Observations of the Cross-Lake Cloud and Snow Evolution in a Lake-Effect Snow Event

FAYE E. BARTHOLD*
Center for Atmospheric Sciences, Division of Illinois State Water Survey, Prairie Research Institute, and Department of Atmospheric Sciences, University of Illinois at Urbana–Champaign, Urbana, Illinois

DAVID A. R. KRISTOVICH
Center for Atmospheric Sciences, Division of Illinois State Water Survey, Prairie Research Institute, University of Illinois at Urbana–Champaign, Urbana, Illinois

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ABSTRACT

While the total snowfall produced in lake-effect storms can be considerable, little is known about how clouds and snow evolve within lake-effect boundary layers. Data collected over Lake Michigan on 10 January 1998 during the Lake-Induced Convection Experiment (Lake-ICE) are analyzed to better understand and quantify the evolution of clouds and snow. On this date, relatively cold air flowed from west to east across Lake Michigan, creating a quasi-steady-state boundary layer that increased from \(675 \text{ to } 910 \text{ m}\) in depth over a distance of 80 km. Once a cloud deck formed 14–18 km from the upwind shoreline, maximum cloud particle concentrations and liquid water content increased from west to east across the lake. Correspondingly, maximum ice water contents, snowfall rates, and maximum snow particle diameters also increased across the lake. Maximum particle concentrations were found below the mean top of the boundary layer and above the cloud base for both cloud and snow particles.

Surprisingly, snow particles were observed 3–7 km upwind of the upwind edge of the lake-effect cloud deck. These snow particles were observed to be rather spatially uniform throughout the boundary layer. Based on available observations, it is hypothesized that of the mechanisms that could produce this snow, the majority of it originated from transient clouds located near the upwind shore. In addition, maximum snow particle concentrations peaked near the middle of the lake before decreasing toward the downwind shore, indicating the location after which aggregation became an important snow growth mechanism. These results show that the evolution of clouds and snow within lake-effect boundary layers may not occur in the uniform manner often depicted in conceptual models.

1. Introduction

Lake-effect snow is a common occurrence in the late fall and winter downwind of the Great Lakes. It forms when cold air flows over the relatively warm lakes and can result in significant amounts of snow (e.g., Rothrock 1969; Niziol 1987; Hjelmfelt 1990). The resulting meso-scale bands of clouds and snow have been categorized into several distinct morphologies (e.g., Braham and Kelly 1982; Forbes and Merritt 1984; Hjelmfelt 1990; Niziol et al. 1995; Laird et al. 2003), the most frequent of which is widespread convection, often in the form of wind-parallel bands (Kelly 1986; Kristovich and Steve 1995; Rodriguez et al. 2007). Similar snow-producing systems generated by cold airflow over relatively warm bodies of water have been observed over such water bodies as the Sea of Japan (e.g., Yamamoto and Hirose 2009; Fujiyoshi et al. 1995, 1998), the East China Sea (e.g., Agee and Howley 1977), the Baltic Sea (e.g., Andersson and Gustafsson 1994), Lake Victoria (e.g., Anyah et al. 2006), and smaller lakes in North America (e.g., Schultz et al. 2004; Laird et al. 2009, 2010).

Lake-effect snow develops and evolves entirely within type I (Agee 1987) cloud-topped convective boundary
layers. The clouds associated with this type of boundary layer form because of strong vertical motions and heat and moisture transport from the relatively warm water below (Agee 1987). Numerous observational and numerical modeling investigations have documented the evolution of the boundary layer between the upwind and downwind shores during widespread lake-effect snow events over Lake Michigan (e.g., Lenschow 1973; Chang and Braham 1991; Kristovich et al. 2003; Tripoli 2005; Schroeder et al. 2006).

It is well known that latent heat release during cloud and precipitation formation can accelerate growth in warm boundary layers (e.g., Stevens 2007; Boers and Melfi 1987). Even at the cold temperatures typical of lake-effect events, similar relationships between boundary layer growth and liquid cloud and ice particle (snow) formation have been documented. Chang and Braham (1991) documented a rapid increase in the boundary layer growth rate about 35 km from the upwind shore during a widespread lake-effect snow event over Lake Michigan. They argued that a likely reason for this increase in growth rate is that clouds and snow were present in large enough quantities at this location that the evaporation and condensation processes began to dominate boundary layer growth. Schroeder et al. (2006) found that the lake-effect boundary layer was deeper in areas where boundary layer clouds were seeded with snow from a higher-level cloud deck. They argued that this increase in depth could be due to increased latent heat release resulting from increased snow formation in the lake-effect cloud deck, reduced stability of the above–boundary layer air by evaporation of the snow falling from above, or mesoscale convergence regions associated with the synoptic system.

As a result of its importance to lake-effect snow production and boundary layer thermodynamics, several studies have highlighted the microphysical characteristics of lake-effect snowbands oriented with the long north–south axis of Lake Michigan using aircraft observations (Braham 1983, 1990; Agee and Hart 1990). The center of the band generally exhibited mixed-phase observations (Braham 1983, 1990; Agee and Hart 1990). Even at the cold temperatures typical of those found by prior studies to be favorable for lake-effect snows, these topics are rarely combined into a comprehensive view of the lake-effect system as a whole. The goal of this work is to develop an understanding of the coevolution of clouds, snow, and the boundary layer across Lake Michigan during a widespread wind-parallel band lake-effect snow event.

2. Data and methodology

The data used in this project were collected over Lake Michigan on 10 January 1998 during the Lake-Induced Convection Experiment (Lake-ICE; Kristovich et al. 2000). Visible satellite imagery on this date shows widespread lake-effect cloudiness, exhibiting both cellular and wind-parallel banded structures (Fig. 1, called “wind-parallel bands” in the rest of the text), which is the most common type of lake-effect system over the Great Lakes (Kelly 1986; Kristovich and Steve 1995; Rodriguez et al. 2007). Tripoli (2005) provided a detailed study of the boundary layer structures observed on this date. Atmospheric conditions were typical of those found by prior studies to be favorable for lake-effect snows. The temperature difference between the air at 850 hPa and the lake surface was approximately 21°C, which exceeds the 13°C difference typically thought to be required to produce significant lake-effect snow (e.g., Rothrock 1969; Niziol 1987). Winds were from the southwest quadrant at 5–10 m s⁻¹. Clear skies were dominant upwind (west) of the lake-effect cloud deck, although a few nonprecipitating clouds were observed over central and northern Wisconsin.
Coordinated aircraft flights by the National Center for Atmospheric Research (NCAR) Electra and the University of Wyoming King Air (UWKA) provided a unique view of both the temporal and spatial evolution of the 10 January 1998 lake-effect system. Figure 1 shows the approximate locations of the aircraft flights. The Electra flew approximately 30 east–west flight legs along 44.3°N at heights of 170–270 m above the lake surface. These flight legs began about 11 km from the Wisconsin shore and continued east to a distance about 51 km from that shore for much of the period before extending out to about 67 km from the Wisconsin shoreline after about 1818 UTC (see Barthold 2008 for information on each Electra flight leg). Over the same time period, the UWKA flew 4 north–south flight stacks between about 44.4° and 44.7°N, an average north-south distance of about 33 km. Each of the flight stacks consisted of four to five individual flight legs at different heights both within and above the boundary layer. The westernmost flight stack was oriented slightly southwest–northeast, approximately parallel to, and 11 km downwind of, the Wisconsin shoreline. The other flight stacks were oriented approximately north–south at fetches of about 39, 67, and 91 km from the upwind Wisconsin shore. Information on each of the UWKA flight legs, which were approximately straight and level, is given in Table 1.

While aircraft can provide over-lake observations of microphysical characteristics, the length of time it takes to observe a lake-effect system makes the analyses susceptible to temporal changes. Indeed, on 10 January 1998, these research aircraft flights occurred over a 4.5-h time period between approximately 1500 and 1930 UTC. However, the entire lake-effect system appears to have been in a quasi–steady state for the majority of the observational period. Prior to approximately 1800 UTC, radiosonde temperature observations, taken every 90 min near the upwind and downwind shores of the lake [see Kristovich et al. (2000) for locations], indicate little change in the depth of the boundary layer (Barthold 2008). Visible satellite imagery shows a consistent pattern of widespread lake-effect clouds with little temporal change evident in the cloud features or the location of the westernmost edge of the lake-effect cloud deck before about 1745 UTC (Fig. 1). Electra observations also support the quasi-steady-state nature of the lake-effect system on this date before 1745 UTC; the location of the westernmost cloud indicated by upward-directed radiometric temperature observations showed little change, in situ midlake potential temperatures warmed by less than 1°C, and two-dimensional cloud probe (2D-C) snow particle concentrations on the eastern ends of the flight legs showed no consistent trends in peak concentration values prior to this time (Barthold 2008). The quasi-steady-state nature of the event for the majority of the observational period suggests that aircraft data from different times can be combined to construct an overall view of the evolution of clouds and snow across the lake, at least until 1800 UTC. The lake-effect system was beginning to weaken while the UWKA was conducting the easternmost flight stack.

Cloud particle concentrations were measured during the aircraft flights using the Particle Measuring Systems, Inc., Forward Scattering Spectrometer Probe (FSSP; see Baumgardner 1989). The FSSP was set to measure particles from 2 to 47 μm in diameter across fifteen 3-μm bins. Average concentrations as a function of size bin were calculated applying all known corrections by NCAR (Electra) and by the University of Wyoming (King Air). It should be noted that in mixed-phase clouds, such as those in this case, FSSP-observed cloud droplet concentrations can be falsely increased by scattering from ice.
Table 1. Average flight information and microphysical characteristics for University of Wyoming King Air flight legs on 10 Jan 1998 during Lake-ICE. Cloud particle characteristics are from FSSP observations. Snow particle characteristics are from 2D-C observations. Flight legs are ordered by altitude.

<table>
<thead>
<tr>
<th>Flight stack (lon)</th>
<th>Flight leg</th>
<th>Alt (m)</th>
<th>LWC (g m⁻³)</th>
<th>Concentration (cm⁻³)</th>
<th>IWC (g m⁻³)</th>
<th>Concentration (L⁻¹)</th>
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<tr>
<td>KA-1</td>
<td>KA-1A</td>
<td>198</td>
<td>0</td>
<td>0</td>
<td>2.8 x 10⁻⁴</td>
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<tr>
<td>(87.4° ± 0.1°W)</td>
<td>KA-1B</td>
<td>318</td>
<td>0</td>
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<td></td>
<td>KA-1C</td>
<td>479</td>
<td>0</td>
<td>0</td>
<td>8.9 x 10⁻⁴</td>
<td>8.1</td>
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<td>0</td>
<td>4.4 x 10⁻⁶</td>
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<tr>
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<tr>
<td>(87.05°W)</td>
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<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
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<td>12.2</td>
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<td>6</td>
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<td>0.1</td>
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<td>17.3</td>
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<td>0.2</td>
</tr>
</tbody>
</table>

* Values given for KA-2A are averages of flight legs KA-2A and KA-2B.

particles (e.g., Gardiner and Hallett 1985; Gayet et al. 1996).

Kristovich and Braham (1998) conducted a study to determine the best way to calculate liquid water content (LWC) in similar lake-effect conditions. Examination of a large number of FSSP spectra in lake-effect boundary layers revealed that particle spectra typically exhibited a peak in particle concentrations for small sizes with a low-concentration “tail” for large sizes. LWC values calculated using the entire spectra would often be falsely large. Comparison of LWC derived from adiabatic lift near the surface, FSSP, King, and Johnson–William probes, as well as the correspondence of peak LWC with locations of upward vertical velocity, revealed that use of the first five bins of FSSP-observed particle concentrations provided the best estimates. As will be discussed later, the same particle spectra patterns were observed in the present dataset, allowing the method developed by Kristovich and Braham (1998) to be used for the present study.

Snow particle concentrations were measured using two optical array probes, the Particle Measuring Systems, Inc., 2D-C and two-dimensional precipitation probe (2D-P). On this date, the UWKA 2D-C probe measured particles with diameters up to 6000 μm while the 2D-P probe measured particles with diameters up to 8000 μm. Observed particles were partitioned into 20 size bins of varying width. The Illinois Interactive Processing and Analysis System Software (II-PASS; Rauber et al. 1995) was used to calculate particle concentrations and display the corresponding size distributions derived from data collected by both the 2D-C and 2D-P probes on the Electra. Specific information on how II-PASS was used and settings for the automatic analyses of these data are in Barthold (2008). The University of Wyoming provided particle concentrations at a rate of 1 s⁻¹ for the 2D-C and 2D-P probes on the UWKA. These data compared well with the II-PASS-derived Electra observations and were used for this study. Ice water content values were calculated using 2D-C snow particle concentration observations in the equation:

\[ IWC_{total} = \int IWC_x M(D_x)N(D_x) \, dx \]

where \( D_x \) is the mean diameter of particles in bin \( x \) in mm, \( N(D_x) \) is the number of particles in that size bin, and \( M(D_x) \) is the mass of those particles in mg; \( M(D_x) \) was calculated from the size–mass relationship derived by Black (1990):

\[ M(D_x) = 0.026D_x^3. \]

This relationship was found by Braham et al. (1992) to be representative of a group of such relationships most appropriate for particle probes, using data from a previous lake-effect field experiment.
Some problems in the 2D particle probe datasets, such as erroneous negative bin concentrations or repeated values in areas of very low ice content and incorrect particle categorization in the smallest size bins in the Electra data, are well known. These issues were addressed as described in Barthold (2008).

3. Synoptic and boundary layer evolution

The lake-effect snow event observed over Lake Michigan on 10 January 1998 occurred behind a cold front that crossed the lake during the previous evening. At the surface, an approximately 1003-hPa low pressure center was located just northeast of Lake Superior, and surface winds were from the southwest to west-southwest at approximately 5–10 m s\(^{-1}\). At 500 hPa, a closed upper-level low was centered over the northern Great Lakes and southern Canada. At 1200 UTC, 850-hPa temperatures ranged from approximately \(-19^\circ\) to \(-15^\circ\)C across northern Lake Michigan, and winds were out of the west-southwest at 15–20 m s\(^{-1}\). Both the surface and upper-level features moved slowly between 1200 UTC 10 January and 0000 UTC 11 January, allowing for a prolonged period of west-southwesterly flow over Lake Michigan.

Radar and surface observations indicate that lake-effect snow began over central and northern lower Michigan around 0930 UTC and had organized into widespread wind-parallel bands and cellular convection by 1030 UTC, several hours before the project aircraft began sampling the lake-effect system. Visible satellite imagery from the Geostationary Operational Environmental Satellite-8 (GOES-8) satellite shows widespread lake-effect clouds exhibiting cellular and wind-parallel-banded structures over the lake, with bands oriented from approximately 260\(^\circ\) to 80\(^\circ\) observed over most of lower Michigan (Fig. 1). The Weather Surveillance Radar-1988 Doppler (WSR-88D) radar observations from Grand Rapids, Michigan, illustrate the change in convective organization downwind of the eastern shore of Lake Michigan well (Fig. 2). Over the lake, convective structures appear to be fairly cellular with superimposed bands oriented northwest–southeast. Tripoli (2005) also noted these “type C” bands, which were not evident in the region of aircraft observations used in the present study. By 30–40 km inland, the dominant

![Image](https://example.com/image.png)

**Fig. 2.** Radar reflectivity observed by the NOAA WSR-88D radar in Grand Rapids, MI. These data were taken with an elevation (tilt) angle of approximately 0.5\(^\circ\) at 1615:43 UTC. The time of these observations is very close to that for the satellite image shown in Fig. 1.
banded structure became oriented west-southwest–east-northeast, close to the boundary layer wind direction. The convective structures discussed here are only apparent to approximately 10 km offshore in the radar imagery because even at the lowest elevation angle, the center of the radar beam quickly overshoots the top of the lake-effect convection. At the location of the westernmost radar-observed structures, the center of the radar beam is approximately 900–950 m above the surface, suggesting that much of the radar beam is in clear air above the boundary layer and limiting the ability to observe the true westward extent of the convective structures. Snowfall totals from this event in western Michigan ranged from about 5 to about 51 mm, with most surface sites reporting around 25 mm.

Lake-effect snow developed within a convective boundary layer that formed over Lake Michigan. Several different methods were used to estimate the top of the lake-effect boundary layer, as detailed in Barthold (2008). Two of these methods provided a realistic representation of boundary layer growth across the lake, identified in previous studies as a consistent west–east increase in boundary layer depth (e.g., Chang and Braham 1991; Kristovich et al. 1999; Kristovich et al. 2003; Schroeder et al. 2006). The observed growth of the boundary layer is consistent with project soundings on this date. The first method assumes that the top of the clouds coincides with the lake-effect boundary layer top, as found by several authors (e.g., Chang and Braham 1991). Using this method, the lake-effect boundary layer top was defined as the height at which the percentage of the flight legs with observed clouds (indicated by cloud particle concentrations greater than 10 cm⁻³) decreased most rapidly. The second method sought to determine the height at which the boundary layer updrafts became negatively buoyant by leaving the mixed layer and penetrating into the overlying stable air of the entrainment zone (e.g., Agee and Gilbert 1989; Schroeder et al. 2006). Under this scenario, the boundary layer top was estimated as the height at which the correlation between cloud particle concentrations and potential temperature became negative on average. More traditional methods of identifying the top of the lake-effect boundary layer, such as determining the location of the largest positive vertical gradient in equivalent potential temperature, were not used because they indicated a decrease in the depth of the boundary layer near the downwind shore. Based on these analyses, the lake-effect boundary layer that developed in the vicinity of the aircraft flights on 10 January 1998 was estimated to deepen from approximately 675 m (905 hPa) to 910 m (880 hPa) over the 80 km between the westernmost (KA-1) and easternmost (KA-4) UWKA flight stacks, an increase of 235 m.

The 235-m increase in boundary layer depth observed in this case is smaller than has been observed in many previous lake-effect snow events over Lake Michigan (e.g., Chang and Braham 1991; Kristovich et al. 2003; Schroeder et al. 2006) and may be the result of a number of different factors. One important factor to consider is the lack of data at the upwind and downwind shores of the lake in the region where the aircraft flights took place. Since the aircraft-based data cannot be accurately extended to the lake shore and other project observational facilities were far to the south, the total upwind shore to downwind shore boundary layer growth cannot be determined as it was in previous cases. Additionally, the westernmost measurement of 675 m indicates a boundary layer depth near the upwind shore that is considerably larger than has been observed in previous cases. Lake-ICE soundings (Barthold 2008) and lidar observations (University of Wisconsin, see online at http://lidar.ssec.wisc.edu/experiments/lakeice) taken upwind of Lake Michigan about 60 km to the south of the flights also show a boundary layer greater than 500 m deep. Heat and moisture fluxes from the lake surface must mix over this initially deep boundary layer, possibly resulting in less rapid boundary layer growth overall.

4. Microphysical evolution

a. Cloud evolution

Cloud particle concentrations were measured by the FSSP carried by the UWKA. Figure 3 shows the flight leg average size distributions of cloud particle concentrations at various heights across the lake, while Table 1 gives estimated cloud liquid water content and total cloud particle concentration.

While no clouds were observed by the FSSP in the westernmost flight stack (KA-1), they were present in the second King Air flight stack (KA-2), indicating that clouds formed between 11 and 39 km downwind from the Wisconsin shore. Observations from an upward-pointing radiometer located on the Electra show that, on average, frequent clouds were first encountered 14–18 km from the Wisconsin shoreline (not shown), several kilometers downwind from KA-1. Cloud particle concentrations increased from west to east across the lake with maximum flight leg average cloud particle concentrations increasing from approximately 380 cm⁻³ in the second flight stack (KA-2) to approximately 675 cm⁻³ in the fourth flight stack (KA-4). In addition, pass-average liquid water content increased to over 0.45 g m⁻³ in the fourth flight stack. The increase in cloud cover with eastward distance from the upwind (Wisconsin) shore is confirmed by visible satellite imagery, radiometric
temperature data, and the percentage of each flight leg in which cloud particle concentrations were greater than 10 cm$^{-3}$ (Barthold 2008).

Within each flight stack, the maximum flight leg average cloud particle concentration and liquid water content values were found just below the top of the boundary layer (in flight legs KA-2C, KA-3B, and KA-4A). The overall maximum values were observed in KA-4A. In each flight leg that contained clouds, the maximum concentration values occurred in bins 2–4, which corresponds to particles with diameters of 5–14 μm (Fig. 3). Cloud bases could not be reliably determined, but were below 640 m and above 100 m, based on aircraft observations.

Cloud particle concentrations in all flight stacks with clouds decreased above the mean top of the boundary layer. Some of this decrease is due to the increasingly limited number of cloudy updrafts that are able to penetrate into the stable layer above the mean boundary layer top. Another possible contributing factor for this decrease is that entrainment of dry air reduced the number of cloud particles. As cloud particles evaporate in response to drier entrained air, some snow particles would be expected to remain due to their slower evaporation rate. Indeed, the percentage of each flight segment that contains snow was observed to be almost twice the percentage of each flight segment that contains clouds above the mean top of the boundary layer (Barthold 2008).

Overall, flight leg average cloud particle concentrations ranged from 200–700 cm$^{-3}$ within the cloud layer, with much lower values within overshooting convective clouds above the average top of the boundary layer. Previous studies of microphysical characteristics in lake-effect storms with widespread wind-parallel bands or cellular convection did not report cloud particle concentration, precluding a comparison. However, Braham (1983) observed similar cloud particle concentrations in shoreline and midlake bands.

b. Snow evolution

The UWKA’s flight pattern on 10 January 1998 allows for the evolution of snow particles throughout the lake-effect boundary layer to be determined while the numerous low-level flights conducted by the Electra allow for continuous observations of lower-boundary layer conditions over the flight period. A direct comparison between the snow particle concentration data observed by the two aircraft cannot be made due to spatial and temporal differences in the data.
Figure 4 shows flight leg average snow particle size distributions measured by both the 2D-C and 2D-P probes at various levels across the lake. Total estimated ice water content and snow particle concentrations are given in Table 1. Snow was observed in all 18 UWKA flight legs by either the 2D-C or the 2D-P probe, although in small concentrations above the average top of the boundary layer. The 2D-P consistently measured lower concentrations overall, which has been previously attributed to the lower resolution of the probe relative to the 2D-C (Gordon and Marwitz 1984; Braham 1990). This is consistent with the improved agreement between the observations from the two probes for larger particle sizes. Regardless, the two probes generally showed a similar pattern in their size distributions.

Within each flight stack, the maximum concentration values from both probes were typically found in the flight legs flown approximately 650 m above the lake surface, the lowest in-cloud flight legs (Table 1). The decrease in snow particle concentrations observed below the cloud base may be due to either aggregation or evaporation. While aggregation was observed, ice water content was also found to decrease from the cloud layer to near the lake surface, indicating some snow evaporation. Flight leg average values of relative humidity with respect to ice (RH_{ice}; Barthold 2008) were less than 100% on average in much of the subcloud layer, supporting snow particle evaporation.

Interestingly, both probes observed snow in the westernmost flight stack. Some particle growth is apparent toward the east; ice water content continually increased across the lake. Maximum particle diameters were around 800 μm in the western flight stacks, while particles with diameters up to 2000 μm are observed in the eastern two flight stacks. Such growth would be anticipated as the cloud layer thickened. Return of snow particles to higher cloud levels by turbulent and mesoscale updrafts is thought to also play a significant role in snow particle growth (Kristovich and Braham 1998). Significant areas of vertical motions greater than 1 m s⁻¹,
suggesitive of upward ice fluxes, were observed in portions of all flight legs at altitudes with snow. Unlike cloud particle concentrations, the maximum snow particle concentrations were found over the middle of the lake. Maximum 2D-C snow particle concentrations were found in the second flight stack, while maximum 2D-P snow particle concentrations were found in the third flight stack.

Previous studies that discussed the microphysical characteristics of lake-effect snow typically used the 200Y probe, which measures particles from 300–4500 μm in diameter, to measure snow particles. Since this size range is similar to the particle size range measured by the 2D-P probe in the current study, these observations were used for comparison. The average snow particle concentration values measured by the 2D-P probe in the current study are quite similar to the snow particle concentrations reported in Braham (1983) and Chang and Braham (1991), which were less than 10 L cm−1 for both shoreline and widespread lake-effect cases. With the exception of the first flight stack, the aircraft observed snow during 80%–100% of each flight leg, which is similar to the values reported in previous studies of lake-effect snow.

5. Noteworthy microphysical features

Figure 4 reveals two surprising features of the evolution of lake-effect clouds and snow on 10 January 1998. First, snow was observed by both the 2D-C and the 2D-P probes in the flight stack closest to the upwind shore even though there were no cloud particles observed by the FSSP (Fig. 3). Second, snow particle concentrations were observed to peak in the middle flight stacks, then decrease toward the downwind shore. These features are discussed below.

a. Snow particles upwind of lake-effect clouds

Three hypotheses were investigated that may explain the presence of snow upwind of clouds. First, it is possible that the snow observed in the westernmost flight stack was blown over the lake from the snow-covered Wisconsin surface (greater than 12 cm of snow fell on 8 January across eastern Wisconsin, see online at http://mrcc.isws.illinois.edu). Blowing snow would allow ice particles to be observed over the lake without associated clouds. If blowing snow were responsible, the relatively high concentrations of snow particles observed near the top of the boundary layer (near 650 m) would have to be explained. Strong vertical motions over the westernmost few km of the lake have been observed and simulated for this case (e.g., Mayor et al. 2003; Tripoli 2005). Mixing due to the turbulent motions could disperse this snow throughout the boundary layer. In addition, the decrease in observed snow particle concentration below 656 m (Fig. 4 and Table 1) could possibly be due to particle growth within moist updrafts to sizes large enough to be detected by the probes. However, it should be noted that relative humidities with respect to ice were subsaturated below 656 m, suggesting particles moving upward would initially experience some evaporation before nearing the cloud level.

Surface air temperatures near −19°C and wind speeds of 5–10 m s−1 were observed at Green Bay, Wisconsin, near the time of aircraft observations. These were generally representative of those along the upwind shore of Lake Michigan (Barthold 2008). This information can be used to assess the likelihood of blowing snow. Li and Pomeroy (1997) examined the likelihood of observed blowing snow for a wide range of surface snow conditions, air temperatures, wind speeds, and snow age. Given the observed surface conditions, the probability of blowing snow increased from <10% at 5 m s−1 up to almost 80% at 10 m s−1, depending on the time since snow fell. This suggests that blowing snow was possible, but not certain, on this date. While this hypothesis cannot be ruled out, it should be noted that hourly observations from along the Wisconsin shore do not indicate any blowing snow on 10 January 1998.

The second hypothesis for the observation of snow upwind of the lake-effect cloud deck was that the observed snow particles may represent “diamond dust” or “clear-sky ice crystals” (Ohtake et al. 1982). Observational studies from Antarctica found that diamond dust formed as a result of homogeneous nucleation at temperatures of −40°C in an ice saturated layer near the surface (Hogan 1975). Ohtake et al. (1982) observed diamond dust at temperatures above −22°C in Barrow, Alaska. In the current case, an ice saturated layer was observed around 650 m, although relative humidities with respect to ice at the other levels in the upwind flight stack were only 80%–90%. The temperature in the ice saturated layer was around −24°C, which is sufficient for diamond dust formation based on Ohtake et al. (1982), but much warmer than the temperatures at which diamond dust was observed by Hogan (1975). While diamond dust formation may have been possible around 650 m, the marginal temperature and humidity conditions throughout the rest of the upwind flight stack make it unlikely that most of the observed snow particles can be attributed entirely to diamond dust.

The final hypothesis was that the snow may have been left behind by transient clouds that formed, produced ice crystals, and dissipated before they could be observed. Imagery from a forward video taken on the UWKA (Fig. 5) indicates two locations where transient liquid clouds were present. Near the surface of the lake, “sea
smoke” with occasional steam devils was observed. Such sea smoke was present across the entire lake on this day according to the flight scientist notes. Snow particles could possibly be generated in sea smoke and carried upward in turbulent eddies. However, as in the blowing snow hypothesis, it is unclear why larger concentrations of ice were observed at higher altitudes. In addition, a few widely scattered clouds were visible in the region of the westernmost flight stack (Fig. 5). If transient clouds near the top of the boundary layer were responsible for the observed snow, it might be expected that snow particles would be present in specific regions where the clouds had been. Other than a few locations with much higher concentrations near the boundary layer top, time series of snow particle concentrations for each flight leg within the boundary layer during the upwind flight stack show that snow was observed nearly continuously. Strong turbulent motions such as those discussed earlier could account for the uniformity observed in the snow particle concentrations.

While none of these three proposed mechanisms were conclusively shown to be the cause of snow upwind of initial cloud deck formation in the 10 January 1998 case, the widely scattered clouds observed near the Wisconsin shoreline seen in the UWKA video and the observation of snow particles throughout the boundary layer with a maximum near the boundary layer top make such transient clouds the most likely explanation for the majority of the observed snow.

b. Midlake peak in snow particle concentration

A second noteworthy feature revealed by the present analyses is a midlake peak in snow particle concentrations, despite steadily increasing ice water content across the lake. This peak was observed distinctly in the snow particle size distributions observed by the UWKA and to a lesser extent in the flight leg time series of low-level snow particle concentrations observed by the Electra (Fig. 4). West of the midlake peak, the size distributions in the current case have large negative slopes, characterized by a large number of small particles, but very few large particles. Between the first and second flight stacks, the number of small particles increases while the number of large particles remains about the same. The large negative slopes and increasing number of small particles are indicative of vapor deposition dominating the snow growth process west of the midlake peak in snow particle concentrations (Lo and Passarelli 1982). East of the midlake peak, the size distributions from 10 January 1998 have smaller negative slopes and are characterized by a decrease in the number of small particles and a substantial increase in both the number and size of the large particles. The decrease in slope between the second and third flight stacks suggests a transition to a combination of deposition and aggregation dominating the snow growth process (Lo and Passarelli 1982).

Although similar changes in slope are more difficult to detect in the Electra data because of the limited eastward extent of the flights, there is weak evidence of a decrease in slope near the easternmost ends. Perhaps as importantly, however, the Electra observations indicate little change in particle size spectra with time. Figure 6 shows approximate snow particle spectra slopes at two locations, 87.3°W (west of the midlake peak observed by the UWKA) and 87.0°W (east of the peak). These are subjectively determined based on calculated average concentrations taken between ±0.05° of the indicated longitudes. At 87.3°W, large negative slopes are observed, with little change until after 1715 UTC. After that time, overall particle concentrations began to decrease, but the large slopes remained. At 87.0°W, smaller negative slopes were evident throughout the observational period, despite a decrease in total snow concentration after about 1806 UTC. While UWKA observations in the easternmost flight stack (KA-4) were likely affected by the observed weakening trend in the lake-effect system near the end of the aircraft observational period, the overall conclusion of a change in slope is supported by the Electra observations.

6. Summary and conclusions

While the growth of the lake-effect boundary layer has been the subject of numerous studies, less is known about how the clouds and snow that develop within the boundary layer evolve between the upwind and
downwind shores of the lake. This study seeks to develop an understanding of the microphysical evolution of clouds and snow in a lake-effect boundary layer during a lake-effect snow event with widespread wind-parallel bands and cellular convection. The data used in this study were collected over Lake Michigan on 10 January 1998 during the Lake-Induced Convection Experiment (Lake-ICE). The quasi-steady-state nature of this event throughout the majority of the observational period made it ideal for investigating the evolution of clouds and snow across the lake within a lake-effect boundary layer.

Figure 7 summarizes the processes believed to be associated with the evolution of lake-effect clouds and snow on 10 Jan 1998. Points indicate the location of individual flight legs within each King Air flight stack. The gray curve indicates the approximate location of the mean top of the lake-effect boundary layer. The solid black line indicates the location of the highest overshooting cloud tops. The dashed black line indicates that the cloud base is unknown but at or below this level.

Four flight stacks were conducted by the UWKA, starting on the west side of Lake Michigan. A lake-effect liquid cloud deck initially developed downstream of the first UWKA flight stack, 14–18 km from the Wisconsin shoreline. Once clouds formed, average cloud particle concentrations were found to increase from 380 cm\(^2\) in the second UWKA flight stack to about 675 cm\(^2\) in the fourth UWKA flight stack, with maximum cloud particle concentrations typically found just below the top of the boundary layer. Most of the clouds that were observed were confined to the boundary layer, but overshooting cloud tops were found in flight legs that occurred above the mean top of the boundary layer. Entrainment of dry air and an increasingly limited number of cloudy updrafts that are able to penetrate into the stable layer above the mean boundary layer top are thought to have played a role in limiting the cloud particle concentrations observed above the mean top of the boundary layer. Overall, concentrations in regions with clouds ranged between 200 and 700 cm\(^2\).

Snow particles were observed in all four UWKA flight stacks by both the 2D-C and 2D-P probes. Total ice water content increased across the lake (and, by inference, snowfall rate; see Braham et al. 1992) while snow particle concentrations increased from the upwind shore toward the middle of the lake, then decreased from the middle of the lake toward the downwind shore. Maximum snow particle concentrations were typically found in the lowest in-cloud flight leg. Evaporation was shown to be the likely cause of the decrease in snow
particle concentrations below cloud base as flight leg average relative humidity with respect to ice indicated unsaturated air below cloud base. Overall, flight leg average snow particle concentration values observed by the UWKA 2D-C probe ranged from 0 to 32 L⁻¹ while values from the 2D-P probe ranged from 0 to 6 L⁻¹.

The analysis of the evolution of clouds and snow across Lake Michigan on 10 January 1998 revealed two unanticipated features. First, snow particles were observed by both the 2D-C and 2D-P probes in the westernmost UWKA flight stack even though the FSSP did not observe any cloud particles in this region. Transient clouds, blowing snow, and Diamond dust were all hypothesized as possible reasons for the observation of snow in this region. While the investigation of the three proposed mechanisms did not strictly rule any of them out, transient clouds that formed, produced snow, and dissipated before they were observed are believed to account for the majority of the observed snow. The transient cloud hypothesis would explain the observation of snow particles throughout the upwind flight stack and is strengthened by the observation of widely scattered small clouds near the Wisconsin shoreline in a video taken by the UWKA.

The second surprising feature was the observed peak in snow particle concentrations near the middle of the lake. An analysis of the slope of the size distributions revealed that the midlake peak in snow particle concentration indicates the location after which aggregation begins to dominate the snow growth process. Snow particle size distributions from the Electra at locations both upwind and downwind of the midlake peak confirm that the transition toward aggregation dominating the snow growth process occurred as a result of distance and not as a result of the temporal difference between the UWKA flight stacks.

Further studies of lake-effect cloud and snow evolution are needed to understand the features observed on 10 January 1998. In particular, determining how often snow is observed prior to cloud deck formation near the upwind shore and whether the midlake peak in snow particle concentration is a typical feature is important to the overall understanding of the formation and maintenance of lake-effect snow events. Both of these features may have implications for the resulting intensity of lake-effect snow. For example, the presence of snow particles prior to cloud development near the upwind shore may aid in the formation of significant downstream snowfall in conditions under which it might otherwise not develop. Similarly, the location of the midlake peak in snow particle concentration and the associated transition to aggregational growth may influence the amount and intensity of snow that is observed along the downwind shore. The opportunities for numerical model verification will allow improvements to be made to model forecasts of lake-effect snow.

Finally, the small amount of boundary layer growth observed in the current study made the relationship between cloud and snow evolution and boundary layer growth difficult to document. Additional observations of cloud and snow evolution in lake-effect snow events with more rapid boundary layer growth would be useful to help better quantify the relationship that appears to exist between cloud and snow formation and increased boundary layer growth rates.

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