14.6 Mesoscale and Microscale Field Observations of a Lake-Enhanced Snowstorm

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1. BACKGROUND

Intensification of snows associated with cyclones by heat fluxes from the Great Lakes can result in some of the most intense local snows in that region. While such "lake-enhanced" snowstorms are known to represent important forecast challenges, little is known about the processes over the lakes which result in the heavy snowfall. This study utilizes observations taken during the Lake-Induced Convection Experiment (Lake-ICE, Kristovich et al. 2000) to document mesoscale and microscale interactions between a nearby cyclone and lake-effect processes over Lake Michigan that resulted in heavy near-shore snows.

Past studies offer possible mechanisms by which intense lake-enhanced snows can occur. Limited static stability upwind and over the Great Lakes may allow the lake-effect convective boundary layer to grow deeper. Kristovich and Laird (1998) found that upwind atmospheric stability played a significant role in the rate at which clouds formed over Lake Michigan in several lake-effect cases. Chang and Braham (1991) reported a rapid acceleration in boundary-layer growth rate about halfway across Lake Michigan as the boundary layer penetrated a higher-level low-stability layer. The authors also hypothesized that additional latent heat release due to snow formation may have contributed to the rapid boundary layer growth.

Another potentially important factor in the development of heavy snowfall in lake-enhanced events is through modification of the lake-effect clouds and snow by seeding from higher-level cloud layers. Studies in several non-lake-effect cases showed precipitation rates may be greatly increased by the "seeder-feeder" process (e.g., Cunningham 1951, Herzegh and Hobbs 1981, Waldstreicher 2002), but this process has not been quantified in a lake-enhanced event. Unique data collected during Lake-ICE will allow for the first detailed observational study of a lake-enhanced snow storm.

The current study seeks to investigate: (1) the cross-lake boundary-layer growth, (2) local variations in boundary-layer structure, and (3) effects of seeding on cloud microphysics in a lake-enhanced event.

2. ENVIRONMENTAL CONDITIONS

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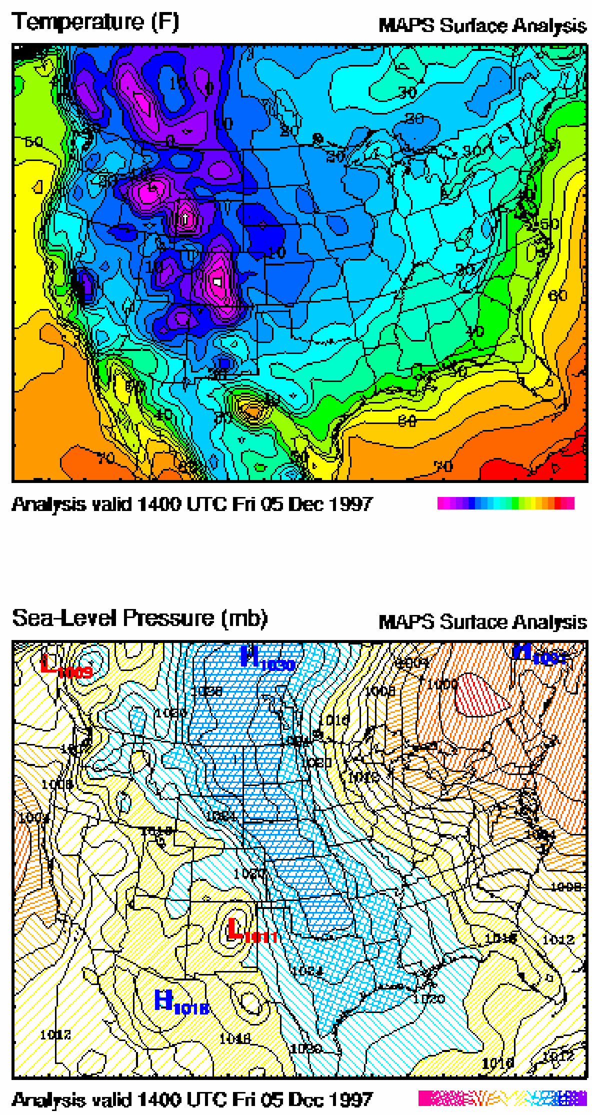

Figure 1. MAPS analyses of surface temperature and sea level pressure (Benjamin and Miller 1990). The 0C isotherm is approximately at the transition from green to blue shading.

The current study focuses on the 5 December 1997 case, which was the first operational day of Lake-ICE. Data taken on 5 Dec 1997 were designed to investigate the lake-effect boundary layer growth as the cold air traveled west-to-east across the lake. In particular, sounding data from three National Center for Atmospheric Research (NCAR) Integrated Sounding

Systems (ISS), in situ data from the NCAR Electra and University of Wyoming King Air, and airborne dual-Doppler radar data from the NCAR Electra Doppler Radar (ELDORA) system were utilized in the current study. Specific datasets are described in Schroeder (2002) and Schroeder et al. (2002).

On that day, a surface trough and a closed upper-level low, both associated with a departing surface cyclone, were present over the Great Lakes region (Figure 1). Near-surface winds across Lake Michigan were generally west-northwesterly, advecting colder air over the relatively warm lake surface, leading to development of a lake-enhanced snowfall event. Observed snow intensity was the greatest of the Lake-ICE days, despite the fact that conditions typically associated with lake-effect snowstorms were only marginally satisfied. Lake suface-to-850hPa temperature differences were only 16-18ºC (13ºC is considered minimum), and winds were across the short axis of Lake Michigan (90-100km fetch).

Observations taken on this date indicate that over about the upwind (western) half of Lake Michigan, upper-level clouds associated with the cyclone and trough over the Great Lakes region, dropped snow into the lower lake-effect boundary layer clouds. Figure 2 shows a vertical cross-section of radar effective reflectivity factor obtained by ELDORA over Lake Michigan. Near-surface lake-effect convection can be seen up to a height of less than 1 km above the lake. Above that level, lower-reflectivity layers can be seen on the right side of Figure 2, with regions where the radar indicates snow extending between the two cloud layers. No evidence of seeding layers can be seen in the left regions at distances over 10 km from the aircraft. Schroeder (2002) and Schroeder et al. (2002) gave extensive evidence for natural seeding of the lake-effect boundary layer clouds by higher-level clouds on this date. These data include King Air-observed snow above the lake-effect clouds, observations of upper-level precipitation by the WSR-88D radar in Green Bay, WI, and ISS soundings indicating multiple cloud layers above the lake-effect convection.

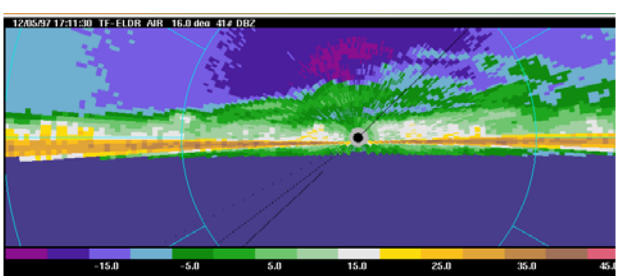

Figure 2. ELDORA observations of radar reflectivity at 1711 UTC on 5 December. These data were taken with the forward radar, at 18 deg from the vertical.

3. CROSS-LAKE GROWTH OF CONVECTIVE BOUNDARY LAYER

While the synoptic environment gives rise to conditions appropriate for lake-effect snow storms, the lake-effect convective boundary layer (CBL) is directly responsible for lake-effect snow development. Sounding data from project aircraft and rawinsondes were used to detail the cross-lake growth of the lake-effect CBL (see Fig. 3, Schroeder et al. 2002). Near the upwind (Wisconsin) shore, the CBL was deeper (with a top height, z_i, of near 940 hPa) than has often been reported upwind of Lake Michigan in classic lake-effect events (e.g. Chang and Braham 1991; Kristovich *et al.* 2003), possibly as a result of reduced stability associated with the nearby cyclone. Also evident upwind of Lake Michigan was a layer of nearly neutral atmospheric stability between the boundary-layer capping inversion and another strongly stable layer at ~750 hPa. NWS soundings taken at 1200 UTC 5 December 1997 at International Falls, MN, Minneapolis, MN, Green Bay, WI, and Alpena and Detroit, MI were examined to determine if the origin of this elevated low stability layer was due to the influences of Lake Superior. Each sounding, including those upwind of Lake Superior, showed evidence of a layer of near-neutral stability (i.e., a nearly dry adiabatic temperature lapse rate) in the mid-to-upper troposphere, suggesting that this layer is not associated with airmass modification by the Great Lakes.

Over Lake Michigan, rapid growth of the well-mixed CBL was observed from the upwind shore to about mid-lake. Upwind of that location, the CBL deepened by approximately 490 m across a fetch of 48 km, for a mean slope of ~1.0%. At about mid-lake, an acceleration in CBL growth rate was observed as the lake-induced convection merged with the higher reduced-stability layer. Near the downwind shore of Lake Michigan, zi had deepened to ~1780 m, across an additional fetch of 76 km, implying a mean slope of 1.15% over this domain; more rapid than those reported previously in lake-effect situations. The rapid deepening of the CBL from west-to-east across the lake would be expected to contribute to increased snow production.

4. LOCAL INFLUENCES OF NATURAL CLOUD SEEDING

Through comparisons of King Air *in situ* observations of snow particles and WSR-88D observations from Green Bay, WI, calculations of radar beam height and reflectivity, and movement of the reflectivity features, Schroeder (2002) concluded that the WSR-88D data could reliably be used to delineate portions of the King Air flight legs in seeded regions from portions where seeding was minimal. It was found that several of the King Air passes in the western flight stacks had both seeded and non-seeded segments.

In situ observations were parsed into seeded and non-seeded areas to determine the effects of natural cloud seeding on the snow particle spectra. Average ice particle size-spectra observed by the 2D-P probe were derived for each King Air pass on 5 Dec 1997 that contained a seeded segment, as determined by KGRB WSR-88D observations. The sample sizes here are comparable to those in Braham (1990) and are generally several times larger, in terms of equivalent flight distances, than the extents of reflectivity features sensed by KGRB (approximately 6 – 9 km).

The table below gives aircraft sampling durations, spectral parameters N_0 (intercept) and λ (slope) found by fitting the observed particle size spectra to a log-linear line, and derived quantities of the distributions of average spectra for seeded and non-seeded regions from within each KA pass in the westernmost flight stack. In all passes, snow tended to be considerably more intense in seeded areas (determined by radar observations). Seeded spectra had larger N_0 values by factors of three to eight, and λ's 1-2 times smaller than their non-seeded counterparts. Thus, the integrals beneath the seeded exponentials, are appreciably larger in seeded regions. For example, the average of the downward snow flux (SF) values for seeded portions of flight track was 15.5 mm d^{-1} versus 1.4 mm d^{-1} for non-seeded segments, an order of magnitude difference. Within individual passes, the increase was a factor of 5 to 35. The maximum observed water-equivalent snowfall rate was 40.8 mm d^{-1}. For reference, the maximum short-term SF reported by Braham and Dungey (1995) over Lake Michigan was 77.7 mm d^{-1} in an examination of midlake/shoreline band events.

5. LOCAL BOUNDARY-LAYER DEPTH INCREASES IN SEEDED AREAS

Because the King Air flight legs on 5 Dec 1997 included both seeded and non-seeded regions, comparison of the observations between these regions could give direct information on the local effects of seeding on the boundary layer. In-situ data show that one effect was to locally deepen the boundary layer.

Typically, in the surface and lower mixed layers, one would expect clouds (moist, buoyant updrafts) to be warmer than their surroundings (e.g. Braham and Kristovich 1996). As some overshooting thermals penetrate the capping inversion and reach the stable layer aloft, however, they become colder than their surroundings. Thus, it would be expected that updrafts/clouds in the lower parts of the boundary layer should be warmer than the environment, whereas at or near boundary-layer top, they should be cooler.

Fig. 3 displays two time-series of potential temperature and cloud-drop concentrations acquired by probes aboard the King Air for passes at different altitudes in the western-most flight stack on 5 Dec 1997. At both altitudes, differences are apparent between seeded and non-seeded areas. In the seeded areas, the two traces are largely out of phase, indicating that clouds were colder than their environments, i.e. the aircraft was flying near the boundary-layer cloud-tops. In non-seeded areas, cloudiness is much less frequent, and environmental potential temperatures are warmer by ~1K. Both observations suggest that the King Air was sampling above the boundary layer, for the most part, in the non-seeded areas. Since aircraft flight legs were level, these observations imply that the boundary layer was locally deeper in regions with seeding from above. Whether this local deepening was due to increased latent heat release in snow formation or mesoscale cyclone-generated upward air motions is not yet determined. Note that these King Air flight passes were perpendicular to the mean boundary layer wind direction, minimizing the effects of boundary layer deepening with fetch on these observations.

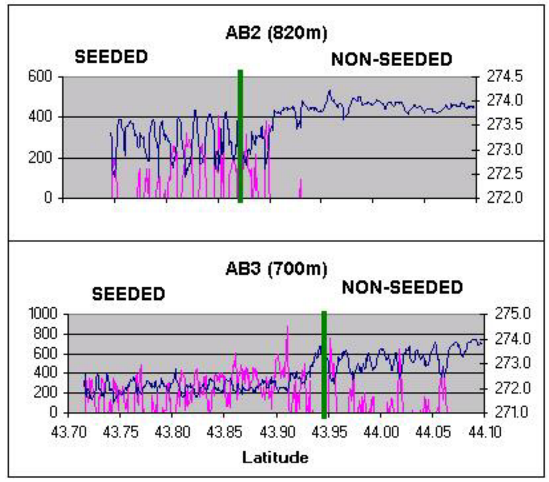

Figure 3. King Air time series of potential temperature (blue; scale at right in K) and total FSSP concentration (red; scale at left in cm^{-3}) for two passes in flight stack AB. Heavy green line demarcates seeded and non-seeded segments of flight, as determined from WSR-88D data.

6. SUMMARY AND CONCLUSIONS

The 5 Dec 1997 Lake-ICE case afforded a unique opportunity for studying the effects of a nearby cyclone on lake-effect boundary-layer processes. Sounding and in-situ aircraft data indicated rapid convective boundary-layer growth across Lake Michigan, despite relatively marginal lake-effect conditions. A rapid acceleration of the growth rate mid-way across the lake occurred as the boundary layer penetrated a higher-level less-stable layer associated with the cyclone. KGRB radar data were used to parse King Air in-situ data into seeded and non-seeded segments. Comparison between these two regimes reveals that the convective boundary layer was locally deepened in seeded areas, apart from the larger scale, cross-lake growth. Snow was also intensified in seeded areas, implying a modification of microphysical processes.

The use of operational radar data to detect regions of seeding from above in a lake-enhanced event represents a new approach. Ongoing research seeks to quantify boundary-layer depth changes in seeded areas, as well as interpreting vertical changes in snow spectra for both seeded and non-seeded areas. Numerical simulations of this event are also in progress.

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Table 1. Comparison of snow spectra parameters between seeded and non-seeded portions of King Air flights.

King Air Passes	Sample Duration (min:sec)	N_0 (mm^{-1} L^{-1})	λ (mm^{-1})	Ice-Water Content (IWC) ($g\ m^{-3}$)	Equivalent Radar Reflectivity Factor Z_e (dBZ)	Water-Equiv. Snow Flux (SF) ($mm\ d^{-1}$)
SEEDED						
AB2	3:10 (15.2 km)	3.06	1.60	0.036	10.5	40.8
AB3	4:47 (23.0 km)	2.28	1.95	0.012	3.3	17.4
AB4	3:59 (19.1 km)	1.23	2.44	0.0027	-6.2	4.3
AB5	1:44 (8.3 km)	3.50	2.36	0.0089	-0.6	14.5
CD1	2:11 (10.5 km)	1.02	3.81	0.00038	-20.6	0.8
NON-SEEDED						
AB2	4:58 (23.8 km)	0.93	2.81	0.0012	-11.7	2.4
AB3	5:44 (27.5 km)	0.76	2.37	0.0019	-7.4	2.9
AB4	5:21 (25.7 km)	0.15	4.29	0.00004	-32.4	0.1
AB5	7:58 (38.2 km)	0.87	2.99	0.00085	-13.9	1.6
CD1	5:51 (28.1 km)	0.20	6.19	0.00001	-42.3	0.04