

**Convective Structures in a Cold Air Outbreak over  
Lake Michigan during Lake-ICE**

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## ABSTRACT

The Lake-Induced Convection Experiment has provided special field data during a westerly flow cold air outbreak (CAO) on 13 January 1998, which has afforded the opportunity to examine in detail an evolving convective boundary layer. Vertical cross-sections prepared from these data, extending from upstream over Wisconsin out across Lake Michigan, show the modifying effects of land-water contrast on boundary layer mixing, entrainment, heating and moisture flux. Through this analysis, an interesting case of lake-effect air mass modification was discovered. The data show atypical differing heights in vertical mixing of heat and moisture, as well as off-shore downwelling and subsidence effects in the atmosphere. Analysis shows evidence of a new observational feature, the moisture internal boundary layer (MIBL) that accords well with the often recognized thermal internal boundary layer (TIBL). The “interfacial” layer over the lake is also found to be unusually thick and moist, due in part to the upstream conditions over Wisconsin, as well as the effectiveness of vertical mixing of moist plumes over the lake (also seen in the aircraft data sets presented). Results show that the atmosphere can be much more effective in the vertical mixing of moisture than heat or momentum (which mixed the same), and thus represents significant departure from the classical bottom-up and top-down mixing formulation.

Four scales of coherent structures (CSs) with differing spatial and temporal dimensions have been identified. The CSs grow in a building block fashion with buoyancy as the dominating physical mechanism for organizing the convection (even in the presence of substantial wind shear). Characteristic turbulence statistics from aircraft measurements show evidence of these multiple scales of CSs, ranging from the smallest (microscale) in the cloud free

path region near the Wisconsin shore, to the largest (mesoscale) in the snow-filled boundary layer near the Michigan shore.

A Large Eddy Simulation (LES) model has also been employed to study the effects of buoyancy and shear on the convective structures in lake-effect boundary layers. The model simulation results have been divided into two parts: 1) the general relationship of surface heat flux versus wind shear, which shows the interplay and dominance of these two competing forcing mechanisms for establishing convection patterns and geometry (i.e., rolls versus cells), and 2) a case study simulation of convection analogous to the CSs seen in the CFP region for the 13 January 1998 CAO event. Model simulations also show, under proper conditions of surface heating and wind shear, the simultaneous occurrence of differing scales of CSs and at different heights, including both cells and rolls and their coexisting patterns (based on the interplay between the effects of buoyancy and shear).

## 1. Introduction

The Lake-Induced Convection Experiment (Lake-ICE) was conducted over Lake Michigan during the winter season (2 December 1997 - 24 January 1998), and Kristovich et al. (2000) have discussed the research objectives of this field program and provided preliminary findings. Three relevant studies pertaining to the Lake-ICE field program are noted (Young et al. 2000; Mayor and Eloranta 2001; Mayor et al. 2003), which have addressed, respectively, the following topics: 1) properties of the interfacial layer at the top of the convective zone; 2) microscale and mesoscale wind fields in the convective layer, based on lidar observations; and 3) Large Eddy Simulations (LES) of convective motions based on volume-imaging lidar data sets. One of the most significant cold air outbreaks (CAO) during Lake-ICE occurred on 13 January 1998, and this CAO event has been the principal focus of the research objectives addressed in this study, as well as the papers cited above. A fourth paper, by Kristovich et al. (2003) has focused primarily on the development of lake-effect snowbands. They reported extensive sea smoke in the surface layer, with disorganized (or cellular) and linear features visually present across the entire lake. Their observed mesoscale structures were generally consistent with past theoretical and numerical modeling results, except for the aspect ratio. Young et al. (2000) show from aircraft measurements that in the entrainment zone, temperature and moisture skewness curves reveal that the last identifiable free atmosphere effects extend down well below the zero crossing of heat flux. Mayor et al. (2003) in an LES simulation of the 13 January 1998 CAO generates reasonable coherent structures (open cells) where the LES technique is expected to perform poorly (near the surface). Domain size was 11.68 km x 11.68 km x 1 km, with a grid spacing of 15 m. Open cells near the bottom had aspect ratios of approximately 1-to-1 (characteristic of large eddy structures). Although the papers discussed above have focused in

part on the same CAO event, the research findings reported in this paper are viewed as complementary to the results of those studies.

Specifically, the findings in this research investigation can be partitioned into three general categories: 1) observational evidence of air mass modification; 2) observational evidence of Coherent Structures (CS) in the convective PBL, and 3) Large Eddy Simulation of CS for the 13 January 1998 CAO event. The observational data sets examined include the 20-hz King Air data, the 25-hz Electra data, ISS soundings, volume-imaging lidar data, and NWS rawinsonde data. The Sorbjan LES model (see Sorbjan 1999; 2001) was used to perform the coherent structure simulations for the CAO event, and to investigate the competing roles played by buoyancy and shear.

#### *a. Air Mass Modification*

The CAO of interest can be easily documented by the surface weather map presented in Fig. 1, which shows a westerly flow of polar air from Wisconsin across Lake Michigan. Figure 2 is a GOES satellite image at 1630 UTC on 13 January 1998, depicting the initial formulation of 2-d (planform) cloud bands that evolve into 3-d (planform) open cells over Lake Michigan. The cloud-free-path (CFP) can also be noted between the cloudy region and the Wisconsin shoreline (similar to the concept introduced by Chou and Atlas 1982, for CAOs). It is interesting to note that prior to this CAO event, the winter season over Lake Michigan and Wisconsin had been unusually mild, with no frozen lakes and 2-inch depth soil temperatures at or above 0°C for the first two weeks of January.

The special data sets available from Lake-ICE have allowed the construction of a vertical WNW-ESE cross-section of air mass properties from Wisconsin out across Lake Michigan. Figure 3 shows this cross-section, based on the Green Bay sounding (KGRB), the Sheboygan

ISS, Wisconsin lidar, King Air vertical stacks VS and random data R, Electra flight paths  $E_1$  and  $E_2$ , and the Montague ISS data sources. The red line represents the top of the heated layer, based on individual soundings and aircraft field measurements. The soundings showed neutrally mixed air below the red line, and slightly stable above. The aircraft data showed strong convective heat (and momentum) flux below the red line, and weak to none above the red line. Below the blue line, the humidity values were high (in the soundings) and the moisture fluxes from the aircraft measurements were also high. The Electra flight paths,  $E_1$  and  $E_2$ , also showed a strong decrease in moisture flux when crossing the blue line. The lidar data and imagery identified the location of the moist plumes and their vertical penetration. Several features in the Fig. 3 cross-section should be noted: 1) the land boundary layer was convectively mixed, most likely attributable to the mild winter conditions and the abnormally high surface soil temperatures, 2) a moist boundary layer over land that extended to a greater height (the blue line) than the height of the heated layer (marked by the red line); 3) evidence of downwelling effects as the surface flow accelerated off-shore, 4) identification of the well-known thermal-internal-boundary-layer (or TIBL), 5) identification of a new concept, the moisture-internal-boundary-layer (or MIBL), 6) heating and moistening (thus thickening) of the boundary layers over Lake Michigan, and 7) evidence that moisture from the lake mixed to greater heights than the heat flux (due to a favorable gradient in the interfacial layer, see Sorbjan 1999). All of these findings will be discussed in more detail in Section 2.

#### *b. Coherent Structures (CS)*

An important aspect of this research has been the identification and study of several CSs on different spatial scales, ranging from the microscale at the air-water interface to the mesoscale. Visual observations, cloud photographs and satellite imagery have helped identify

these features, but more importantly they have been identified (and studied) in both the lidar and aircraft data sets. In general, there is no agreed upon definition of CSs (see Sirovich 1989; Sreenivasan 1999) but in this study the authors have elected to define CSs as structures in atmospheric flows with *spatial organization*. For moderately large Reynolds numbers, one can possibly view flows as temporally chaotic but spatially organized. Four different coherent structures are identified in this study, but the three smallest scales (CS1, CS2, and CS3) have been the focus of this research. Visible cloud photography in the CFP region shows evidence of CS1 and CS2 structures. Lidar data show spatial patterns of CS2, also in the CFP region near the Wisconsin shoreline. Lidar derived wind fields and satellite cloud photography, both show evidence of CS3 within and near the CFP region. Aircraft measurements across the lake provide statistical evidence of CS2 and CS3 spatial structures, and GOES satellite imagery shows the largest spatial scale CS4.

*c. Large Eddy Simulations (LES)*

Large Eddy Simulation has been employed in this study to simulate the Lake-ICE CAO event, and any associated CS patterns, as well as the role of buoyancy versus shear in 3-d versus 2-d patterns. As noted above, four CS spatial scales (ranging from 10<sub>3</sub>m to a few kilometers) have been observed and documented to the extent possible using the available data. As discussed later in this paper, it is not tractable to have one LES model simulation capture all four CS scales (due primarily to computational requirements). Also, the variety of different physical processes at work at the air-water interface and through the depths of the CAO convective PBL have not been completely incorporated into an LES model. A cloud-free LES model was viewed as acceptable for studying convection in the CFP region, which has been initialized in this study with domain size and spatial grid size that are capable of capturing structures CS1 and CS2. The

presence of steam fog at the surface, although technically speaking is a "cloud", provides negligible latent heat release, and represents a field of hydrometeors that are far less dense than off-shore clouds that form at the top of the boundary layer. Such clouds, for example, are barriers to the lidar beam, while the steam fog hydrometeors make convenient lidar aerosol targets.

## **2. Observations of Air Mass Modification on 13 January 1998**

Observational evidence of air mass modification is provided in Fig. 3, along with the respective mixed-layer heights of proposed heating (red) and moistening (blue). Possible downwelling effects that occur for accelerated flow moving offshore can be noted (surface winds increased from  $6 \text{ ms}^{-1}$  to  $10 \text{ ms}^{-1}$  in the CFP region, aided by a combination of continuity effects and reduction in surface roughness). These winds were derived from the lidar field measurements (see Mayor and Eloranta 2001). One can interpret this, along with results in subsequent sections, as possible evidence of a new finding referred to as a moisture-internal-boundary-layer (MIBL), which is denoted in Fig. 3. This MIBL is also documented in part by the lidar imagery shown in Fig. 4, which shows steam fog from the air-lake interface extending vertically to a height of nearly 500 m. It is also noted that these more intense columns likely represent steam devils that were frequently observed during field operations. This height of 500 m is well above the TIBL, which is documented in the data sets and illustrated as such in Fig. 3. It is noteworthy that previous LES model simulations by Sorbjan (2001) show evidence that scalar quantities can mix to substantially different heights in convective PBLs, as observed in this CAO event. Since moisture is regarded as a passive scalar and is usually associated with the momentum field, the above result is even more intriguing. In this case the layer above the convectively mixed region was moist and neutrally stable (and not the usual dry inversion) and

as a consequence, vertical moisture diffusion was much more effective and did not require strong convective momentum vertical fluxes. A study by Sorbjan (1999) goes far in helping to explain this result, and in rectifying the role that can be played by the scalar gradient in the interfacial layer, when compared to the classical bottom-up and top-down theory by Wyngaard and Brost (1984).

More discussion and details of data sets, data acquisition and synoptic setting for the 13 January 1998 CAO event can be found in Kristovich et al. (2003) and Young et al. (2000).

#### *a. Heating*

The data sets that helped produce the vertical cross-section in Fig. 3 have also provided quantitative values of air-mass heating by the warmer lake surface. Figure 5 shows an isotherm analysis of temperature change ( $\Delta T$ ), based on King Air aircraft measurements compared to upstream soundings (at the same level) over Wisconsin. Air moving off the Wisconsin shoreline warmed by nearly  $9\text{C}^\circ$ , with the height of the heated layer extending to 850 m (ALS) over the eastern half of Lake Michigan. The bold thick line ( $\Delta T = 0$ ) in Fig. 5 identifies the top of the heated layer, and the "M" in the cross-section also *independently* locates the top of the mixed layer, just above this layer. The "M" location was determined by looking at the King Air vertical flight stacks, and the vertical fluxes of both momentum and heat (which were all strong until this layer, or bold line, was intersected by the aircraft). Subsidence warming of over  $3\text{C}^\circ$  (associated with apparent downwelling) is also evident in this cross-section, as well as the condensational heating and thicker convective boundary layer over the central and eastern part of the lake.

#### *b. Moistening*

In a manner similar to Fig. 5, a vertical cross-section of *lake moistening* is presented in Fig. 6. This shows an isohume analysis of specific humidity change ( $\Delta q$ ) ranging from .2 to .7

$\text{gkg}^{-1}$  moving west-to-east across the lake.  $T_L$  marks the top of the lidar moist plumes ( $\sim 500$  m ALS), and  $T_E$  marks the top of the moistened layer based on measurements of moisture content collected by the east-to-west Electra Aircraft flight path (see Fig. 3). It is again noted that moisture from the open waters of the lake surface extended to considerably greater heights ( $\Delta Z \sim 250$  m more) than the top of the heated layer. The reader is again referred to Fig. 3 that shows, respectively, these mixed layer heights of heating (red) and moistening (blue).

### *c. Sublayers Associated with CAO*

Results presented thus far, along with aircraft measurements (to be discussed in this section) have identified three distinctive sublayers over Lake Michigan associated with the 13 January 1998 CAO. These layers are noted in Fig. 3, and they have been further identified and examined by select aircraft flight data: 1) Layer I is the lowest sublayer, which is extremely turbulent with moisture and heat flux from the lake, and this sublayer extends from the surface to the top of the convection zone (red line), 2) Layer II is the next sublayer, which represents an atypical interfacial layer (due to residual moisture advected from over land as well as additional moisture from the lake), and 3) Layer III is the typical capping warm and dry inversion layer. The interfacial layer (sublayer II) represents an uncharacteristically thicker and more moist region than typically seen in convective marine CTBLs (see Agee 1987) in CAO events. Young et al. (2000) have studied this layer and its properties most thoroughly, based on analyses of the Electra data. This layer became additionally important to this study, because of its connection to upstream conditions over land as well as the lake moisture present. The identification of different properties of vertical mixing of heat and moisture in a CAO convective PBL over water has not been seen to this extent, and far exceeds that as originally suggested in the classical work by Wyngaard and Brost (1984) or Agee and Gilbert (1989). As discussed earlier, LES studies by

Sorbjan (1999, 2001, 2004) have shown that near the top of a layer where the turbulence is governed by scalar gradients, the vertical mixing of heat and moisture can be substantially different (more than explained by bottom-up and top-down mixing). Moisture should diffuse to greater distances through a moist environment compared to a dry layer. Figure 7 shows 25 hz data profiles of  $w$ ,  $T$  and  $q$  collected by Electra Flight Leg #9, moving east-to-west across Lake Michigan at a constant flight altitude of 575 m (ALS). Layers I, II, and III are seen to have the physical properties as defined above. Layer II shows evidence of entrainment spikes of moisture from below, and heat from above. Also, it is noted that all profiles in Fig. 7 are measured by the Electra flight path from east (in the middle of the convective PBL) to the west (across the interfacial layer).

### **3. Observations of Coherent Structures**

Four different scales of coherent structures were noted in the introduction, which occurred during the 13 January CAO at various spatial and temporal scales within the convective PBL.

#### *a. CS1*

Figure 8 shows an enhancement of a photograph taken by Dave Rogers (Colorado State University) aboard the Electra, at 575 m above lake surface (ALS) near the Wisconsin shoreline. Visual evidence of two scales of coherent structures (CS1 and CS2) are annotated in Fig. 8. The smallest scale CS1 is a manifestation of steam fog at the air-lake interface, which may be initiated by Langmuir circulations in the surface layer of the lake. However, this is not required, and it is readily noted that steam fog patterns move rapidly downstream with the wind field. Agee et al. (2000) have estimated these circulations to have individual length scales of 30 m and

depths of about 6 m. It is further proposed (although no supportive detailed sea surface temperature data exist), that these CS1 patterns may reflect small scale SST differences.

*b. CS2*

Figure 8 also shows a larger hierarchical pattern of coherent structures (CS2) represented by the much taller visible patterns of steam fog or sea smoke. Figure 9 is an independent representation of the same pattern of coherent structures captured by the Wisconsin lidar imagery (Mayor and Eloranta 2001). Agee et al. (2000) have estimated that these CS2 patterns of irregular open cells have representative length scales of 200 m and a vertical extent of 400 m to 500 m. Spectral decomposition of select aircraft data (King Air Vertical Stack 1, Level 1; see Fig. 3) has also provided statistical evidence of CS2. These data were collected in the CFP region and serve to complement the lidar and visual observations. Figure 10 shows a spectral plot of vertical velocity,  $w$ , at 125 m ALS, including an enhanced view of statistically significant spectral peaks (379 m, 253 m and 190 m), based on the lower 95% confidence limit (see Shumway and Stoffer 2000). The Electra data, which also showed evidence of CS2, are discussed in a later section.

*c. CS3*

Lidar derived horizontal components of wind have also been analyzed to determine the horizontal wind divergence pattern, shown in Fig. 11. This 2-d pattern is representative of CS3 (1.5 km horizontal spacing, 0.5 km vertical mixing) and is consistent with the onset of 2-d cloud bands that developed adjacent to the CFP region (see Fig. 2). The King Air Vertical Stack flights were also examined, and evidence of CS3 structures could be noted in the raw data sets. However, no spectral plots for vertical velocity are presented due to the limited sampling of CS3

in the 22 km flight segments. Again, the Electra data (discussed later) also showed evidence of CS3.

*d. CS4*

CS4 is the largest coherent structure identified in the CAO event, which is represented by the pattern of open cellular convection seen in Fig. 2 over the central and eastern portions of Lake Michigan. CS4 requires a much longer fetch (thus time) and favorable conditions to allow development, while scales C1-C3 occur across the lake. There were no field data collected during Lake-ICE that would support any statistical analysis of CS4. The authors do feel that the spatial scales of organization seen in this CAO event have evolved from the microscale (CS1) up to the larger mesoscale (CS4).

#### **4. Electra Observations of Coherent Structures**

The sampling path through Layer I in Fig. 7 has provided a useful 34 km segment of homogenous turbulence measurements by the Electra aircraft. These 25 hz data sets for all 12 flights (see  $E_2$  in Fig. 3) have been analyzed and evidence of CS2 and CS3 structures have been found. Figure 12a-b shows statistically significant (same method as section 3b) spectral peaks for  $q'$  and  $w'$  for all 12 flight segments, collected over a three-hour window of time. All 12 Electra flights were back and forth at 575 m ALS. Figure 12a shows a random pattern of spectral peaks for  $q'$ , extending over a length scale of 250 m to 4200 m. Figure 12b, however, shows a much more organized pattern of spectral peaks for  $w'$  that collectively represent CS2 and CS3 length scales. The population of spectral length scales for CS2 and CS3, range respectively from 250 m to 800 m; and 1250 m to 1900 m. The results for  $T'$  (not shown) were similar to  $w'$ . It is noted again (as discussed in section 2) that the mixing of the scalar quantities  $w'$ ,  $T'$  and  $q'$  is not the same. Figure 12a-b adds further insight into the random nature of

moisture flux, compared to a more selective mixing pattern for heat and momentum, dictated by the coherent structures.

## **5. LES Model Simulations of CS.**

LES model simulations of the development of convective planetary boundary layers during CAO events have received considerable attention (Chlond 1992; Rao and Agee 1996; Mayor et al. 2000). Details of these model simulations and results are often seen to be dependent on the three common considerations in such numerical experimentation: 1) how large is large enough (i.e., domain size), 2) how small is small enough (i.e., grid size), and 3) how long is long enough, for the time of integration? These questions have been addressed by Agee and Gluhovsky (1999) and de Roode and Duynkerke (2004) and their results are pertinent to the LES model simulations conducted in this research.

It is further noted that considerable effort has been made in the mid-1990s regarding the effects of buoyancy and shear in LES model simulations of convective PBLs. The best example of the interacting roles of these two forcing mechanisms is seen in the work by Moeng and Sullivan (1994). The current LES model results, presented later in this study, go beyond those findings by showing small scale 3-d structures near the bottom boundary, that give way to larger scale 2-d and 3-d structures at higher levels (consistent with the lidar field observations for the Lake-ICE CAO event over Lake-Michigan). It is possible, although somewhat contrary to classical Monin-Obukhov theory, to have buoyancy production exceed that by mechanical shear at the bottom boundary, but becoming less than shear production above the surface layer (discussed below; also, see discussion by Agee 1999). Lumley and Yaglom (2001) have noted that coherent structures can cause strong deviations from Monin-Obukhov similarity in the convective atmospheric surface layer.

The Lake-ICE field experiment, and in particular the VIL measurements near the Wisconsin shoreline on 10 and 13 January 1998 by Eloranta et al. (1999), provided unprecedented confirmation of the sensitivity of wind shear and surface heat flux to the geometry of convective structures. The VIL imagery showed 3-d cellular patterns of convective steam fog in the surface boundary layer in the off-shore CFP region. These cells extended vertically several hundreds of meters, in spite of the strong vertical shear in the horizontal wind. Agee (1999) proposed an explanation for the occurrence of either 2-d planform or 3-d planform convective structures, based on the relationship of the vertical profiles of the production of turbulent kinetic energy (TKE) by mechanical eddies 'versus' thermal eddies and the existence of  $z^*$  (the free convective height). Similar studies that are supportive of this explanation are found in Sikora et al. (2000), which shows strong northwesterly flow off the east coast of the United States for conditions of both a strong CAO and air-sea surface temperature in equilibrium. Figure 13 (courtesy of Todd Sikora) shows SAR (Synthetic Aperture Radar) imagery of sea surface deformations for these two events, which reveals a 3-d pattern of sea surface deformation in the CAO event and 2-d pattern of deformation of the sea surface for the case of air-sea temperature equilibrium. The 3-d structures are driven by strong surface heat flux ( $\Delta T = 14.2^\circ\text{C}$ ) in spite of surface wind speeds of  $10.9 \text{ m s}^{-1}$ . In the case of no surface heat flux ( $\Delta T \simeq 0$ ), the wind shear (for surface wind speeds of  $15.1 \text{ m s}^{-1}$ ) forced a 2-d structure in the sea surface deformations.

The Sorbjan LES model was employed in this study (for more details see Sorbjan 1996, 1999, and 2001). LES models can directly resolve much of the turbulence from the Navier-Stokes equations, but must include a parameterization of sub-grid scale (SGS) turbulence. The Sorbjan LES model is non-hydrostatic and Boussinesq incompressible, and contains six

prognostic equations: the Navier-Stokes equations for the three components of the wind, a thermodynamic equation for the equivalent potential temperature, a conservation equation for the total moisture mixing ratio, and a SGS TKE equation. The unknown quantities include the three components of the wind, the virtual potential temperature, specific humidity and pressure. A finite difference numerical scheme is used in the horizontal and vertical. The time advancement scheme is a 3<sup>rd</sup>-order Runge-Kutta method with a variable time step. The Courant-Friedrichs-Levy (CFL) condition is held constant; therefore the maximum allowable time step is computed dynamically at each iteration for computational efficiency. Periodic boundary conditions are used in the horizontal direction and Monin-Obukhov similarity theory is used to construct the lower boundary condition. A damping layer is used as the top boundary condition to dissipate gravity waves before they can be reflected back into the model.

The LES model simulations have been divided into two parts: 1) the relationship of surface heat flux versus wind shear to study convective geometry, and 2) LES model simulation of the CFP region of the 13 January 1998 Lake-ICE CAO event.

*a. LES of the relationship of surface heat flux to wind shear*

The LES model (described above) was initialized with 128 grid points in both horizontal directions and 100 grid points in the vertical. Grid spacing was set to 10 m in the horizontal and vertical directions, resulting in a model domain of 1.28 km x 1.28 km x 1 km (viewed as acceptable in this study; to be discussed later). The initial inversion layer height was set at 450 m (no higher than ½ the domain height) to allow for boundary layer growth throughout the model run. The basic state (mixed layer) potential temperature was set at 300 K, a surface roughness length of 0.01 m, and the Coriolis parameter at  $10^{-4} \text{ s}^{-1}$ . Each model run was set for

6000 time steps. Several runs (all for clear sky conditions) were completed by varying the horizontal winds and the surface heat flux (see Table 1).

Figures 14, 15 and 16 show the results from Runs 2, 5, and 6, respectively. The top two plots in each figure show a plan view of vertical velocity at approximately 30 m and 100 m above the surface (blue is upward motion and red downward) and the bottom plot in each figure shows a plan view from above for the contour of  $w = 1 \text{ m s}^{-1}$ . Run 2 (Fig. 14) was initialized with light winds of  $x = 5 \text{ m s}^{-1}$  and  $y = -5 \text{ m s}^{-1}$  and a surface heat flux of  $50 \text{ W m}^{-2}$ . Banded (2-d) structures are evident at both the 30 m and 100 m heights as well as in the perspective plan view graph. The bands are approximately 450 m apart and extend to a depth of 380 m, resulting in an aspect ratio of 1.2:1. Run 5 (Fig. 15) was also initialized with the same light winds but the surface heat flux was increased to  $400 \text{ W m}^{-2}$ . The plan view of vertical velocity at both 22 m and 100 m show evidence of (3-d) cellular structures, yet the cells are much smaller when closer to the surface. At the 22 m height, the cell diameter is approximately 67 m, which results in an aspect ratio of 3:1. The 100 m plan view shows that the cells have coalesced into larger features with diameters of 640 m that extend to a height of 650 m, resulting in an aspect ratio of 1:1.

Run 6 (Fig. 16) was initialized with increased wind speeds of  $x = 13 \text{ m s}^{-1}$  and  $y = -10 \text{ m s}^{-1}$  and an increased surface heat flux of  $600 \text{ W m}^{-2}$ . Cellular structures are evident at the 30 m level (i.e. buoyancy dominating over shear, and a resulting aspect ratio of 3.3:1), whereas 2-d banded structures and 3-d cells coexist at the 100 m level (i.e., shear begins to dominate over buoyancy). From the perspective plan view, aspect ratios of 1:1 for the bands and 1.1:1 for the cells were calculated.

Run 2 shows that the light winds are dominating over buoyancy, resulting in the appearance of 2-d structures throughout the boundary layer. Run 5 (with increased surface heat

flux), however, indicates that buoyancy is dominating over the light winds resulting in 3-d structures throughout the boundary layer, that start as small cells near the surface and coalesce into larger cells upon ascent in the boundary layer. Run 6 (with both increased winds and surface heat flux) shows that at various levels in the boundary layer, 2-d and 3-d (planform) structures coexist. This finding shows the change of dominance from buoyancy at the lower levels forcing 3-d structures, to shear at the upper levels forcing 2-d structures.

The LES model results may also be considered in terms of the coherent structures defined and discussed in Sections 3 and 4. Runs 5 and 6 show evidence of 3-d cellular structures at the 30 m level with resulting aspect ratios of approximately 3:1. These structures may be classified as CS1, which was defined as 3-d open cells driven by buoyancy due to surface heating (see Agee et al. 2000). Both of these model runs also show the cells coalescing into larger cells higher up in the boundary layer with aspect ratios of 1:1 or CS2. Furthermore, Run 6 shows evidence that supports the conclusion that a “footprint” of 2-d structures is embedded within the 3-d cells (or CS3). Again, it is evident from these model simulations that buoyancy can dominate over shear and support 3-d planform structures (or cells) in the presence of strong winds. These model runs show remarkable agreement with the Lake-ICE field observations.

As mentioned above, Agee and Gluhovsky (1999) addressed the concerns of grid size, domain size, and simulation time. They concluded that the grid size must at least extend down into the inertial subrange, and the horizontal domain size should be at least 2.5 times larger than the characteristic horizontal length scale of the phenomena to be simulated (which is consistent with a recommendation by Wyngaard 1983; and de Roode and Duynkerke 2004). In this study, no clouds (or moisture) are present in the LES model, which allows for a smaller domain size (as noted by de Roode and Duynkerke). All model simulations in this study were run with a grid

size of 10 m x 10 m x 10 m, well into the inertial subrange (Cuxart et al. 1997), and a domain size of 1.28 km x 1.28 km x 1 km. All cells and bands that were simulated fell within the 2.5 times the wavelength recommendation, except for the cells in Run 5 that had a wavelength of 640 m, resulting in the domain being only 2 times larger than the wavelength of the structure.

*b. LES of the 13 January 1998 Lake-ICE CAO event*

The Sorbjan LES model was also used to simulate CSs that have been identified in visual photography and VIL imagery in the CFP region directly off the Wisconsin shoreline during the 13 January 1998 CAO event. These structures include: a) CS1, buoyancy driven 3-d open cells with aspect ratios of 5:1, b) CS2, larger (and buoyancy driven) 3-d open cells with aspect ratios of 1:2 and 1:1, and c) CS3, 2-d mesoscale bands driven by heating and shear with aspect ratios of 3:1.

The model was initialized using the ISS sounding data collected at Sheboygan, WI at 16:30 UTC on 13 January 1998. This time was chosen to be as close to the VIL imagery time of 16:25:07 UTC as possible. The initial inversion layer height was set at 275 m, the horizontal winds at  $x = 13 \text{ m s}^{-1}$  and  $y = -10 \text{ m s}^{-1}$ , and the surface heat flux at  $600 \text{ W m}^{-2}$ . The basic state (mixed layer) potential temperature was set at 252.5 K, surface roughness length set at 0.01 m, and the Coriolis parameter set at  $10^{-4} \text{ s}^{-1}$ . The model results in the previous section showed that grid spacing of 10 m x 10 m x 10 m with 128 grid points in both horizontal directions and 100 grid points in the vertical resulted in an adequate domain size (1.28 km x 1.28 km x 1 km) for simulating the CSs. The model was run for 6000 time steps, which resulted in a simulation time of 2112.9 s.

Figure 17a-d shows vertical velocity at 4 levels; a) 30 m, b) 100 m, c) 200 m and d) 300 m. The 30 m plan view of vertical velocity (in Fig. 17a) shows 3-d cellular structures driven by

strong surface heat flux. The cells have 85 m diameters that result in aspect ratios of 2.8:1 (which match well with the enhanced photograph of CS1 (see Fig. 8)). At the 100 m level (Fig. 17b), a 2-d banded structure starts to emerge and coexist with the 3-d cells. The cells have 400 m diameters and extend up past the 300 m level, resulting in aspect ratios of about 1:1. These cells are equivalent to CS2 that were found in the VIL imagery. The bands are approximately 450 m apart and extend up to the 200 m level (Fig. 17c) resulting in aspect ratios of 2.25:1, which are equivalent to CS3. Figure 18 shows a plan view (from above, looking down) of vertical velocity. The underlying plot (in red-yellow-green) is the 30 m vertical velocity field which shows cellular structures; and the top plot (in blue) is the  $w = 1 \text{ m s}^{-1}$  contour showing a banded structure that reaches a height of over 300 m. This simulation accords well with the proposed concept that the coherent structures start at the air- sea interface as microscale 3-d cells (CS1) dominated by surface heating, and continuing upward (and through time) by a combination of effects due to both buoyancy and shear, producing in a “building block” fashion the mesoscale 2-d bands (CS3) and 3-d cellular clouds (CS4).

## 6. Summary and Conclusions

The Lake-ICE special field data sets collected during the westerly flow CAO event of 13 January 1998 afforded the opportunity to examine an evolving convective boundary layer in unprecedented detail. Using well-timed sounding data, VIL imagery and special aircraft data sets, a west-to-east schematic cross-section of the CAO event was developed. The upstream land boundary layer (over Wisconsin) was convectively well-mixed and moist, which are less common features of the upstream PBL during a westerly CAO event over Lake Michigan. This was due, in part, to the unusually mild winter conditions prior to this event and the abnormally warm soil temperatures. As the flow extended out across Lake Michigan, not only did the

thermal internal boundary layer (TIBL) form, but also a new observational feature was identified and named, the moisture internal boundary layer (MIBL). The MIBL is seen to develop because 1) the unusual upstream land boundary layer of heat and moisture, and 2) the moisture from the lake mixing to a much greater vertical extent than the heating that formed the TIBL. This has been attributed, in part, to penetrative steam devils that extend into the MIBL region, and the effectiveness of moisture to diffuse into an overlying moist layer, resulting in a more favorable scalar gradient in the interfacial layer.

An area of downwelling was also observed directly off-shore which lowered the heights of the PBL as well as the temperature and moisture boundary layers, accompanied by a region of subsidence warming aloft. This downwelling is attributed to the acceleration of air off the land surface over the much smoother water surface (representing a response similar to that of the upwelling of water). Lake heating and moistening were quantified and found to be in agreement with other CAO studies,  $9^{\circ}\text{C}$  and  $.7 \text{ gkg}^{-1}$ , respectively.

As the land air mass advected out over the lake, three very distinct layers formed within and near the top of the PBL. The first layer (Layer I) resides closest to the lake surface, and is characterized by new vigorous, moist and turbulent convection (and includes the TIBL). The second layer (Layer II), which lies between the top of the first layer and the base of the inversion (and containing the MIBL) is the residual convective layer from the land that has been enriched by moisture from the lake. The third, and final, layer (III) is the typical capping warm and dry stable layer. The turbulence statistics calculated from the KA data sets show 1) the maximum moisture flux in VFS2 is located in the MIBL (at a height of 799 m ALS, or  $z/z_i = 0.85$ ) which coincides with the minimum of the heat flux, and 2) moisture being mixed further upward above the lower boundary layer (evidenced in VFS3).

The Electra data were separated into three data sets based on the three distinct atmospheric layers discussed above, and a spectral analysis was performed to determine the existence of spectral peaks. In Layer I, the significant spectral peaks of the  $w'$  field are organized into two identifiable length scales; the smaller CS scale (CS2) ranging from aspect ratios of 1:3.4 to 1:1, and the larger CS scales (CS3) ranging from aspect ratios of 1.5:1 to 2.2:1. The  $T'$  field matches well with the  $w'$  field, whereas turbulent fluctuations in the  $q'$  field appear at “all” wavelengths. Moisture fluxes are viewed as more passive to the existence of CSs, which may support in part the ability of different scalar quantities to mix to different heights at different length scales (i.e. moisture mixing to a greater depth than heat). Therefore, it can be said that coherency is seen in the  $w'$  and  $T'$  fields with little or no coherency in the  $q'$  field. The convection in Layer I is seen to occur in organized, detectable selective length scales, or CSs. These 12 Electra flights over a 3 hours period show that CSs are persisting over time in an evolving boundary layer demonstrating the constancy of turbulence.

Through the analysis of VIL imagery, aircraft data, cloud photography and satellite imagery, four scales of coherent structures (CSs) with differing spatial and temporal dimensions were identified. For the purpose of this research, the term coherent structures was defined as *structures in atmospheric flow with spatial organization, yet temporally chaotic, that exist longer than several “local” large eddy turnover times.* The CSs start as visible steam fog showing microscale 3-d open cellular structures near the lake surface (CS1) with aspect ratios of 5:1, which grow in a building block fashion to a 3-d open cellular array of VIL steam fog that extends up to 500 m in the boundary layer (CS2). CS3 is a 2-d footprint of mesoscale convection found in the vertical velocity field derived from the VIL horizontal winds, and is also seen as 2-d cloud bands in the visible satellite imagery with aspect ratios of 3:1. CS1, CS2 and CS3 are embedded

within one another and are found in the CFP region directly off the Wisconsin shoreline. Finally, CS4 is a large array of open 3-d cellular clouds with diameters of 5 km found in the satellite imagery and commonly referred to as mesoscale cellular convection. Through analysis of the energy spectrum of the three vertical flight stacks of KA data, significant spectral peaks were found in the  $w'$ ,  $q'$  and  $T'$  fields with aspect ratios ranging from 1:1 (suggesting the presence of CS2) to 3:1 (suggesting the presence of CS3). The vertical extent of CS1 (6 m) was too low for the aircraft to sample and the horizontal extent of CS4 (5 km) was too large to obtain significant statistical verification from the data sets.

In view of the above concepts, definition, and observations with special field data sets, large eddy simulation was viewed as an appropriated technique to model coherent structures. Model runs show evidence of 3-d cellular structures at 30 m above the surface, with aspect ratios of approximately 3:1. These structures may be classified as CS1, which is defined as 3-d open cells driven by buoyancy (due to surface heating). Model runs also show the cells coalescing into larger cellular patterns higher up in the boundary layer with resulting aspect ratios of 1:1 (defined as CS2). Further, the model runs show evidence that support the conclusion that a “footprint” of 2-d structures (CS3) is embedded within and near the top of the 3-d cells. It is evident from these simulations that buoyancy can dominate over shear and create 3-d structures in the presence of strong winds, resulting in agreement with the Lake-ICE field observations.

Through this LES study it was also found that buoyancy can dominate in a strong shear environment. It was seen that light winds dominate over very weak buoyancy, resulting in the appearance of 2-d structures throughout the boundary layer. By increasing surface heat flux, however, buoyancy is seen to dominate over the light winds resulting in 3-d structures throughout the boundary layer that start as small cells near the surface and coalesce into larger

cells upon ascent in the boundary layer. Finally, by increasing both the winds and surface heat flux, 2-d and 3-d structures are seen to coexist at various levels in the boundary layer. This finding shows the interchange of dominance from buoyancy (over strong shear) at the lower levels, forcing 3-d structures; to shear at the upper levels, forcing 2-d structures.

The 13 January 1998 CAO event was also simulated with LES. The 30 m plan view of vertical velocity showed 3-d cellular structures with aspect ratios of 2.8:1 that match well with the enhanced photograph of CS1. These cells are driven by strong surface heat flux. At the 100 m level, a 2-d banded structure is seen to emerge and coexist with the 3-d cells. The cells have diameters of approximately 400 m and extend up above the 300 m level for a resulting aspect ratio approaching 1:1. These cells are equivalent to CS2 that were found in the VIL imagery. The bands (that are coexisting with the cells at the 100 m level) are approximately 450 m apart and extend up to the 200 m level. These bands have a resulting aspect ratio of 2.25:1 that may be considered equivalent to CS3; the ‘footprint’ of what is developing further downstream. A plan view (from above, looking down) of vertical velocity showed cellular structures in the 30 m vertical velocity field, and banded structures in the  $w = 1 \text{ m s}^{-1}$  contour that extended to heights of over 300 m. This simulation is in agreement with the proposed concept that the coherent structures start near the air-sea interface as microscale 3-d cells (CS1) and, through a shifting of dominance from surface heating to wind shear, coalesce and grow in a “building block” fashion up to the mesoscale 2-d bands (CS3) and eventually the 3-d cellular clouds (CS4).

A unique feature in this CAO event is the presence and structure of steam fog and steam devils. From visual photography and communication with the Lake-ICE field crew, it was evident that steam fog and steam devils approximately 100 to 150 m high were present across the entire surface of the Lake during this CAO event. In fact the extraordinary VIL imagery by the

Wisconsin Group shows that some of the steam fog and/or steam devils actually penetrated to depths of 500 m ALS in the CFP region. The lidar aircraft data showed evidence of steam devils penetrating deep into the boundary layer, suggesting that it is these steam devils that transport some of the moisture to greater depths than heat. Previously it was thought that the steam fog and steam devils were independent from the overlying cloud formation. However, this research shows that the steam fog and devils in the CFP region can be viewed as part of the initial building blocks that grow and coalesce with neighboring cells to form the larger mesoscale cloud bands and cells. Where present in an array of cellular steam fog patterns, the steam devils can be interpreted as vertex vortices.

## **7. Acknowledgements**

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## 9. Figure Captions

Figure 1. Surface weather map of the USA Midwest on 1200 UTC, 13 January 1998.

Figure 2. GOES satellite image at 1630 UTC on 13 January 1998 depicting (from west to east over the lake) the cloud-free path, the initial formation of 2-d cloud bands evolving into 3-d open cells.

Figure 3. Schematic cross-section of convective (red) and moist (blue) boundary layer depths for westerly CAO of 13 January 1998, and data sources. Dots represent KA flight levels. Distances of aircraft vertical stacks (VS) from Wisconsin shoreline are shown.  $E_1$  marks the first (slanted) flight path, and  $E_2$  marks the multiple horizontal flight levels for the Electra data at ~575 m above Lake Michigan. The geographical location of the data platforms is given in Fig. 1 by Kristovich et al. (2003), and is therefore not repeated in this paper.

Figure 4. Vertical scan of VIL imagery showing the vertical extent of the steam fog and steam devil columns from the Wisconsin shoreline out to 11 km (the CFP region). Image provided by the courtesy of Ed Eloranta and Shane Mayor, University of Wisconsin Lidar Research Group.

Figure 5. A vertical cross-section of *lake heating*, depicted by  $\Delta T$  isotherm analysis ( $C^\circ$ ). The thick bold curved line denotes the top of the heated layer, and M identifies points near this boundary that are independently verified by aircraft data vertical fluxes (both momentum and temperature).

Figure 6. A vertical cross-section of *lake moistening* depicted by  $\Delta q$  isohume analysis ( $gkg^{-1}$ ).

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. The dashed line is an extension of the lake moistening height that conforms to the analysis pattern.

Figure 7. Plots of raw 25 Hz vertical velocity ( $w$ ), air temperature ( $T$ ) and mixing ratio ( $q$ ) from Electra flight leg 9. Layer I represents the new vigorous, moist and turbulent layer, Layer II is the residual convective layer from land that is enriched by moisture from the lake and Layer III is the capping warm and dry stable layer.

Figure 8. CS1 embedded within CS2 identified in visual photography. An example of CS2 is outlined with the dotted line in the top image. The inset photograph was enhanced to show CS1 in detail (photograph by Dave Rogers, CSU, taken at 575 m ALS, near the Wisconsin shoreline).

Figure 9. CS2 evident in the VIL imagery taken on 13 January 1998 at 16:25 UTC as 3-d open cells. The lidar was located in the upper left-hand corner of the image, the left side is the Wisconsin shore and the cells exist in clear air over the water surface (courtesy of Eloranta and Mayor, University of Wisconsin, Madison).

Figure 10. Spectral plot of vertical velocity,  $w$ , from Vertical Flight Stack 1, Level 1 (125 m ALS) on 13 January 1998. The inserted enlarged view shows three spectral peaks of interest.

Figure 11. The horizontal wind divergence field on a 5 km by 5 km domain shows CS3 as 2-d mesoscale bands embedded within a field of 3-d cellular steam fog. This banded structure is a footprint to the 2-d cloud bands that evolve downstream, just off-shore from Sheboygan, Wisconsin (see Mayor and Eloranta 2001).

Figure 12a. Layer I significant spectral peaks of  $q'$  (plotted Electra flight leg versus wavelength in meters).

Figure 12b. Layer I significant spectral peaks of  $w'$  (plotted Electra flight leg versus wavelength in meters).

Figure 13. Synthetic aperture radar (SAR) signatures of microscale air-sea interactions (courtesy of Todd Sikora). Figure a) shows 3-d sea surface deformation structures in a CAO event with winds of  $10.9 \text{ m s}^{-1}$  and air-sea temperature difference of  $14.2^\circ\text{C}$ . Figure b) shows 2-d sea surface deformation structures in an air-sea temperature equilibrium event with winds of  $15.1 \text{ m s}^{-1}$ . Images are taken over the USA East Coast region, near Long Island, NY.

Figure 14. Model Run 2 vertical velocity fields for surface heat flux of  $50 \text{ K m s}^{-1}$  and winds at  $x = 5 \text{ m s}^{-1}$  and  $y = -5 \text{ m s}^{-1}$ . Top plots are plan views of vertical velocity with blue upward motion and red downward motion at 30 m and 100 m, respectively. The bottom graph is a plan view (from above, looking down) for the  $w = 1 \text{ m s}^{-1}$  contour.

Figure 15. Model Run 5 vertical velocity fields for surface heat flux of  $400 \text{ K m s}^{-1}$  and winds at  $x = 5 \text{ m s}^{-1}$  and  $y = -5 \text{ m s}^{-1}$ . Top plots are plan views of vertical velocity with blue upward motion and red downward motion at 22 m and 100 m, respectively. The bottom graph is a plan view (from above, looking down) for the  $w = 1 \text{ m s}^{-1}$  contour.

Figure 16. Model Run 6 vertical velocity fields for surface heat flux of  $600 \text{ K m s}^{-1}$  and winds at  $x = 13 \text{ m s}^{-1}$  and  $y = -10 \text{ m s}^{-1}$ . Top plots are plan views of vertical velocity with blue upward motion and red downward motion at 30 m and 100 m, respectively. The bottom graph is a plan view (from above, looking down) for the  $w = 1 \text{ m s}^{-1}$  contour.

Figure 17. Lake-ICE Model Run vertical velocity fields for surface heat flux of  $600 \text{ K m s}^{-1}$  and winds at  $x = 13 \text{ m s}^{-1}$  and  $y = -10 \text{ m s}^{-1}$ . The plots are plan views of vertical velocity with blue upward motion and red downward motion at a) 30 m, b) 100 m, c) 200 m, and d) 300 m.

Figure 18. Lake-ICE Model Run vertical velocity fields for surface heat flux of  $600 \text{ K m s}^{-1}$  and winds at  $x = 13 \text{ m s}^{-1}$  and  $y = -10 \text{ m s}^{-1}$ . The graph is a plan view (from above, looking

down) for the  $w = 1 \text{ m s}^{-1}$  contour combined with the 30 m vertical velocity (blue is upward motion and red is downward).

Table 1. Horizontal winds, surface heat flux, mixed-layer depth and simulation time for each model simulation. The highlighted runs are discussed in detail below.

Run	x direction wind $\text{m s}^{-1}$	y direction wind $\text{m s}^{-1}$	Surface heat flux $\text{W m}^{-2}$	Mixed-layer depth m	Simulation time s
2	5	-5	50	489.15	5214.6
3	5	-5	100	524.55	4770.3
4	5	-5	200	568.54	4343.2
5	5	-5	400	709.3	3908.1
5c	5	-5	600		
5b	13	-10	100	464.3	2418.5
5a	13	-10	400	539.0	2182.7
6	13	-10	600	535.7	2133.8