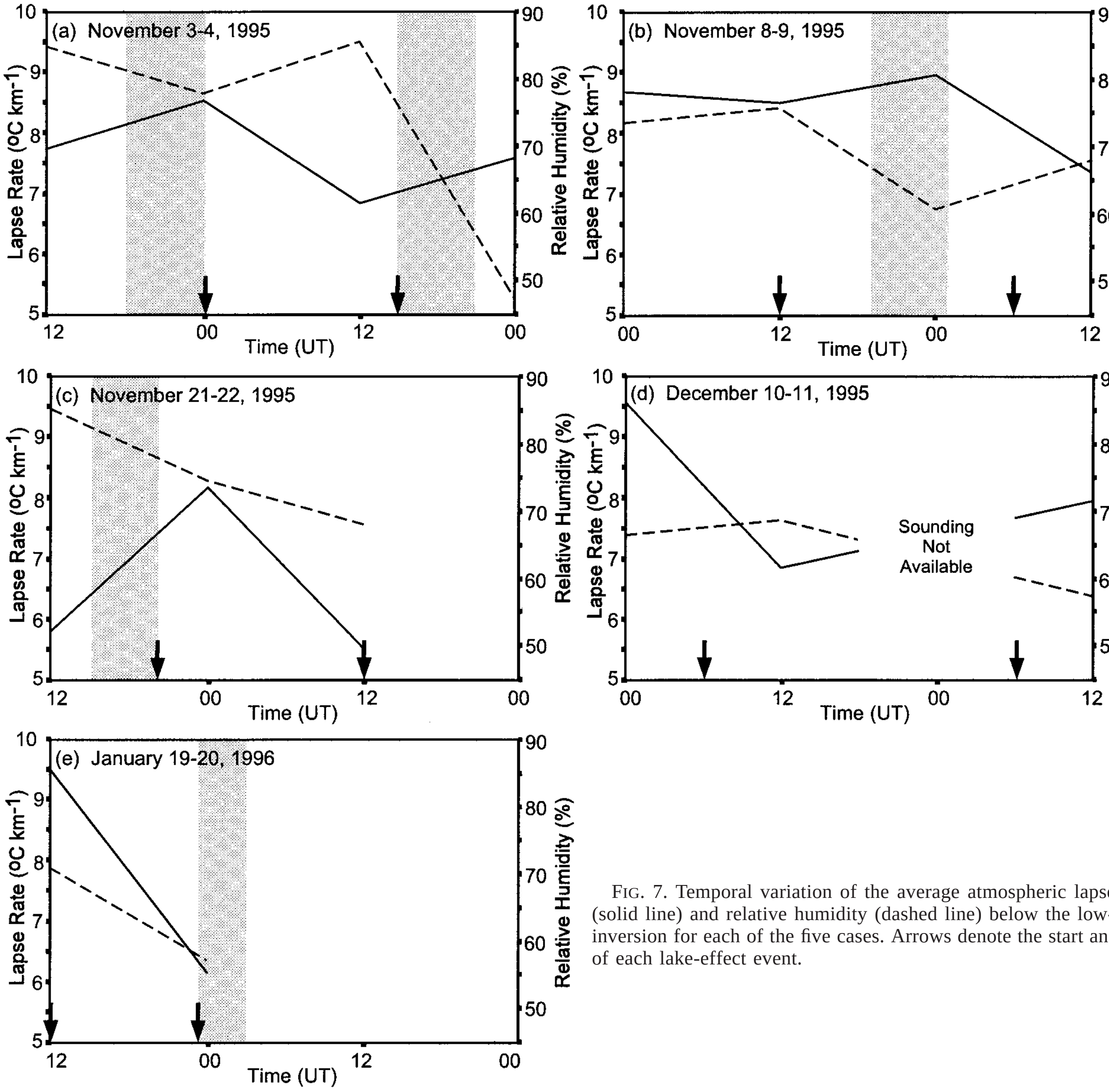

FIG. 7. Temporal variation of the average atmospheric lapse rate (solid line) and relative humidity (dashed line) below the low-level inversion for each of the five cases. Arrows denote the start and end of each lake-effect event.

effect cloud edge have been shown to be related to spatial variations in surface fluxes, which are influenced by both the distribution of lake surface water temperatures and variations of the synoptic/mesoscale environment. Conceptually, during the onset of each westerly wind event, clouds develop close to (within ~20 km) the upwind shore due to the nearly neutral upwind low-level static stability profile. At this stage of the event, even small amounts of positive total flux will result in convection reaching the condensation level. However, as the lake-effect event proceeds and the low-level static stability increases, the location of upwind lake-effect cloud edge becomes more influenced by the distribution of surface water temperatures, air temperatures, and wind speed, the primary factors leading to variations in heat and moisture fluxes.

Atmospheric moisture upwind of Lake Michigan may be expected to play several roles that are only partially accounted for by estimates of surface fluxes presented here. The use of a dry-adiabatic lapse rate does not take into account buoyancy of moist parcels of air or the effects of latent heating, for example. However, since this paper focuses on cold air outbreaks and the precloud environment, these factors are thought to be negligible. In addition, moist air upwind of the lake might be expected to allow convective parcels to reach saturation earlier than when the upwind air is dry. On the five cases studied, upwind humidity varied by a relatively small amount (e.g., surface vapor density differences between air and lake only varied by about ±6% from the mean). No systematic relationship was found between the location of the upwind cloud edge and these small spatial or temporal variations of upwind surface relative humidity.

It is important to note that other factors influence the development of convective boundary layers. For example, several investigators have observed rapid increases in the depth of the convective boundary layer during cold air outbreaks at the location where clouds and precipitation develop over warm water bodies (e.g., Boers and Melfi 1987; Chang and Braham 1991). Large-scale subsidence is thought to influence the depth of the boundary layer on scales of the east–west distance across Lake Michigan (~100 km). We hypothesize that on spatial scales of approximately 10–50 km, typical distances to the location of the upwind cloud edge, total flux, and low-level atmospheric stability play larger roles. Due to the nature of our observations, this investigation was unable to determine the possible influence of gravity waves and changes in local surface friction, which may lead to transient local variations of the boundary layer depth (e.g., Clark et al. 1986; Steve 1996).

The premodification of the cold air by the presence of upwind lakes is another factor that could influence the development and growth rate of the lake-effect boundary layer (e.g., Byrd et al. 1995; Cosgrove et al. 1996). Green Bay and Lake Superior can have this type of influence on lake-effect storms over Lake Michigan when the winds are north or northwesterly. In the cases studied, this appears to be a secondary effect to the influence of lake surface temperature distribution. During events when the winds in the lowest kilometer shifted between northwesterly and westerly, the plume of modified air from Green Bay and Lake Superior would have been expected to drift toward the northern parts of Lake Michigan. However, the north–south discontinuity in the upwind cloud edge location did not move northward in response to the shift in winds. Instead, the north–south discontinuity in the upwind cloud edge remained stationary near the location of northward increase in lake surface temperature.

Numerical sensitivity studies should be carried out over a wide range of upwind conditions to help better quantify the role of upwind humidity, wind speed, surface fluxes, and atmospheric stability. Further numerical and observational work is also needed to fully understand the complicated influences on lake-effect boundary layer development by cloud and precipitation formation, mesoscale boundary layer circulations, and topographic changes (i.e., land features and upwind water bodies). Since the observational data are now available (Schwab et al. 1992), it is important to incorporate variations in lake surface water temperature, especially when examining lake-effect events.

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