14B.6 THE SPATIAL EVOLUTION OF CLOUDS AND SNOW IN A LAKE-EFFECT BOUNDARY LAYER

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1. INTRODUCTION

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 processes can significantly enhance snowfall on the downwind shore of the Great Lakes.

Although clouds and snow are an important part of the lake-effect system, their 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), and radar observations indicate that the heaviest snow occurs at low levels (Braham 1983). 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 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. The 10 January 1998 lake-effect snow event was chosen to examine the microphysical evolution of clouds and snow for several reasons. During this event, aircraft observations were available at numerous locations throughout the lake-effect boundary layer, lake-effect clouds and snow were widespread, and synoptic scale clouds and snow were not observed in the region during the observational period (approximately 1500 UTC-1900 UTC). Additionally, the lake-effect system as a whole appears to have been in an approximately steady state throughout most of the observational period. Rawinsonde observations taken near the upwind (Wisconsin) and downwind (Michigan) shores of Lake Michigan indicate little change in the boundary layer depth prior to 1800 UTC. Similarly, *in situ* aircraft observations indicate little change in potential temperature or snow particle concentrations, and satellite imagery indicates the location of the upwind cloud edge remained nearly stationary between approximately 1500 UTC and 1800 UTC. The quasi-steady state nature of the event suggests that data from different times during the aircraft flights can be combined to produce an overall view of the evolution of clouds and snow across the lake.

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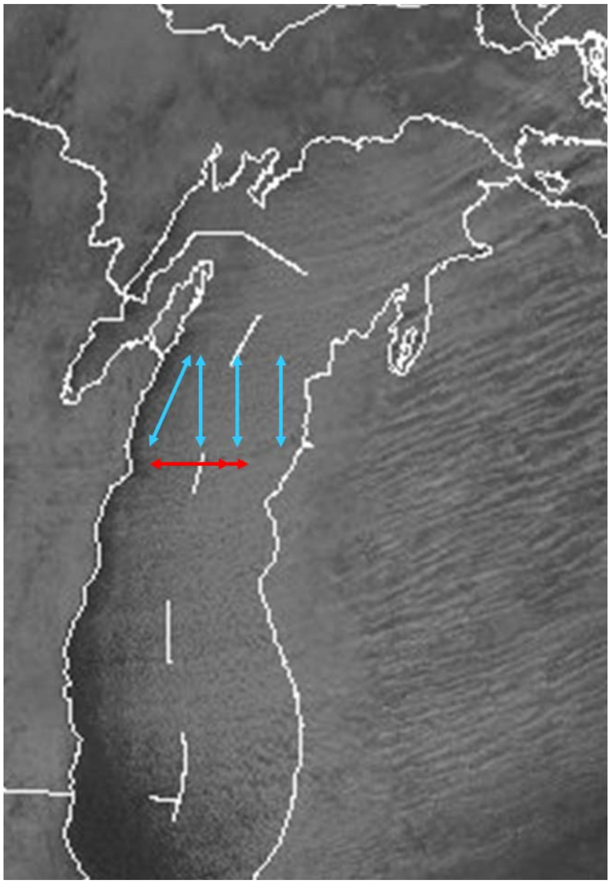

Figure 1. GOES 8 visible satellite image of Lake Michigan from 1645 UTC 10 January 1998 showing a widespread lake-effect event. The red line indicates the approximate location of the low level Electra flights. Blue lines indicate the approximate locations of the four King Air flight stacks.

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 flight legs at 320-400 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 Wisconsin shore, eventually extending 67 km from the Wisconsin 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 upwind shore. Both planes carried a variety of sensors for observing the microphysical, radiation, 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, are of particular interest.

3. 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 developed behind a cold front that crossed the region during the early morning hours of 10 January. At 1200 UTC, surface air temperatures ranged from -19ºC to -11ºC near the north-central portions of the lake. Winds were out of the west-southwest at 5-10 m s^{-1} near the upwind shore and out of the southwest at 5-8 m s^{-1} near the downwind shore. The Lake Michigan surface temperature was approximately 4°C. At 850 hPa, temperatures were between -15ºC and -19ºC across northern Lake Michigan, with winds out to the west-southwest at 15-20 m s^{-1}. The temperature difference between the lake surface and the air at 850 hPa exceeds 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.

The top of the lake-effect boundary layer was identified using a combination of two methods. First, since the lake-effect boundary layer is well mixed compared to the air in the stable layer above, the location of the largest gradient in a variety of atmospheric variables was identified. The second method was to determine the relationship between potential temperature and both clouds and updrafts. A cloud or updraft rising within the boundary layer can overshoot the top of the boundary layer into the stable air above. Since the overshooting cloud or updraft contains relatively cold boundary layer air, observations of clouds or updrafts that are cold relative to their surroundings indicate that they are likely above the mean top of the boundary layer. Therefore, the change in this relationship with height can be used to estimate the top of the boundary layer.

Taking both methods into account, on 10 January 1998 the lake-effect boundary layer was estimated to increase in depth from approximately 910 m near the upwind shore to approximately 1150 m near the downwind shore. This increase in depth of about 240 m over a fetch of 80 km is smaller than has previously been observed in lake-effect cases with precipitation (e.g. Chang and Braham 1991; Kristovich et al. 2003; Schroeder et al. 2006).

4. CLOUD AND SNOW EVOLUTION

4.1 *Cross-Lake Evolution*

Figure 2 shows size distributions of cloud particles between 0-50 μm in diameter averaged over each King Air flight leg. These size distributions indicate that clouds formed between the first and second King Air flight stacks since there were no clouds observed by the FSSP in the flight stack closest to the upwind shore. 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 top of the boundary layer, entrainment may play a role in limiting the number of cloud particles. Dry air from above the boundary layer that encounters a snow filled cloud will generally evaporate the cloud more rapidly than it evaporates the snow particles within it. This difference in evaporation rate is due to both the smaller size of the cloud droplets and the increased vapor pressure over a water droplet compared to an ice particle. Above 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 paying a role in reducing the concentration of cloud particles.

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 3). 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, below the height of the maximum cloud particle concentrations. 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 using multiple 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 is 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.

Two hypotheses may explain the presence of significant snow particle concentrations upwind of the location where clouds were first observed. The first was that the snow may be left behind by transient clouds that formed, produced snow, and dissipated before they could be observed. In fact, a few widely scattered clouds were visible in this region in a video recorded by the King Air. The second was that the snow observed in the upwind flight stack was blown off the snow covered Wisconsin land mass and out over the lake. If transient clouds were responsible for the observed snow, snow particle observations would be expected to be patchy near the upwind shore. Since snow was observed relatively continuously throughout the upwind flight stack, this suggests that transient clouds did not play an important role in its formation. While blowing snow would allow snow

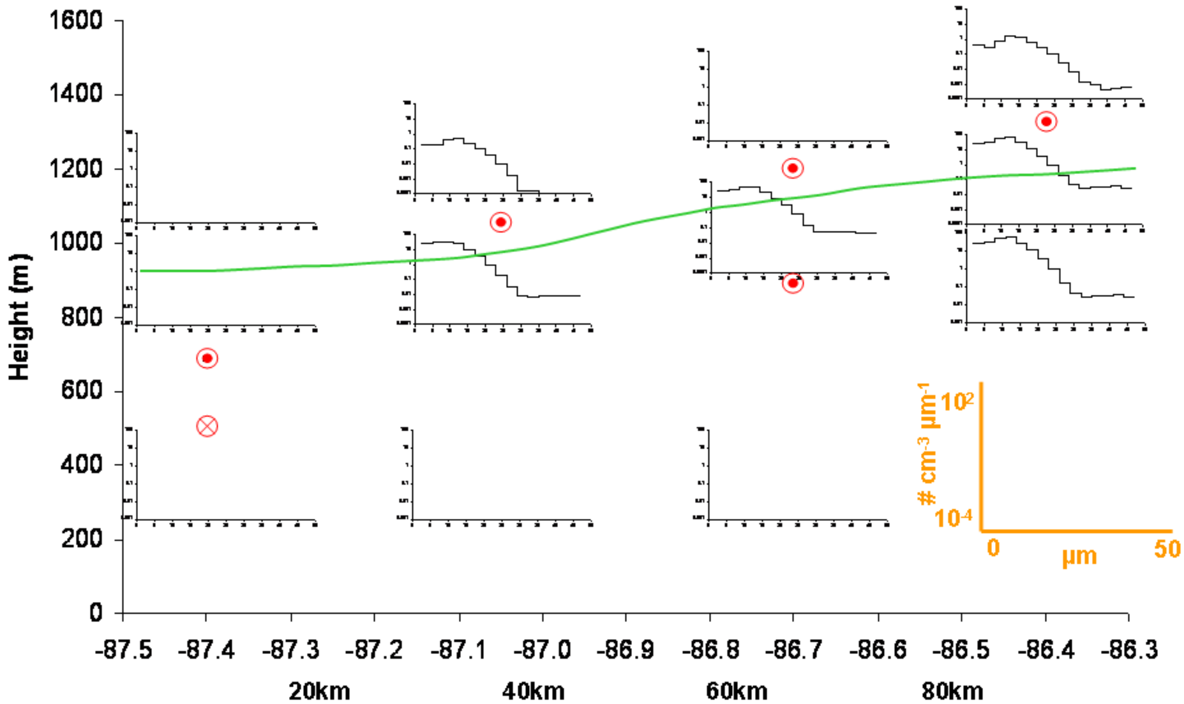

Figure 2. Flight leg average cloud particle size distributions measured by the FSSP. Red symbols indicate the locations of additional King Air flight legs that were not included due to limited space. The green line indicates the approximate location of the top of the lake-effect boundary layer on 10 January 1998. Orange graph indicates the scale of the size distribution plots.

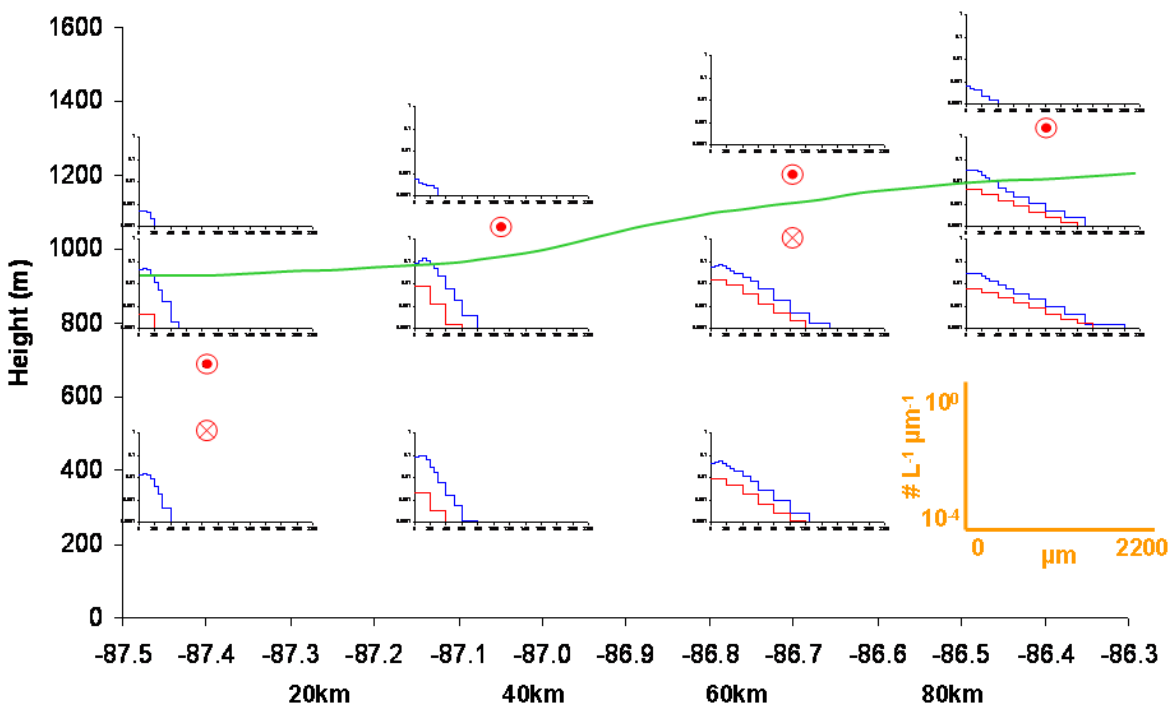

Figure 3. Flight leg average snow particle size distributions measured by the 2D-C (blue) and 2D-P (red). Red symbols indicate the locations of additional King Air flight legs that were not included due to limited space. The green line indicates the approximate location of the top of the lake-effect boundary layer on 10 January 1998. Orange graph indicates the scale of the size distribution plots.

to be observed over the lake without associated clouds, there were no observations of blowing snow at locations along the Wisconsin shoreline on 10 January 1998. Neither transient clouds nor blowing snow appear to explain the observation of significant snow particle concentrations before clouds formed near the upwind shore of the lake. Investigations of other possible explanations are ongoing.

The second interesting feature is a peak in snow particle concentrations near the middle of the lake. Snow particle size distributions in Figure 3 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. West 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 3). East of this point there are fewer small particles, but a significant increase in the number and size of large particles (smaller negative slopes in Figure 3). The shift in the size distributions is thought to indicate a change from deposition dominating snow growth before the midlake peak to aggregation dominating after, with the transition occurring near the location of the peak in 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 4 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 240 m from the upwind shore to the downwind shore. Despite the relatively small amount of boundary layer growth, bands of clouds and snow developed across much of the lake. Once clouds formed, the cloud base was below a height of 880 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. The exact reason for this observation is unknown, although it does not appear to be due to either transient clouds or blowing snow. Secondly, a midlake peak in snow particle concentrations as measured by the 2D-C 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 after which 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.

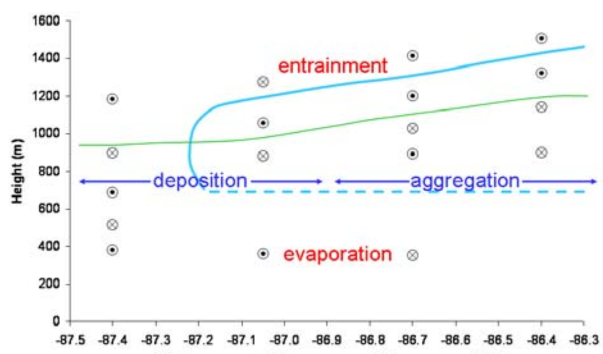

Figure 4. Summary of cloud and snow evolution across Lake Michigan on 10 January 1998 indicating important processes. Points indicate the location of individual flight legs within each King Air flight stack. The green line indicates the approximate location of the top of the boundary layer. The blue line indicates the location of clouds.

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