8.2 THE EFFECTS OF A PRECIPITATING WINTERTIME SYNOPTIC SYSTEM ON A LAKE-INDUCED CONVECTIVE BOUNDARY LAYER

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1. INTRODUCTION

Some of the most intense local snows in the Great Lakes region occur when there is an interaction between lake-effect boundary layer and mid-latitude cyclone precipitation processes. Such events are often termed “lake-enhanced”. It might be anticipated that cyclones could enhance lake-effect precipitation in two ways; by increasing the boundary layer growth rate and by seeding the lake-effect clouds with snow from higher-level clouds.

Few studies have investigated the boundary layer evolution in cases of lake-effect storms occurring in conditions similar to those near cyclones. In one example, Chang and Braham (1991) reported an unusual rapid acceleration in boundary-layer growth rate about halfway across Lake Michigan. This increased rate was hypothesized to have been due to either latent heat release caused by rapid snow formation or to the presence of a higher-level low-stability layer. As convection penetrated the low-stability layer, air parcels were able to ascend deeper into the atmosphere.

Seeding of low-level clouds from above is a well-known process (e.g., Cunningham 1951), but has not been carefully documented in lake-effect situations. Indeed, the number of studies of lake-effect microphysical properties is quite limited. For example, Braham (1990) analyzed snow particle-size spectra over Lake Michigan, and Kristovich and Braham (1998) documented profiles of moisture fluxes and contents in all three phases for several classic lake-effect cases.

The current study focuses on the 5 December 1997 case, which was the first operational day of the Lake-Induced Convection Experiment (Lake-ICE; Kristovich et al. 2000). 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. 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).

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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. DATA AND METHODOLOGY

2.1 *Lake-ICE Data*

The Lake-ICE dataset, described by Kristovich et al. (2000), was utilized in the current study. Of particular importance for the 5 Dec 1997 case were vertical profiles from the National Center for Atmospheric Research (NCAR) Integrated Sounding Systems (ISS), which were deployed at three sites during the project, and in-situ aircraft measurements obtained by the University of Wyoming King Air and NCAR Electra. Fig. 1 gives an overview of relevant Lake-ICE data collection sites and aircraft flight areas in the vicinity of Lake Michigan. Additionally, National Weather Service (NWS) sounding and Weather Surveillance Radar 1988-Doppler (WSR-88D) data from Green Bay, WI (KGRB) were used in these analyses.

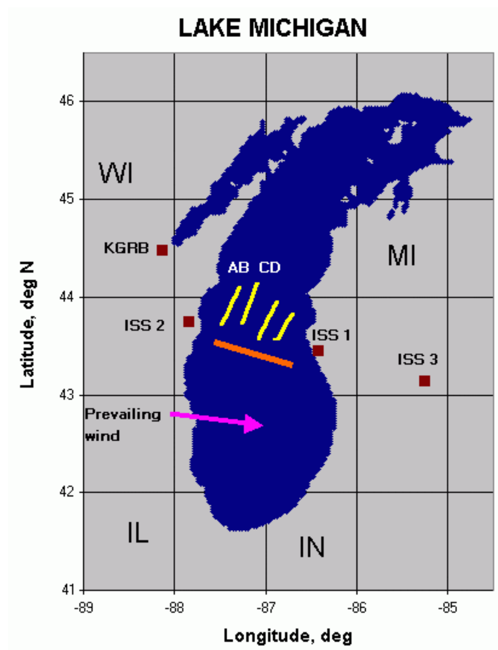

Figure 1. Lake-ICE data collection sites on 5 Dec 1997. Yellow lines indicate the location of King Air flight stacks, with stacks AB and CD designated; orange line indicates Electra cross-lake passes. Green Bay, WI sounding and WSR-88D site (KGRB) location and prevailing surface wind direction are also shown.

Project soundings were taken every three hours at each of the three ISS sites. These, along with NWS synoptic GRB soundings, were a major component of the data used to investigate the cross-lake boundary-layer growth. The other component consisted of in-situ measurements of atmospheric state parameters made by instrumentation aboard the King Air and Electra. The King Air flew a series of cross-wind flight stacks at several fetches across the lake, while the Electra made repeated cross-lake passes, as depicted in Fig. 1. The King Air was equipped with two Particle Measuring Systems probes: the Forward-Scattering Spectrometer Probe (FSSP)-100, for counting and sizing of particles in the size range of 2.0-47.0µm (primarily cloud droplets), and a Two-Dimensional Precipitation (2D-P) optical array probe, for particles with diameters 200-8000 µm (snowflakes). Together with the King Air state parameter measurements, these probe data were used to infer the local effects of seeding from above on boundary-layer depth and cloud microphysics. WSR-88D data from KGRB were used to distinguish between seeded and non-seeded regions.

2.2 *Distinguishing Seeded from Non-Seeded Areas*

Seeding of boundary-layer clouds from above might be expected in a lake-enhanced event, and observational evidence strongly suggests that this occurred on 5 Dec 1997. First, surface observations indicated a widespread area of light snow throughout much of the Upper Midwest, including upwind of Lake Michigan. Thus, precipitation in the region could not have solely been due to lake-effect processes. Second, ISS vertical profiles suggest the existence of multiple cloud layers, i.e. cloud decks both within and above the boundary layer. An example from ISS 3 is provided in Fig. 2. A lake-induced well-mixed (in terms of potential temperature) layer was present from the surface up to about 825hPa, with drier air above the capping inversion. Saturation is again observed near 650hPa, suggesting the presence of clouds associated with the upper-level disturbance. The King Air flight video confirmed the presence of these cloud layers above the boundary layer. In the two westernmost King Air flight stacks (designated 'AB' and 'CD' in Fig. 1), passes were flown between the boundary layer top and the higher cloud layer. In each of these passes, snow (defined as a total 2D-P concentration of ≥ 0.1 L^{-1}) was detected ~50% of the time, yet clouds (total FSSP concentration ≥ 10 cm^{-3}) were present during < 5% of the each pass' duration. These observations, taken from several different sources, suggest that seeding was taking place in certain locations over the lake.

If meaningful comparisons are to be made between seeded and non-seeded segments of aircraft passes, then some independent means of distinguishing the two regimes is needed. For this particular case, WSR-88D data from KGRB were used.

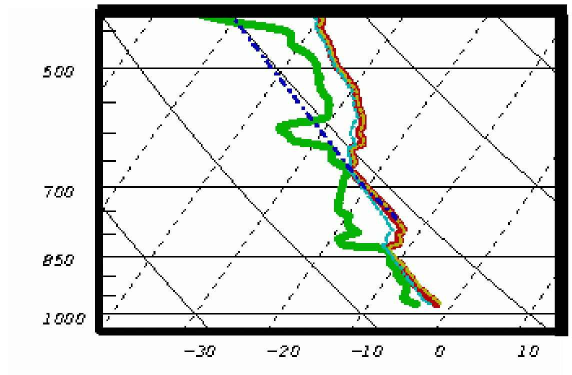

Figure 2. Skew-T/Log p diagram representing the ISS 3 sounding from 1500 UTC 5 Dec 1997. Heavy lines represent temperature and dewpoint traces (ºC). Vertical axis is pressure (hPa).

Calculations of radar beam height, using a standard atmosphere, suggest that the radar beam would be primarily sensitive to precipitation above the boundary-layer top at flight stack locations AB and CD. Based upon previously observed boundary-layer snow profiles (e.g. Kristovich and Braham 1998), it was estimated that the radar would be largely insensitive to hydrometeors in the boundary layer at the lowest scan angle (0.4º).

Patterns of WSR-88D-observed reflectivity features and their movements are consistent with precipitation from above the boundary layer. By tracking specific reflectivity features, mean advective wind speeds and directions were determined. Winds advecting these features generally had a strong northerly component (N or NNW), while boundary layer winds were generally W or WNW, as indicated in ISS profiles. The movement of the features was consistent with winds near the cloud layer (around 700hPa), as opposed to those in the boundary layer, further suggesting that the KGRB reflectivity signatures were due to precipitation generated in the upper-level cloud layers.

For this study, we used WSR-88D observations as indicators of where seeding was taking place. Using these data, the King Air in-situ data were parsed into seeded and non-seeded regions. For flight stack AB, seeded regions were toward the south end of each pass, with non-seeded areas to the north. Comparison of seeded and non-seeded flight segments permitted illustration of the effects of seeding on boundary-layer and microphysical characteristics.

3. CROSS-LAKE GROWTH OF CONVECTIVE BOUNDARY LAYER

Fig. 3 shows a cross-lake vertical cross-section of equivalent potential temperature for 5 Dec 1997 from multiple observations. Boundary-layer growth differed in several ways from observations of classic lake-effect cases. For example, upwind boundary-layer depth is substantially deeper than that reported by several recent studies (e.g. Kristovich 1993, Kristovich et al. 1999).

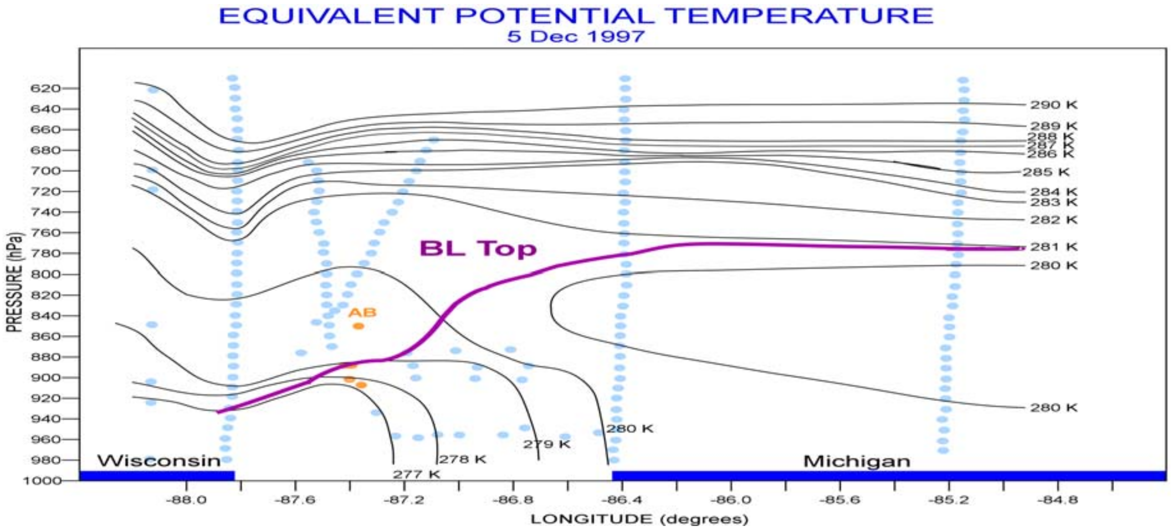

Figure 3. Vertical cross-Lake Michigan section of equivalent potential temperature for 5 Dec 1997. Wisconsin and Michigan shores are indicated. Thin lines are contours of θ_e at 1-K intervals. Dots represent data points used in the analysis; orange dots are positions of passes in Stack AB, made perpendicular to the plane of this figure. Estimated boundary-layer top height is indicated with the heavy purple line.

Boundary-layer growth rate is similar to that of classic cases until roughly 75% of the way across Lake Michigan. At that fetch, the merging of lower- and upper-level reduced-stability layers resulted in a rapid acceleration of growth rate, similar to that observed by Chang and Braham (1991). An examination of soundings from the Upper Midwest suggests that the upper reduced-stability layer resulted from synoptic-scale processes associated with the departing cyclone.

4. LOCAL BOUNDARY-LAYER DEPTH INCREASES IN SEEDED AREAS

It was determined that the King Air flight legs on 5 Dec 1997 included both seeded and non-seeded regions. This afforded an opportunity to study directly 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. 4 displays two time-series of potential temperature and cloud-drop concentrations acquired by probes aboard the King Air for passes at different altitudes in Stack AB (see Figs. 1 and 3) 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 (especially in AB2), 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

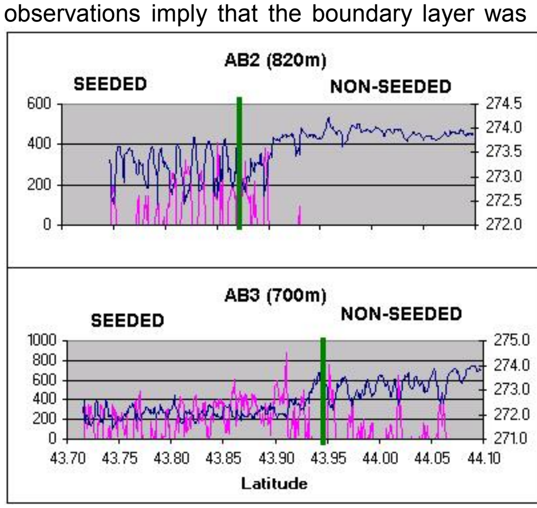

Figure 4. King Air time series of potential temperature (blue; scale at right in K) and total FSSP concentration (red; scale at left in cm^{-3}) for two passes in flight stack AB. Heavy green line demarcates seeded and non-seeded segments of flight, as determined from WSR-88D data.

deeper in regions with seeding from above. AB passes were perpendicular to the plane of Fig. 3; thus, local deepening was not impacted by the cross-lake boundary-layer growth. 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.

5. LOCAL MICROPHYSICAL CHANGES IN SEEDED AREAS

Seeding from above also caused changes in snow size spectra. Fig. 5 shows mean spectra from seeded and non-seeded portions of one King Air pass at 820m altitude (AB2), obtained with the 2D-P probe. Both spectra are fit well by exponential functions, as also reported by Braham (1990). The seeded spectrum has a larger N_0-value and a smaller λ, clearly indicating more intense snowfall. Other passes in which the King Air encountered both seeded and non-seeded regions (not shown) displayed similar differences.

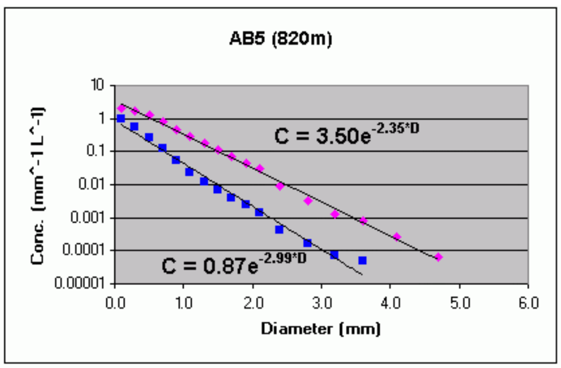

Figure 5. 2D-P spectra for seeded (red) and non-seeded (blue) segments of King Air flight pass AB5. Best-fit exponentials are shown, along with equations of the form $C = N_0\, e^{-\lambda D}$.

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.

Acknowledgements: We wish to acknowledge Dr. Neil Laird for his assistance with computer software used in these analyses. This research was funded by a grant from the National Science Foundation (ATM-9816306) and does not necessarily represent the views of the National Science Foundation.

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