J5.5 THE EVOLUTION OF LAKE-EFFECT CLOUDS AND SNOW ACROSS LAKE MICHIGAN

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1. BACKGROUND

Lake-effect snow is a common occurrence in the late fall and winter downwind of the North American Great Lakes. It forms when cold air flows over relatively warm lake water, creating convective instability in an otherwise stable environment (Niziol et al. 1995). Lake-effect snow storms develop and evolve entirely within a Type I cloud-topped boundary layer; the clouds associated with this type of boundary layer form due to strong vertical motions and heat and moisture transport from the warm water below (Agee 1987). Since the primary source of energy for this type of boundary layer is the temperature difference between the water and the overlying air instead of direct solar radiation, this type of boundary layer can persist for multiple days.

Lake-effect storms can have dramatic impacts on the local and regional climate. For example, energy transfers over the lakes produce increases in fall and winter cloudiness, precipitation, and temperature (numerous studies, such as Scott and Huff 1996), decreases in surface pressure (e.g., Petterssen and Calabrese 1959), and alterations in the evolution and movement of cyclones passing over the lakes (e.g., Weiss and Sousounis 1999; Angel and Isard 1997). Societal and economic impacts of lake-effect storms are generally associated with large snowfall amounts (e.g., Niziol 1987). Lake-effect storms can produce large amounts of snow (frequently observed to be greater than 30 cm in 24 hr) and snowfall rates exceeding 4 cm hr^{-1} at times. Such large amounts of snow can have large impacts on communities near the lakes, including disruptions to land and air traffic, elevates snow-removal costs, and personal injuries (e.g., Rodriguez et al. 2007).

Although lake-effect snow can result in important impacts, its evolution within the lake-effect boundary layer has not been widely documented. Observations from various cases over Lake Michigan indicate that cloud base is often located between 100 m and 500 m above the lake surface and that cloud droplet concentrations range from 200-700 cm^{-3}, with higher values in updrafts (Braham 1983, 1990). There is some evidence that cloud base increases with distance across the lake (Agee and Hart 1990, Chang and Braham 1991), which may be the result of entrainment of drier air into the boundary layer. Numerous studies have found the lower portion of the lake-effect boundary layer to be 70-90% snow filled (e.g., Braham 1990; Chang and Braham 1991; Kristovich et al. 2003). Cloud and precipitation development, which is common in lake-effect systems, has been found to enhance boundary layer growth rates in both lake-effect (Chang and Braham 1991, Schroeder et al. 2006) and non-lake-effect cases (Boers and Melfi 1987, Stevens 2007).

While many studies have discussed some aspects of the microphysical characteristics of a

Figure 1. GOES 8 visible satellite image of Lake Michigan from 1645 UTC 10 January 1998 showing a widespread lake-effect event. The red line indicates the approximate location of the low level Electra flights. Blue lines indicate the approximate locations of the four King Air flight stacks.

lake-effect snow event, the detailed microphysical evolution of clouds and snow within the lake-effect boundary layer has not been well documented. The current work seeks to understand the evolution of clouds and snow within the boundary layer during a widespread, wind parallel band lake-effect snow event over Lake Michigan.

2. DATA

This study utilizes observations of a lake-effect snow event taken during the Lake-Induced Convection Experiment (Lake-ICE, Kristovich et al. 2000), which was conducted over Lake Michigan during December 1997 and January 1998. Figure 1 shows the locations of the coordinated aircraft flights conducted on 10 January 1998 overlaid on a visible satellite image of Lake Michigan. The National Center for Atmospheric Research (NCAR) Electra flew thirty east-west oriented flight legs at 170-270 m above the lake. These flight legs began about 11 km from the Wisconsin shoreline and continued east to a point about 51 km from the shore, eventually extending 67 km from the shoreline later in the period. The University of Wyoming King Air flew four approximately north-south flight stacks, with each flight stack containing four to five flight legs at different altitudes both within and above the boundary layer. The flight stacks were flown approximately 11 km, 39 km, 67 km, and 91 km from the Wisconsin shore. Both planes carried a variety of sensors for observing the microphysical, radiative, and thermodynamic properties of the atmosphere. The Forward Scattering Spectrometer Probe (FSSP), which measures cloud particles, and the two dimensional cloud and precipitation probes (2D-C and 2D-P), which measure snow particles, were particularly useful for this study.

3. SYNOPTIC AND BOUNDARY LAYER EVOLUTION

On this date, visible satellite imagery (Figure 1) shows a widespread lake-effect event over Lake Michigan with wind-parallel bands oriented approximately from the west-southwest to the east-northeast. These lake-effect clouds

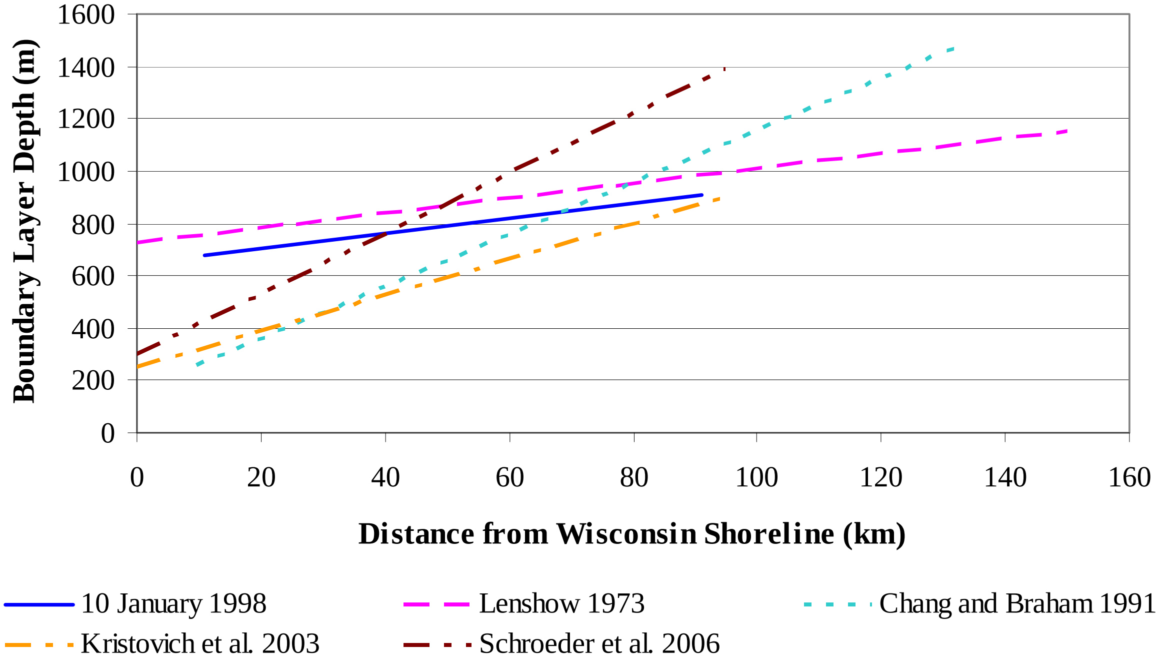

Figure 2. Comparison of boundary layer growth between the upwind and downwind shores of Lake Michigan between the current case (10 January 1998) and four previously observed lake-effect snow events. A linear interpolation between the boundary layer depth near the upwind and downwind shores is shown for all cases.

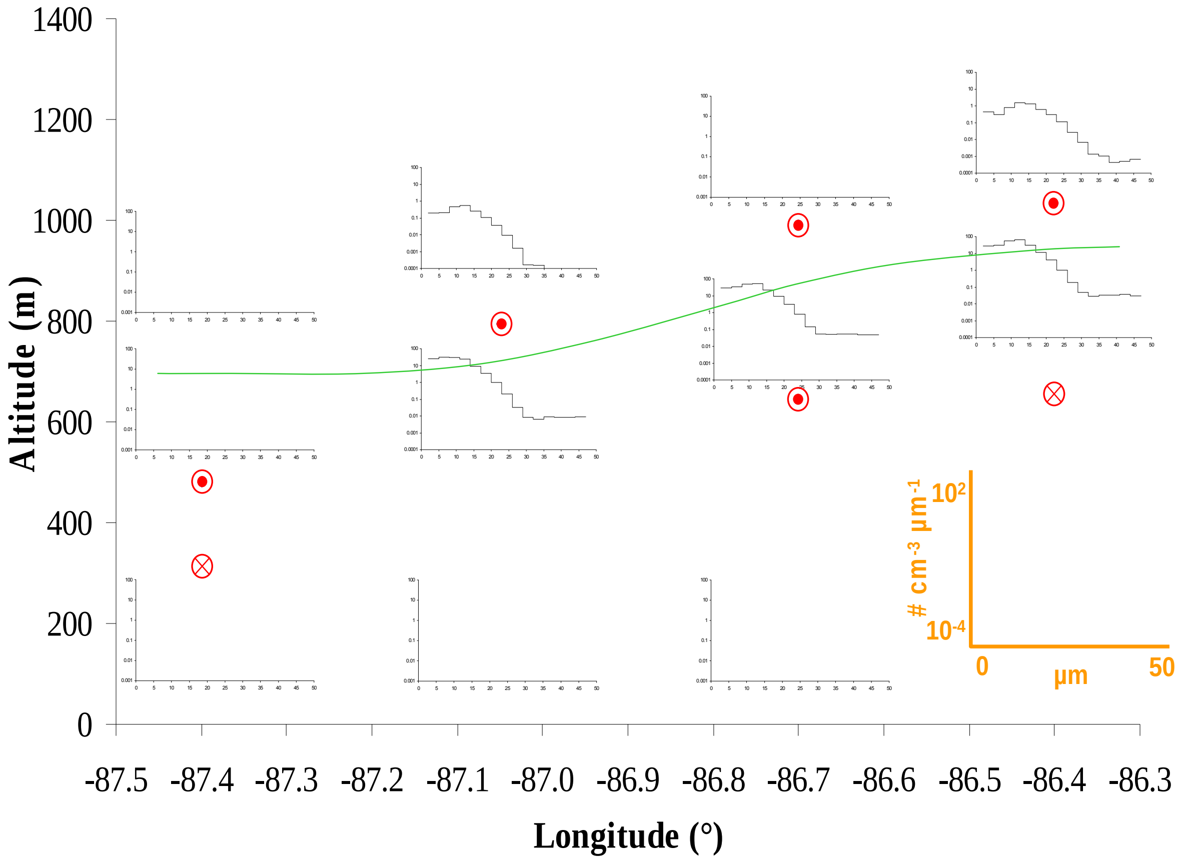

Figure 3. Flight leg average cloud particle size distributions measured by the FSSP. Red symbols indicate the locations of additional King Air flight legs that were not included due to limited space. The green line indicates the approximate location of the top of the lake-effect boundary layer on 10 January 1998. The orange graph indicates the scale of the size distribution plots.

developed behind a cold front that crossed the region during the evening of 9 January. At the surface, an approximately 1003 hPa low-pressure center was located just northeast of Lake Superior, and winds were from the west-southwest at approximately 5-10 m s^{-1}. At 850 hPa, temperatures were between -15ºC and -19ºC across northern Lake Michigan, with winds out of the west-southwest at 15-20 m s^{-1}. With Lake Michigan surface temperatures of approximately 4°C, the temperature difference between the lake surface and the air at 850 hPa on 10 January 1998 exceeded the 13ºC difference typically associated with significant lake-effect storms (e.g. Rothrock 1969; Niziol 1987). Although lake-effect precipitation occurred for much of the day, snowfall amounts in western Michigan were generally less than five centimeters.

Within this synoptic environment, a lake-effect boundary layer developed over Lake Michigan. Aircraft observations were used to determine the lake-effect boundary layer growth across the lake based on multiple atmospheric variables. These methods are described in Barthold and Kristovich (2008) and Barthold (2008) and are consistent with those used by previous observational studies (e.g., Agee and Gilbert 1989; Braham 1990; Chang and Braham 1991; Braham and Kristovich 1996; Kristovich et al. 2003). On 10 January 1998, the lake-effect boundary layer was estimated to increase in depth from approximately 675 m to 910 m over the 80 km distance between the westernmost and easternmost King Air flight stacks. As shown in Figure 2, the 235 m increase in boundary layer depth observed in this case is smaller than has previously been observed in lake-effect events with precipitation (e.g., Chang and Braham 1991; Kristovich et al. 2003; Schroeder et al. 2006). While some of this difference may be the result of a lack of suitable observations very near the upwind and downwind shores, it is interesting to note that the initial depth of the boundary layer near the upwind shore in the current case is deeper than was observed in previous cases with precipitation. Given the otherwise limited boundary layer growth, the increased depth near the upwind shore may indicate that less growth is needed in order to reach a depth at which significant clouds and snow can form.

4. CLOUD AND SNOW EVOLUTION

4.1 *Cross-Lake Evolution*

Figure 3 shows size distributions of cloud particles between 0-50 μm in diameter averaged over each King Air flight leg. King Air observations indicate that clouds developed between 11 and 39 km from the Wisconsin shore, the locations of the two westernmost flight stacks. Observations from an upward pointing radiometer located on the Electra are consistent, showing that, on average, clouds were first encountered near the westernmost flight stack 14-18 km from the shoreline. Once clouds formed, they were generally observed in all flight legs except those closest to the surface of the lake. Average cloud particle concentrations increased across the lake from about 380 cm^{-3} in the west to 540 cm^{-3} in the east. Within each King Air flight stack, cloud particle concentrations increased upward from cloud base to maximum values in the flights immediately below the mean top of the boundary layer. Above these maximum values, cloud particle concentrations were observed to decrease with height, with the smaller concentrations above the mean top of the boundary layer indicating the presence of occasional overshooting cloud tops.

Above the mean top of the boundary layer, the percentage of each flight segment that contains snow is almost twice the percentage of each flight segment that contains clouds (not shown). Since snow is observed much more frequently than clouds above the top of the boundary layer, entrainment of dry air may be

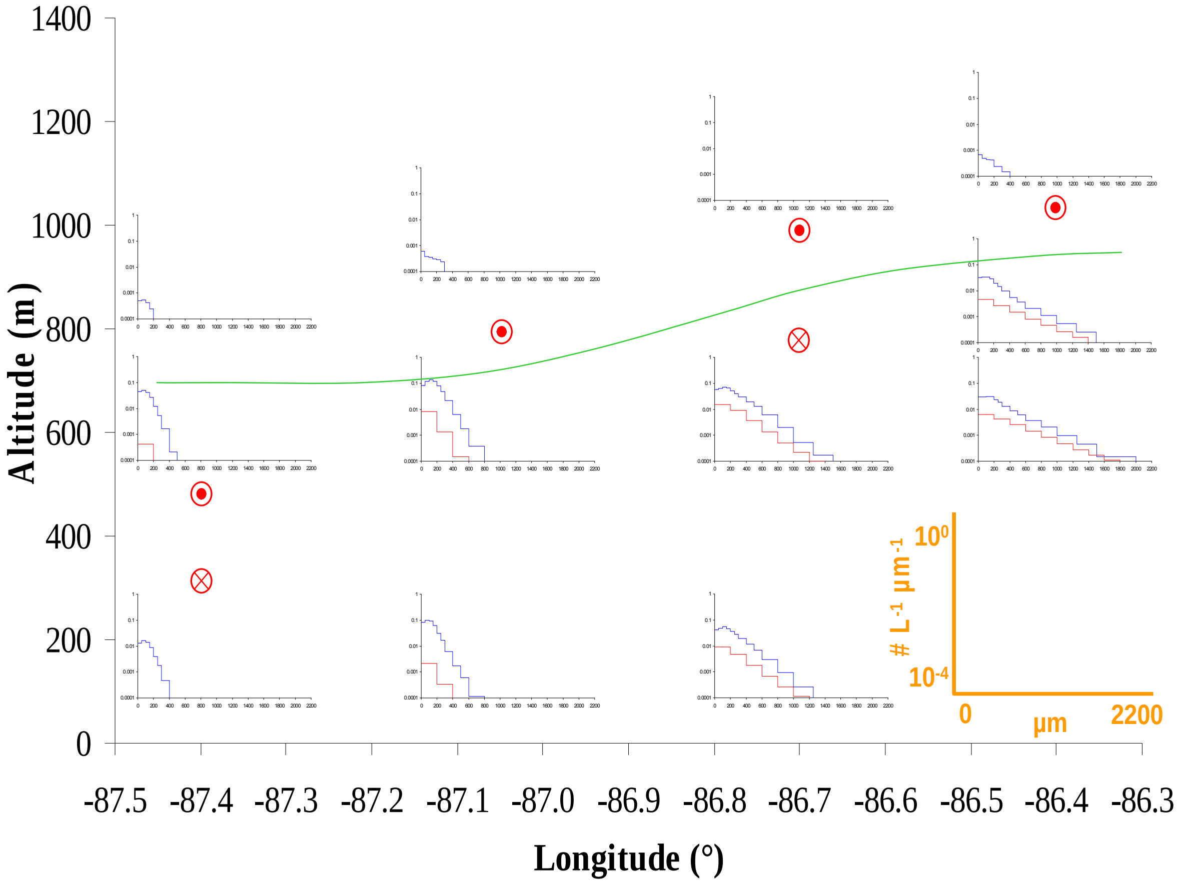

Figure 4. Flight leg average snow particle size distributions measured by the 2D-C probe (blue) and the 2D-P probe (red). Red symbols indicate the locations of additional King Air flight legs that were not included due to limited space. The green line indicates the approximate location of the top of the lake-effect boundary layer on 10 January 1998. The orange graph indicates the scale of the size distribution plots

playing a role in reducing the concentration of cloud particles, since cloud particles would tend to evaporate more rapidly than snow particles within a mixed phase cloud.

The evolution of snow across Lake Michigan was examined using size distributions of snow particles between 0-2200 μm in diameter averaged over each King Air flight leg (Figure 4). Snow particles were observed throughout all four King Air flight stacks, with maximum concentration values found over the middle of the lake. Small particles dominated over the western portion of the lake, and particles became larger with distance to the east. Maximum snow particle concentrations ranged from 9 L^{-1} to 32 L^{-1} and typically occurred in the lowest flight leg within the cloud layer. Concentrations were observed to decrease both below cloud base and above the mean top of the boundary layer.

The decrease in snow particle concentration values below cloud base can be attributed to either evaporation or aggregation. Evaporation decreases snow particle concentrations by reducing the total amount of snow, while aggregation decreases snow particle concentrations by merging small particles to create larger particles. Flight leg average ice water content values were observed to decrease below cloud base, suggesting that evaporation was largely responsible for this observed decrease. Additionally, the air was supersaturated with respect to ice within the cloud layer, but unsaturated near the lake surface. Since snow must fall through an unsaturated environment for some portion of the distance between cloud base and the surface of the lake, some evaporation of snow particles can be inferred.

4.2 *Surprising Features*

The evolution of clouds and snow across Lake Michigan on 10 January 1998 reveals two surprising features. First, snow was observed in the flight stack closest to the upwind shore even though no clouds were observed. Second, snow particle concentrations decreased downwind of the middle of the lake.

Three hypotheses that may explain the presence of significant snow particle concentrations upwind of the location where clouds were first observed were investigated. The first hypothesis was that the snow observed in the upwind flight stack was blown off the snow-covered Wisconsin land mass and out over the lake. The second is that the observed snow particles may represent "diamond dust," which is clear-sky ice crystals that are most often observed in arctic regions at very cold temperatures (Hogan 1975, Ohtake et al. 1982). Finally, the snow may have been left behind by transient clouds that formed, produced snow, and dissipated before they could be observed.

The investigation of the three proposed mechanisms for the production of snow upwind of initial cloud formation on 10 January 1998 was inconclusive. There were no observations of blowing snow at the surface observing stations along the Wisconsin shoreline. In addition, maximum snow particle concentrations occurred at a height of about 600 m, which would not be anticipated if blowing snow from Wisconsin was the responsible mechanism. While diamond dust cannot be completely ruled out as a possible formation mechanism, temperature and humidity conditions near the top of the boundary layer were observed to be slightly outside the range of those found in previous studies. Thus, diamond dust formation is unlikely. The remaining hypothesis is that the snow developed within transient clouds upwind of the main lake-effect cloud deck. Although no cloud particles were observed by the FSSP during the upwind flight stack, a video recorded by the King Air does show a few widely scattered clouds in this region. In addition, the radiometer observations from the Electra indicated that clouds were commonly observed only 3-7 km downwind of the first flight stack. This suggests that the most feasible, but not conclusively proven, mechanism is the third hypothesis.

The second interesting feature is the peak in snow particle concentrations near the middle of the lake. Snow particle size distributions in Figure 4 show that over the western portion of the lake (11-39 km from the Wisconsin shore) the snow particles are primarily small, with very few particles greater than 800 μm in diameter. Significantly larger snow particles can be found to the east, with maximum diameters around 2000 μm at a distance 91 km downwind from Wisconsin. Near the location of the midlake peak in snow concentration, the characteristics of the size distributions change. Upwind of the midlake peak, the size distributions are characterized by a large number of small particles, but very few large particles (large negative slopes in Figure 4). Between the two westernmost flight stacks, the large negative slopes of the snow particle size spectra remained nearly constant while the number concentration of all sizes increased. Lo and Passarelli (1982) found that such changes are indicative of deposition dominating the snow growth processes in this region.

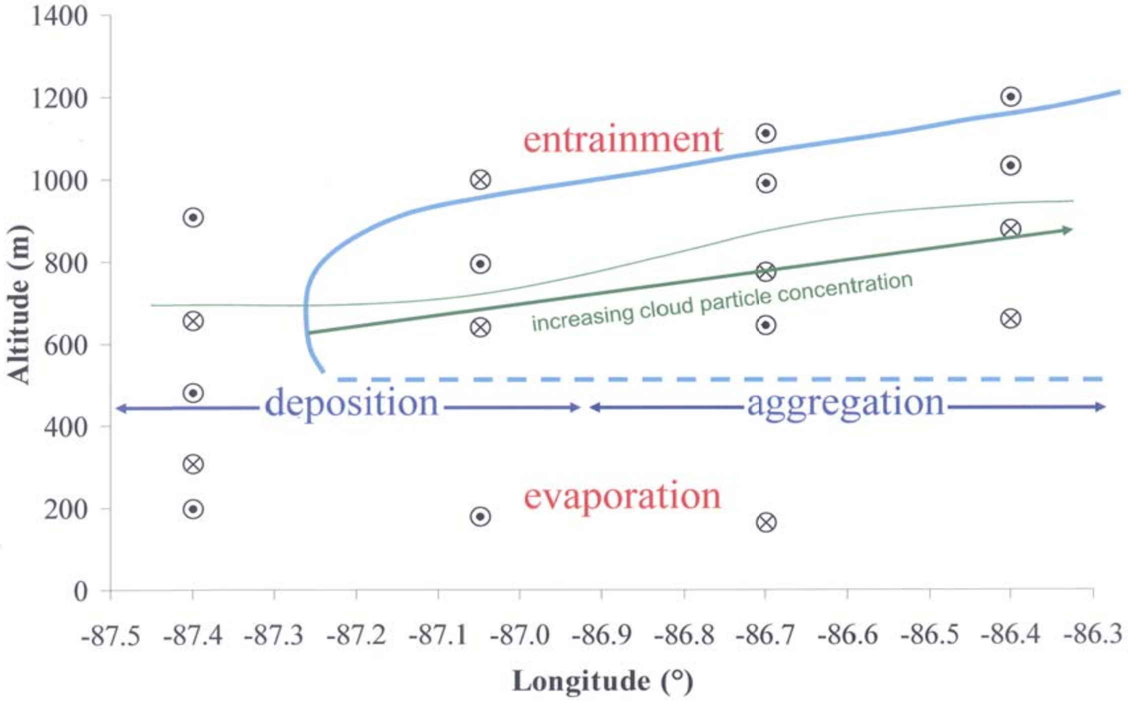

Figure 5. Summary of the processes found to be associated with the evolution of lake-effect clouds and snow on 10 January 1998. Points indicate the location of individual flight legs within each King Air flight stack. The light green line indicates the approximate location of the top of the lake-effect boundary layer. The blue line indicates the location of the clouds.

Downwind of the midlake peak in snow particle concentration, there were fewer small particles, but a significant increase in the number and size of large particles (smaller negative slopes in Figure 4). A similar midlake decrease in the slope of the snow particle size spectra was also observed in the 2D-C observations from the Electra. Lo and Passarelli (1982) argued that this type of change is indicative of aggregation dominating the snow growth process. Therefore, we conclude that changes in snow particle size spectra across the lake indicate that snow growth was primarily through deposition over western portions of the lake, shifting to aggregation as large particles became more prevalent over eastern portions of the lake. The midlake transition between these snow growth mechanisms occurred near the location of maximum snow particle concentrations.

5. CONCLUSIONS

The evolution of clouds and snow within the convective boundary layer is an important part of the lake-effect snow process, but there has been little in-depth work on this aspect of lake-effect storms. Figure 5 summarizes the processes that appear to be associated with the development and evolution of lake-effect clouds and snow on 10 January 1998. This case featured a widespread wind parallel band lake-effect snow event over Lake Michigan in which the boundary layer grew about 235 m. Despite the relatively small amount of boundary layer growth, bands of clouds and snow covered much of the lake. Once clouds formed, cloud base was below a height of 640 m, and cloud particle concentrations increased from west to east across the lake. Above the top of the boundary layer, snow was observed more frequently than clouds, possibly indicating that entrainment limits the number of cloud particles above the top of the boundary layer. Snow was observed throughout the boundary layer, with maximum concentrations in the lowest in-cloud flight segments. Evaporation of snow particles below cloud base is shown to reduce snow particle concentrations near the lake surface.

Two surprising features were revealed during the analysis of cloud and snow evolution. First, snow was observed upwind of significant cloud development near the Wisconsin shoreline. Three hypotheses were investigated to explain this observation. Transient clouds that formed, produced snow, and dissipated before they could be observed were found to be the most likely cause. Secondly, a midlake peak in snow particle concentrations, as measured by the 2D-C probe, was noted in data from both the Electra and the King Air. An analysis of size distributions suggests that this midlake peak represents the distance at which depositional growth becomes less important and aggregation begins to dominate the snow growth process.

Lake-effect snow is the result of complex interactions involving land-air and lake-air exchanges, mesoscale circulations, radiative exchanges, microphysical processes, and a variety of other factors. Given the importance of understanding and predicting lake-effect snow, greater emphasis should be placed on observational and numerical studies of the role of microphysical processes in lake-effect boundary layers under a wide range of conditions.

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