LIDAR OBSERVATIONS AND COMPARISON WITH NUMERICAL SIMULATION OF A LAKE MICHIGAN LAND BREEZE FRONT

G. de Boer[1], E.W. Eloranta[2], G. J. Tripoli[1]

[1] *Department of Atmospheric and Oceanic Science, 1225 W. Dayton St. Madison, WI 53706 USA, gdeboer@wisc.edu:*
[2] *Space Science and Engineering Center, 1225 W. Dayton Street Madison, WI 53706 USA, eloranta@lidar.ssec.wisc.edu:*

ABSTRACT

As a part of the Lake-Induced Convection Experiments (Lake-ICE), on December 21, 1997 the University of Wisconsin Volume Imaging Lidar (UW-VIL) observed a visually stunning example of a shallow (~75-100 m) land breeze circulation over Lake Michigan. Backscatter returns revealed a steady offshore flow extending 1.5 to 4 km offshore, at which point it met the prevailing winds, which directly opposed the circulation. Since the prevailing onshore flow was weak enough to not overpower the local circulation, there was a consistent convergence zone offshore at the nose of the land breeze. Noting that the observed flow pattern is likely a simple combination of the large-scale atmospheric state and the local thermal forcing, we have simulated the day's events using a high-resolution version of the University of Wisconsin Non-Hydrostatic Modeling System (UW-NMS). The lidar data was used as a validation tool for the model output.

1. INTRODUCTION

As electronic computing resources become increasingly available at lower and lower prices, we are able to increase the level of complexity at which atmospheric models operate. The planetary boundary layer, a region of incredible importance due to our everyday interactions with it at the surface of the earth, is one of the areas that can be more accurately represented with these increases in resolution. One common problem, however, is that it is difficult to assess the correctness of these simulations, due to a lack of verification techniques available at the scales which we are now investigating. Lidar observations of the boundary layer provide invaluable insight into the structure and evolution of features found in this section of our atmosphere. Because these observations are taken at high resolutions both temporally and spatially, they can accurately depict structures such as the land breeze front discussed in this paper. Previous studies of land breezes over Lake Michigan, such as those done by Passarelli and Braham [5], Alpert and Neumann [1], Keen and Lyons [3], and Ballentine [2] have relied on things such as satellite imagery, as well as visual observations of smoke plumes and data taken by airplane to confirm the presence of a land-breeze circulation, and to attempt verification of the numerical simulations that were produced. Although these methods somewhat accurately depict the position of the land breeze front, as well as the general circulation and possibly strength of the flow pattern, they cannot demonstrate the complex structure of the flow itself. Also, in a case such as this, where the circulation is very shallow, it is possible that the phenomenon would not be observed at all. With the lidar data, however, we can gain a great deal of knowledge on several aspects of the boundary layer flow and circulation. The position as well as horizontal and vertical structures of the front can be observed with great accuracy, as can the size of cellular convective structures outside of the land breeze circulation. The depth of both the planetary boundary layer as well as the land breeze circulation can be determined, cloud base and top heights can be observed [6], and estimated wind vector, divergence, and vorticity fields of the viewed area can be constructed [4]. Of course, attaining these parameters from the lidar returns is not in itself a new concept or ability. With our increased ability to model at scales similar to those observed by the lidar, however, these techniques are thrust back into the spotlight. Here we look at some of these aspects of the data taken by the University of Wisconsin Volume Imaging Lidar (UW-VIL) for comparison with output from the UW-NMS [7]. The model is run forward from the ECMWF analysis for the date of the event using nested grids in order to achieve the desired resolution. We compare the position of the front, the depth of the circulation, the strength and direction of the flows, as well as the size of cellular, convective structures seen outside of the land breeze circulation, and discuss the results of these findings.

2. THE UNIVERSITY OF WISCONSIN VOLUME IMAGING LIDAR (UW-VIL)

The UW-VIL is a unit that has evolved over the last several decades. It is an elastic backscatter lidar, built for four-dimensional data collection (3 spatial, and time) primarily in the atmospheric boundary layer. The most recent version came together in 1995, when a new Infinity Coherent 40-100 diode-pumped Nd:YAG laser was purchased for the system, along with an SGI workstation for data collection.

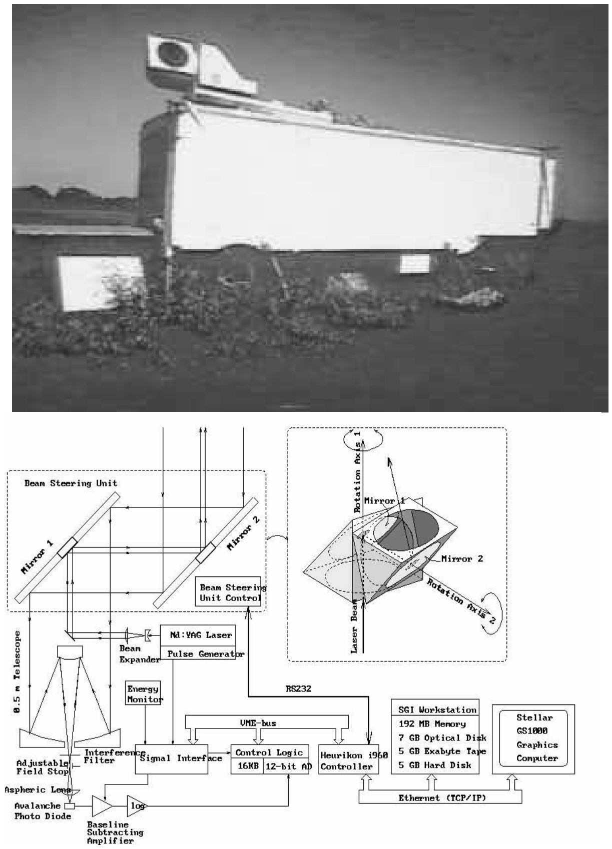

FIG. 1 The University of Wisconsin VIL in its semi-trailer housing (top) and a schematic of the system components (bottom).

The transmitter operates at a 1064 nm wavelength, with an average power of 40 watts, and a 100 Hz repetition rate. The receiver utilizes a 50 cm telescope with a 1 nm optical bandwidth, allowing for 15 m range resolution and a maximum angular scan rate of 20 degrees per second. The chosen wavelength allows the measurement range to be strongly related to the aerosol distribution of the atmosphere and the range squared dependence of the backscatter, as molecular absorption is relatively insignificant at 1064 nm. Due to the high sensitivity of the system, differences in aerosol concentration accompanying convective structures, as those found in different types of air masses can be detected for clear air. The powerful laser coupled with the large telescope mirror allows the system to detect aerosols up to 30 km away in a clear atmosphere. The system is not eye-safe, and an observer armed with a switch that closes the shutter is utilized to watch for air traffic inside the scan area. For boundary layer applications, the VIL typically will scan a 40 degree azimuthal sector and a 15 degree elevational angle range. The resolution for these scans is typically 15 m radially, 0.5 degrees azimuthally, and 0.33 degrees of elevation angle. The position of the beam is controlled by a beam steering unit (fig. 1) that utilizes two flat rotating mirrors mounted at 45 degree angles on the

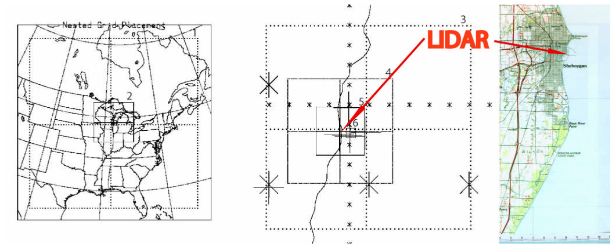

FIG. 2 The placement of the 6 nested grids in our simulation, and a map of Sheboygan, WI (right).

optical axis of the transmitter-receiver system, and has the ability to cover 20 degrees per second, allowing a 100 km^3 volume to be scanned at five million data points in approximately 3 minutes. This entire system is housed inside a semi-trailer (fig. 1) making it semi-portable for field experiments.

3. THE UNIVERSITY OF WISCONSIN NON-HYDROSTATIC MODELING SYSTEM (UW-NMS)

For our simulations of the land breeze case, we utilized the UW-NMS. Several features of this particular model make it attractive for simulation of large boundary layer eddies. First, as the name implies, it is non-hydrostatic, meaning the vertical momentum equation is solved, allowing higher horizontal resolution as well as the formation of convective circulations and the land breeze itself. Also, the model is scalable in space and time, utilizing a two-way grid nesting system to attain higher resolutions. Topography is handled by a variable step system, meaning that a step coordinate system is used, with a varying thickness in the bottom grid box. This allows the model to handle both steep and very subtle topographical changes. Also, a high-resolution (100 m) topographical data set was utilized to represent the state of Wisconsin in order to accurately portray shoreline geometry and topographical features that may influence the flow. In our simulation, we employed six nested grids (fig. 2), the smallest of which featured 32 meter horizontal resolution. Vertical resolution inside the boundary layer was set to 20 meters. The resolution used allowed us to resolve some of the structures observable with the lidar. Vis5D output was created at 15-second intervals for the smallest grid in order to see the evolution of the flow in manner similar to that of the VIL.

4. LAKE-ICE: DECEMBER 21, 1997

The Lake-Induced Convection Experiment was a collaborative effort between several entities, including the National Centers For Atmospheric Research (NCAR), the University of Wisconsin-Madison, the University of Michigan, and the Pennsylvania State University. Several observing platforms were utilized

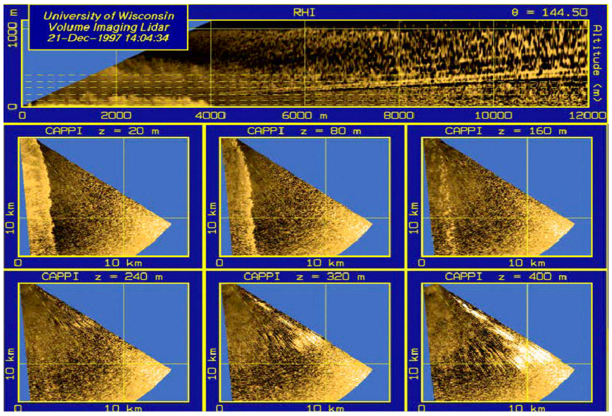

FIG. 3. An RHI of the land-breeze (top), and several CAPPIs (bottom) showing the shallow nature of the circulation.

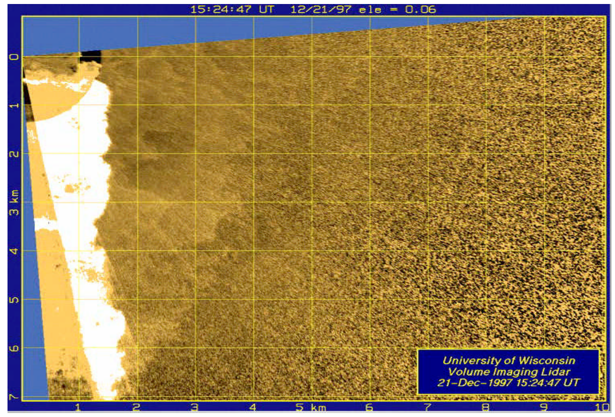

FIG. 4. A PPI of the land breeze with a median high pass filter applied to see structure of the easterly flow.

to study the convection taking place when cold air is advected over the warmer surfaces of the Great Lakes during the early portion of the winter. The VIL was stationed at Sheboygan Point, on the western (Wisconsin) shoreline of Lake Michigan (fig. 2). On December 21, 1997, the VIL observed a land breeze circulation flowing offshore from its location.

4.1 <u>Lidar Data</u>

Predawn on the morning of December 21, the scientists at the lidar trailer observed partly cloudy conditions, with a surface temperature of –3.8 C, and a measured water temperature of 2.2 C. A weak westerly breeze was observed at the surface, and data collection began. Several minutes later, it was noticed that the emission plume coming from the smoke stack of the Sheboygan power plant was blowing towards the west, while surface winds were westerly. At this point the team realized that they were observing a land breeze circulation with the lidar, and that the land breeze front was in their scan area. The scanning strategy was adjusted to encompass the front, and cover 15 degrees in elevation angle from the surface. Range-height indicator (RHI) scans revealed the shallow aerosol rich circulation extending out over the lake (fig. 3), and showed the intersection between the land breeze and the prevailing easterly winds fluctuating from 1.5 to 4.5 km offshore. Also visible in the RHIs is the top of the boundary layer, which features an undulating structure, and occasional clouds right along it. Constant altitude plan-position indicator (CAPPI) scans reveal a similar structure extending offshore along the shoreline, and also reveal the depth of the land breeze circulation as scans were done at increasing altitudes (fig. 3). At 160 m altitude there is very little evidence of the circulation, with only some plumes showing up right at the convergence zone. The bright streaks in the low level CAPPIs at approximately 0.5 and 3.5 km south of the lidar are thought to be associated with industrial sites on the shore, which were likely causing localized aerosol maxima. A median high pass filter was applied to some of the CAPPI data in order to enhance our ability to see the aerosol structure of the cleaner onshore (easterly) flow (fig. 4), and allowing us to make comparisons between the cellular structures observed in that flow in the model, and those seen in the filtered lidar data. Data from the filtered CAPPIs was also used to generate 30 minute average wind vector fields as outlined in [4].

4.2 <u>Model Output</u>

Results from our simulation reveal a striking similarity to lidar observations. Looking at the output from the fifth grid (160 m resolution), the land breeze front shows up very clearly at around 4 km offshore in the velocity components, a strong vertical velocity maximum at this point, as well as in relative humidity and temperature discontinuities. The intersection of the two air masses is undulating in nature, and the front, when viewed over time, does fluctuate in its offshore distance. Cellular convective structure can be seen in the onshore, easterly winds, especially looking at the vertical velocity output of the model. A vertical cross section of the sixth grid output reveals that the depth of the land breeze circulation is approximately 90 m. The boundary layer depth can be determined from a cross section of the fifth grid (fig. 5), and is estimated to be at around 1 km. Virtual scattering created using the model relative humidity field resembles the CAPPI scans at 20, 80 and 160m (fig. 5). Finally model vector fields showed the west-northwesterly land breeze being somewhat weaker in nature than the prevailing easterly winds.

5. CONCLUSIONS

A crude comparison of the output from the UW-NMS and the data attained using the UW-VIL reveals generally good agreement. The front shows up well in the model, and has approximately the correct

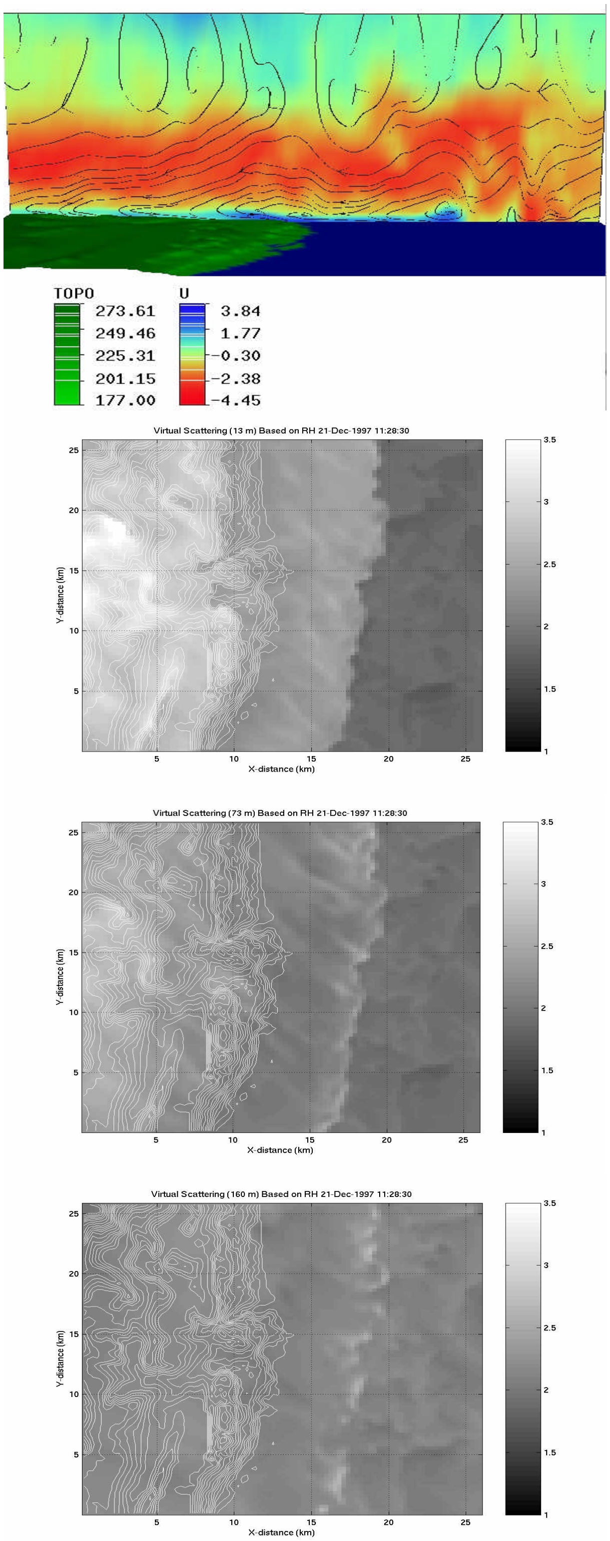

FIG. 5 UW-NMS output: A vertical cross section (dz=1400m) of the zonal wind from the grid 5, with streamlines and topography (top), and virtual scattering from model RH output at 13 m, 73m, and 160 m (bot.)

dimensions. It does seem as though the front is somewhat farther offshore in the model run when compared to its position in the lidar data, this likely being the result of only using a limited area fine scale grid. Increasing the area of this domain may allow forcing features not resolvable in the fourth and fifth domains to control the position of the front with greater accuracy. We are lead to believe this by looking at the fourth grid output, where the front is brought significantly closer to shore in the region of the fifth grid. The boundary layer height seems to match well, as does the depth of the land breeze circulation. A visual comparison of the vector fields shows general agreement in the directions and relative wind speeds of the two systems. Finally, convective structures outside the land breeze circulation are of similar size (~ 450m radius) and travel at similar speeds across the domain when the data is put into motion. This limited verification of the nested model output is a large step in the direction of using models such as the UW-NMS for prediction of small-scale events caused by local forcing, particularly on the timescale of 12-30 hours, when synoptic flow is reasonably predictable.

6. References

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