8.8 WESTERLY FLOW COLD AIR OUTBREAK OVER LAKE MICHIGAN DURING LAKE-ICE

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1. INTRODUCTION

Wintertime outbreaks of cold air masses over the Great Lakes region of USA and Canada continue to provide excellent research opportunities for intensive field investigation of convective marine boundary layers. Results from studies over Lake Michigan in particular include those by Agee and Hart (1990), Agee et al. (1993), Kristovich and Braham (1998), and Kristovich et al. (1999), based on the special field program Project LESS conducted in the winter of 1983-84. A more recent and more thorough field investigation of cold air outbreaks (CAOs) over Lake Michigan has been carried out during Lake-ICE (see Kristovich et al. 2000), which provides unique data sets for the study of multiple scales of coherent structures (CSs) within the evolving convective boundary layer (see Agee et al. 2000). Prior to Lake-ICE the Purdue research group had concentrated on the convective regions that had experienced longer fetches of cold air flow over warmer water, concentrating on quasi-steady state well mixed PBLs. Over Lake Michigan this has been northerly flow events with over 400 km of fetch and marine boundary layer depths up to 1.5 km over southern Lake Michigan. Lake-ICE data sets now provide the opportunity to study onset and development in westerly flow CAOs off the Wisconsin shoreline, and west-to-east across Lake Michigan. This includes the study of the onset of heat and moisture transfer in the cloud-free path (CFP) region offshore, as well as the development of a cloud-topped boundary layer (CTBL) over the lake. This study shows the upstream PBL conditions over Wisconsin, and how this land PBL is modified by Lake Michigan heat and moisture.

2. WESTERLY CAO ON 13 JANUARY 1998

Although two westerly CAO case studies are being investigated, only the CAO event of 13 January 1998 is discussed in this paper. The upstream land PBL over Wisconsin for this event was convectively well-mixed and moist as indicated in Figure 1 (roughly a west-to-east cross section from Wisconsin to Michigan). The features in the upstream PBL over Wisconsin were due in part to the mild winter prior to this CAO, with above normal soil temperatures (and no frozen lakes and ponds). Also this convective PBL over Wisconsin showed an atypical vertical profile of temperature and moisture distribution in a CAO, in that the moisture depth exceeds the heating depth. These upstream layers are defined as TBL_L (thermal boundary layer over land) and MBL_L (moisture boundary layer over land), which is inclusive of the TBL_L). Sorbjan (2001) has done LES modeling of the mixing of scalar quantities, and has shown that differences in vertical mixing of heat and moisture are possible. Now extending this flow across a warm and open lake surface (as seen in Figure 1) reveals not only the formation of a TIBL (thermal internal boundary layer) but also a new concept called a MIBL (moisture internal boundary layer) that extends to a greater depth. As this “old” land PBL advected to the east across Lake Michigan, three distinct layers evolved within and near the top of the PBL. *First* (as shown in Figure 1) was the bottom layer of new vigorous, moist and turbulent convection, *secondly* above this was the somewhat residual convective layer from land with enriched moisture from the lake, and *thirdly* was the customary capping warm and dry stable layer. Previous researchers (e.g., Agee and Gilbert 1989; Young, et al. 2000) have made reference to such convective PBLs as containing a characteristic interfacial region or entrainment zone, between the new rigorous convective layer below and the stable region above. This study goes beyond such findings to show the unusual characteristics found in the second or middle layer, due in part to the initial upstream conditions over land. Research aircraft flights (both the King Air and the Electra) during Lake-ICE have allowed for detailed analysis of both the mean properties of the PBL as well as the turbulence fields. The middle layer in this case study is unusually deep (much more so than the typical entrainment zone or interfacial layer), and is moisture enriched due to greater vertical mixing of moisture than heat, a somewhat atypical event.

Figure 1 also shows a schematic representation of the observed downwelling of air, as the flow accelerates out from the Wisconsin shoreline. The next section will show detailed aircraft measurements that help verify the features presented in the Figure 1 schematic. Also, the lidar data (Mayor and Eloranta 2001) show the vertical extent of large moist plumes, probably at times attributed to steam devils that extend into and form the MIBL, well above the height of the TIBL. Vertical profiles of temperature and moisture from all sounding data and aircraft data have allowed the determination of heating and moistening effects of the lake, as shown respectively in Figures 2 and 3. T_L in Figure 1 marks the top of the lidar moisture plumes, and T_E marks the boundary of moisture flux based on the Electra flight.

Figures 2 and 3 have been prepared by using the vertical cross-section from KGRB, through the King Air flights over Lake Michigan. Three King Air vertical stacks (VS) and random (R) flight levels are indicated in both figures. The Green Bay sounding was 1200 UTC on 13 January 1998, and all downstream King Air 20 Hz

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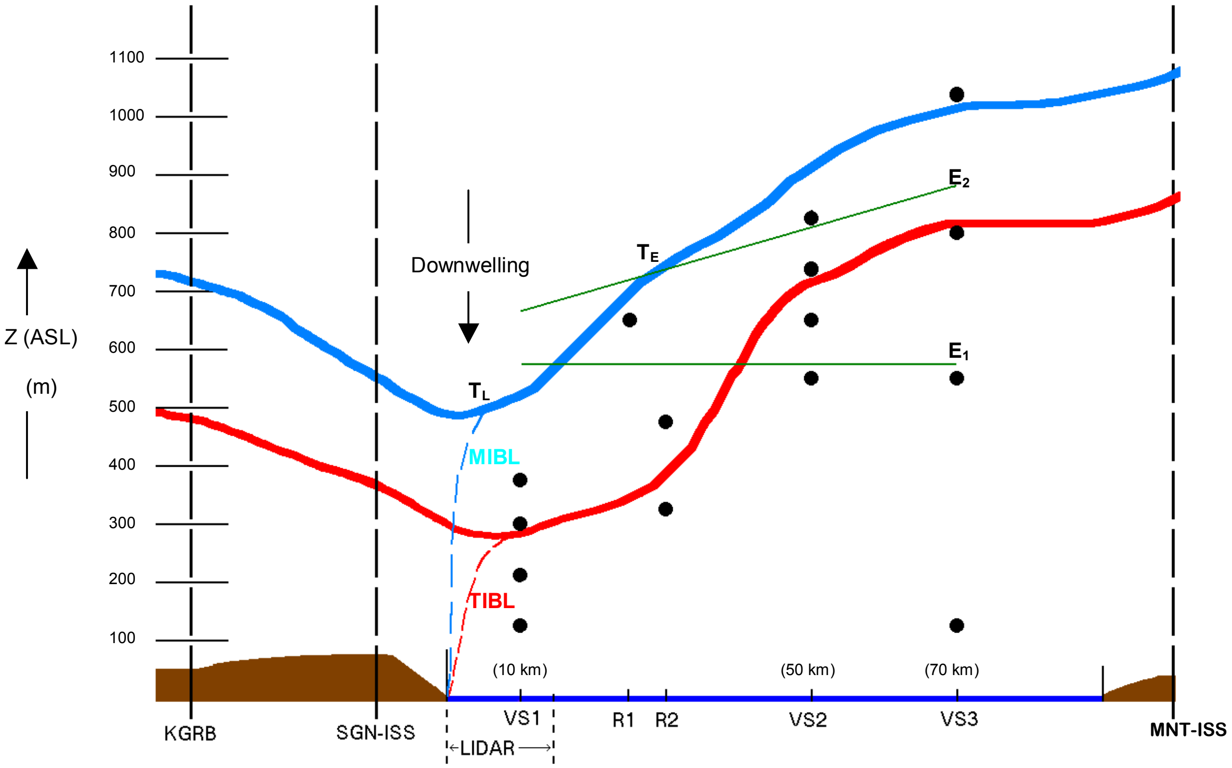

Figure 1. Schematic cross-section of thermal (red) and moisture (blue) boundary layer depths for westerly CAO of 13 January 1998, and data sources. Dots represent King Air flight levels. Distances of aircraft vertical stacks (VS) from Wisconsin shoreline are shown. E_1 marks the multiple horizontal flight levels for the Electra data at ~575 m above Lake Michigan, and E_2 marks a slanted flight path.

measurements were taken from 1349 UTC to 1652 UTC. The times, and spatial cross-section, provided by these data were excellently positioned for analysis, and the determination of heating and moistening by the lake. Figure 2 shows the *lake heating* (ΔT), determined by using the KGRB profile as an upstream initial state, which is subtracted respectively from each King Air measurement over the lake. The bold, thick curved line shows the top of the heated layer due to lake warming, and the increased thickness of the layer farther east due to convective clouds. Isotherms in °C intervals show maximum heating effect near the Michigan shoreline, obviously corresponding to the longest fetch (ΔT ≅ 9°C).

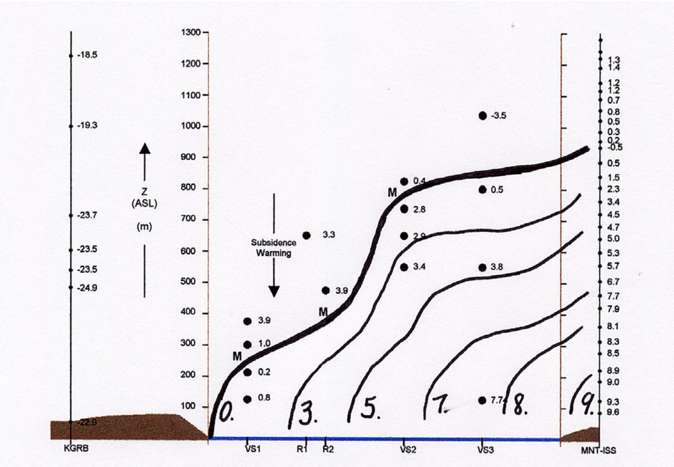

Figure 2. A vertical cross-section of *lake heating*, depicted by ΔT isotherm analysis. The thick bold curved line denotes the top of the heated layer, and M identifies points on this boundary that are independently verified by aircraft data vertical fluxes (both momentum and temperature).

Subsidence warming off the Wisconsin shoreline is also evident (ΔT ≅ 4°C). Figure 3 has been derived in a similar manner but for the change in specific humidity (Δq), again by subtracting the KGRB sounding values from the King Air measurements. *Lake moistening* (Δq) is shown to extend to a greater height than lake heating, and is indicated by the bold, thick curved line. T_L marks the height of the moisture layer (actually the MIBL) in Figure 1, determined by the offshore lidar measurements. T_E marks the height of the moisture layer based on the 25 Hz Electra data (see flight paths noted in Figure 1). The maximum effect of moistening is found (again) near the Michigan shoreline, and at the bottom of the atmosphere (Δq ≅ .7 gm kgm^{-1}). However, Δq values as high as .5 gm kgm^{-1} are found at the 800 m level above the lake. As previously suggested the atmosphere has been more effective in the vertical mixing of moisture than heat, i.e., the vertical mixing coefficient (K_q) of moisture exceeds that for heating (K_h).

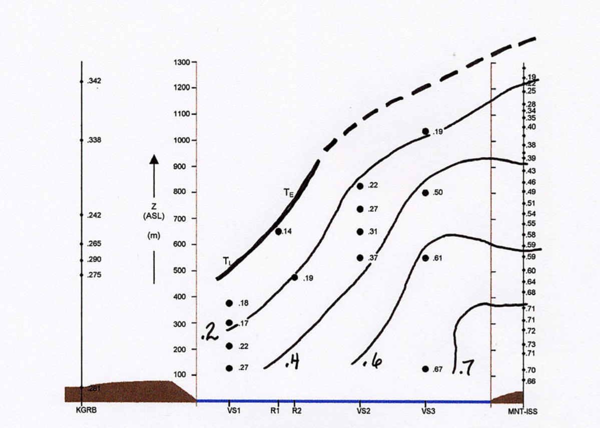

Figure 3. A vertical cross-section of *lake moistening* depicted by Δq isohume analysis. The thick bold curved line denotes the top of the moistened layer, where T_L is the top of the lidar plumes and T_E is the intersection point of the Electra Aircraft.

3. AIRCRAFT DATA

Large amounts of King Air and Electra data are available for study, including the determination of mean properties of air mass modification, as well as higher order characteristic turbulence statistics. Due to the limited size of this conference paper, a few select examples of results are now presented. Figure 4 is chosen to show the entire flight path measurements of vertical velocity (w) for King Air Vertical Stack 1 (also see Figure 1). This vertical stack of measurements shows the lowest layer (I) of strong turbulent mixing, an intermediate middle layer (II) of significant turbulent mixing, and an upper layer (III) that is relatively quiescent. It is also noted that vertical momentum turbulence in layer I corresponds to the layer of lake heating (seen in Figure 2), i.e., w' and T' are highly correlated. However, vertical mixing of humidity (q') is to a greater height. Therefore, the mixing coefficients for heat, momentum and moisture would be related, respectively, as $K_h \cong K_m < K_q$.

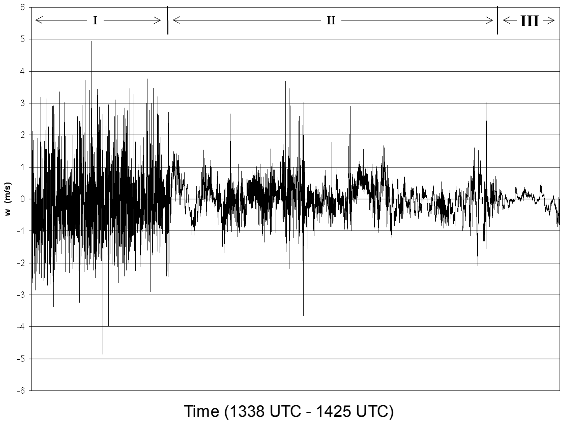

Figure 4. University of Wyoming King Air Vertical Stack 1 (VS1) on 13 January 1998 at 10 km from the Wisconsin shoreline in the CFP region (also see Fig. 1). Heights above lake level range from 200 m at 1338 UTC, to 380 m at 1425 UTC. The three layers identified in this study are marked as regions I, II and III, from the lowest level to the highest level, respectively.

Another verification of these three regions (I, II, and III) can be seen in Figure 5. This is one of several 25 Hz Electra flight profiles taken along flight path E_1, depicted in Figure 1. Selected profiles of humidity and heat fluxes for both the King Air and Electra data sets (not shown) will be presented at the conference.

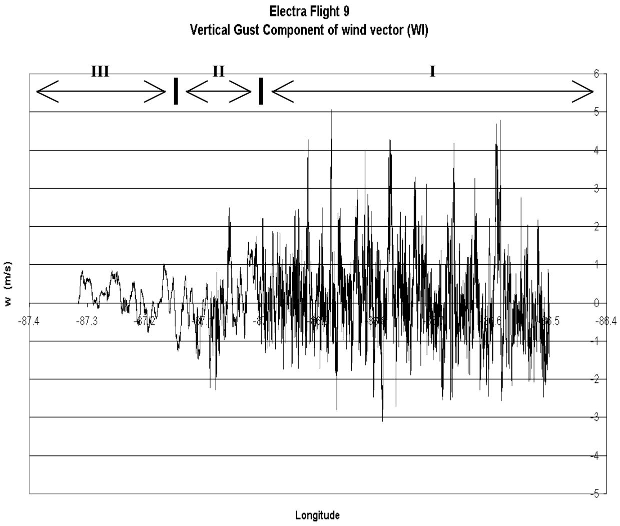

Figure 5. NCAR Electra aircraft data at 584 m flight level above the lake on 13 January 1998, from near the Michigan shore (on the right) to near Wisconsin shore (on the left). Again the three layers of interest are noted, the same as those in Figure 4. Flight times are from 1543 UTC to 1555 UTC, flying east to west.

Finally, the interest in coherent structures noted in the Introduction (see Agee et al. 2000) has been partially addressed by the results in Figure 6. This flight level (Level 1 in Vertical Stack 1) was chosen because of its location in the heated and moistened CFP region. A meteorologically homogeneous and statistically stationary record of 22 km length has provided almost 6,000 data points at ~4 km sampling intervals (i.e., 20 Hz measurements, at King Air speed of 75 ms^{-1}). The vertical velocity spectrum in Figure 6 shows 3 candidate spectral peaks of 190 m, 253 m and 379 m. Statistical methods are currently being explored to determine the validity of these peaks as representing coherent structures (viewed as building blocks in the mesoscale convective 2-d/3-d cloud patterns seen in satellite imagery over Lake Michigan). The q spectra (not shown) for this same King Air flight leg revealed analogous CSs in the moist, convective field, particularly the 379 m spectral peak.

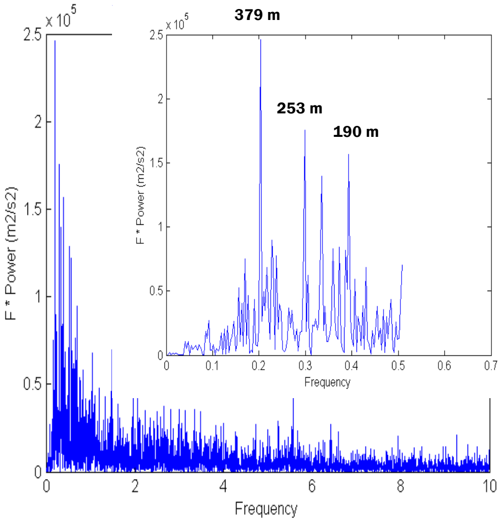

Figure 6. Spectral plot of vertical velocity, w, from Vertical Stack 1, Level 1 (125 m ASL) on 13 January 1998. The inserted enlarged view shows three spectral peaks of interest.

4. CONCLUSIONS

The study of westerly CAOs during Lake-ICE has produced an unusual, and extremely fascinating case of air mass modification. This includes a) an unusually structured temperature and moisture field (in the PBL) upstream over Wisconsin, b) a pronounced subsidence effect due to downwelling of air off the Wisconsin shoreline, including the lowering of the PBL height and subsidence warming, c) a detailed cross-section analysis that quantifies lake heating and moistening, d) observational evidence of moisture flux exceeding heat and momentum flux, e) the introduction of a new concept, the MIBL, f) aircraft measurements that identify the physical properties of three distinct layers over Lake Michigan, including an unusual modifying effect of the so-called entrainment zone, g) mean and turbulence statistics for T, w and q, based on multiple independent aircraft measurements by the Wyoming King Air and the NCAR Electra, and h) statistical evidence of CSs in the spectra of vertical velocity in the CFP region near the Wisconsin shoreline.

5. ACKNOWLEDGEMENTS

The authors are indebted to all Lake-ICE scientists and support staff that made this study possible. Gina Richey is acknowledged for preparing the manuscript. This work was supported by NSF Grant ATM-9813687 awarded to Purdue University.

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