Lidar Validation of Numerical Simulations of a Lake Michigan Land Breeze

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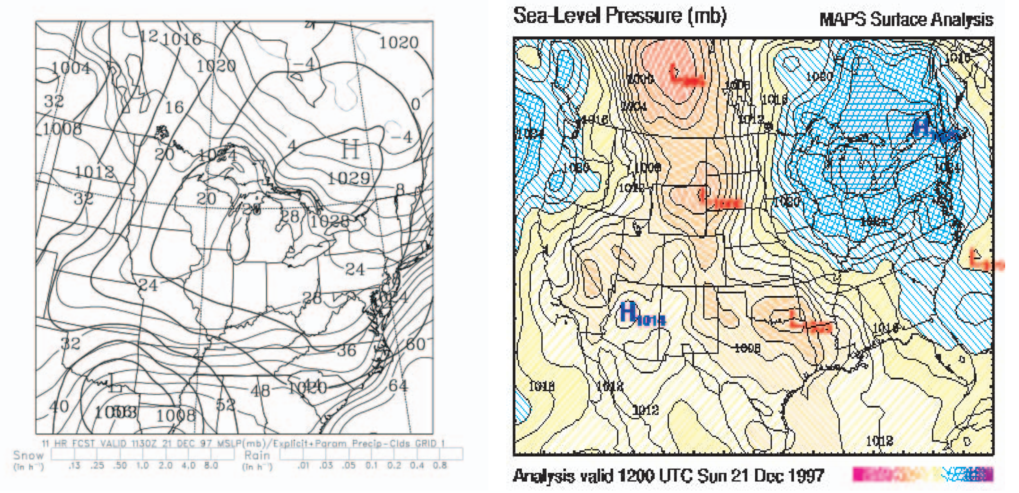
Introduction

As a part of the Lake-Induced Convection Experiments (Lake-ICE; Kristovich, 2000), the University of Wisconsin Volume Imaging Lidar (UW-VIL) was stationed at Sheboygan, Wisconsin, during the winter of 1997-1998. On December 21, 1997, an intriguing shallow land breeze circulation was observed over Lake Michigan with the VIL.

It is hypothesized that micro-α structures such as this land breeze, that are forced primarily by the interaction of meso-β and larger scale features and the local forcing resulting from topographical influences can be reproduced with high accuracy using a dynamical downscaling technique. In this experiment, the dynamical downscaling is accomplished using the nesting ability of the University of Wisconsin Non-Hydrostatic Modeling System (UW-NMS; Tripoli, 1992). The outer domain was run at 60-kilometer horizontal resolution, while the inner domain featured 32-meter horizontal spacing of grid points. All six domains utilized the same stretched vertical resolution, with 20 meter spacing up to 220 m above ground level, and stretched grid cells thereafter, with a maximum vertical step of 750 meters. This combination allows both large and small scales to be simulated simultaneously, and allows for interaction between the evolution of the large-scale and the small-scale land breeze.

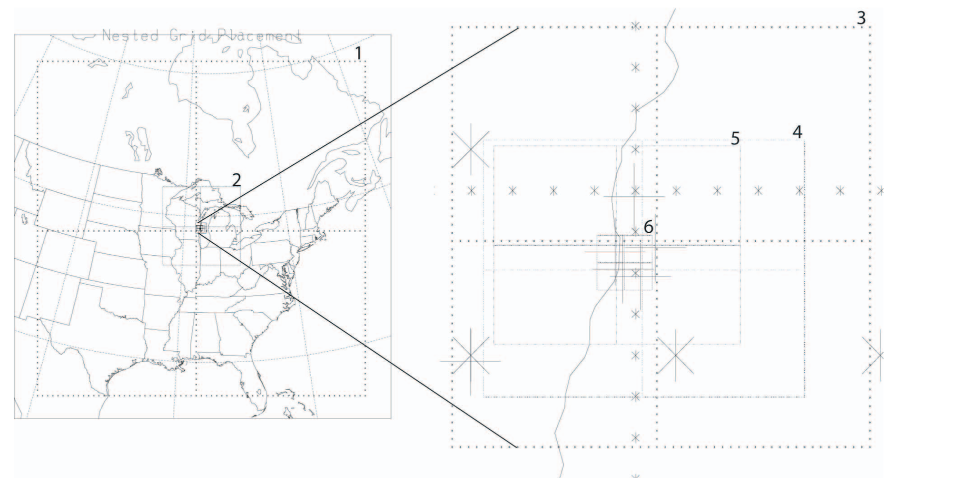
Validation of these simulations through the utilization of traditional point measurement methods is difficult because of the high temporal and spatial resolutions needed to resolve the simulated structures. To address this issue, the VIL data from the event was utilized in order to test the accuracy of the numerical simulations. Parameters such as the horizontal extent of the land breeze, the vertical extent of the land breeze and land breeze head, wind speed and direction, and timing of the simulation were compared between the simulation and the lidar data through the utilization of several analysis methods. This comparison shows good agreement between the simulation and the observed structure, and reveals some weaknesses of the nesting technique when used to simulate very small-scale events. Additionally, comparison between the simulation and traditional point measurements shows the importance of validation of the simulation output using lidar data.

The Synoptic Picture



The 1130Z surface analysis from the UW-NMS run is shown on the left, while the 1200Z surface analysis for the 21st of December, 1997 is shown on the right. Both analyses feature high pressure over south-eastern Canada, as well as an area of low pressure over south-eastern Oklahoma. The model appears to be in good agreement with the analysis as far as the strengths and positions of these systems.

Positioning of the 6 Nested Grids

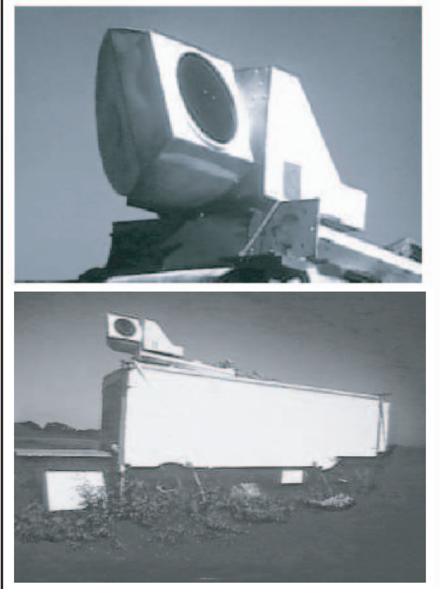


The grid positions of the six grids used in the UW-NMS simulation. The left image shows the outer domains, with the right image being an enlarged view of the the third, fourth, fifth and sixth grids. The Wisconsin shoreline can be seen in the right image. The innermost grid has 32m horizontal resolution, similar in scale to the 15m resolution achieved with the VIL and the outermost grid features 60 km resolution in order to capture the evolution of the large scale.

The University Of Wisconsin Volume Imaging Lidar (UW-VIL)

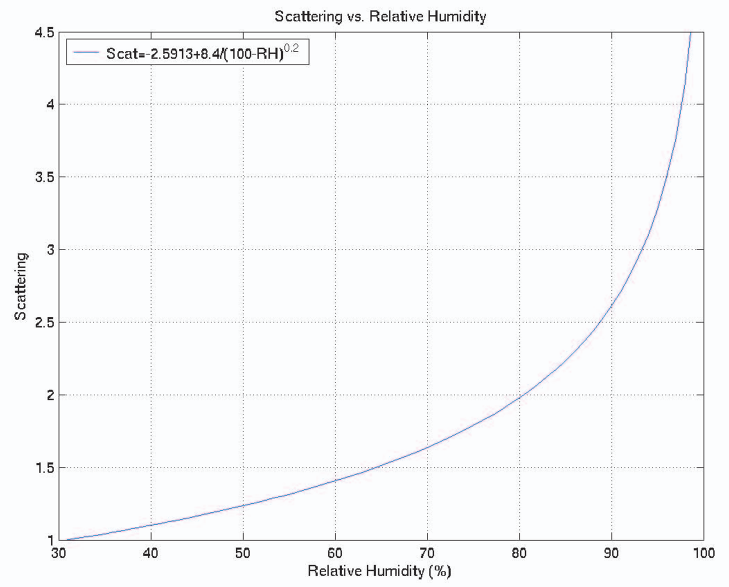
The VIL uses a Nd:YAG laser to transmit 400 mJ pulses at 1.064-micron wavelength at 100 Hz. The VIL resides in a semi-trailer van, employs 0.5 m optics, a beam steering unit, log-amplifier, and real-time displays. Data are stored on write once optical disks.

Transmitter	
Wavelength	1064 nm (Nd:YAG)
Average Power	20 W
Repetition Rate	100 Hz
Receiver	
Telescope Diameter	50 cm
Optical Bandwidth	1 nm
Detector Quantum Efficiency	~35%
Range Resolution	15 m
Maximum Scan Rate	~20 degrees/second
Data Acquisition	
Data Rate	~500 MB/h
Length of Data Buffer	16K x 16 bit
Data Acquisition Computer	Heurikon i960
Controlling Computer & Real-time Graphics	SGI
Optical Data Storage	Hitatchi 7 GB Disk



On the left is a map of the Sheboygan area, with an indication as to where the lidar was situated during the experiments. The VIL trailer, as well as the beam-steering unit can be seen in the above images. Below are some photos taken from Sheboygan Point during the Lake-ICE experiments. The right two photographs show the trailer sitting on the Lake Michigan shoreline.

Model Derived Scattering



Model derived scattering is calculated using a best-fit curve to data taken by Fitzgerald and Hoppel in 1982 in their study of the aerosol humidity effect. The curve fitting this data is shown at left, and the equation fitting the curve is shown below. This relative humidity relationship is then multiplied by a the concentration of a model passive tracer. This tracer is introduced at model initiation, and is meant to represent aerosol population. This method was first used by Mayor (2001), in his work utilizing the UW-VIL in validation of Large Eddy simulation of Lake-ICE dates. Although somewhat crude, having some representation of aerosol inside the simulation is of great assistance in determining the accuracy of the simulation, particularly in a case involving two contrasting air masses such as this one.

Also shown in this section are lidar data from December 21, along with simulated backscatter fields from the same date. Additionally, the variance of the gradients in these fields is calculated in an attempt to illustrate more effectively the position of the land breeze along with features such as the depth of the land breeze, land breeze head and boundary layer.

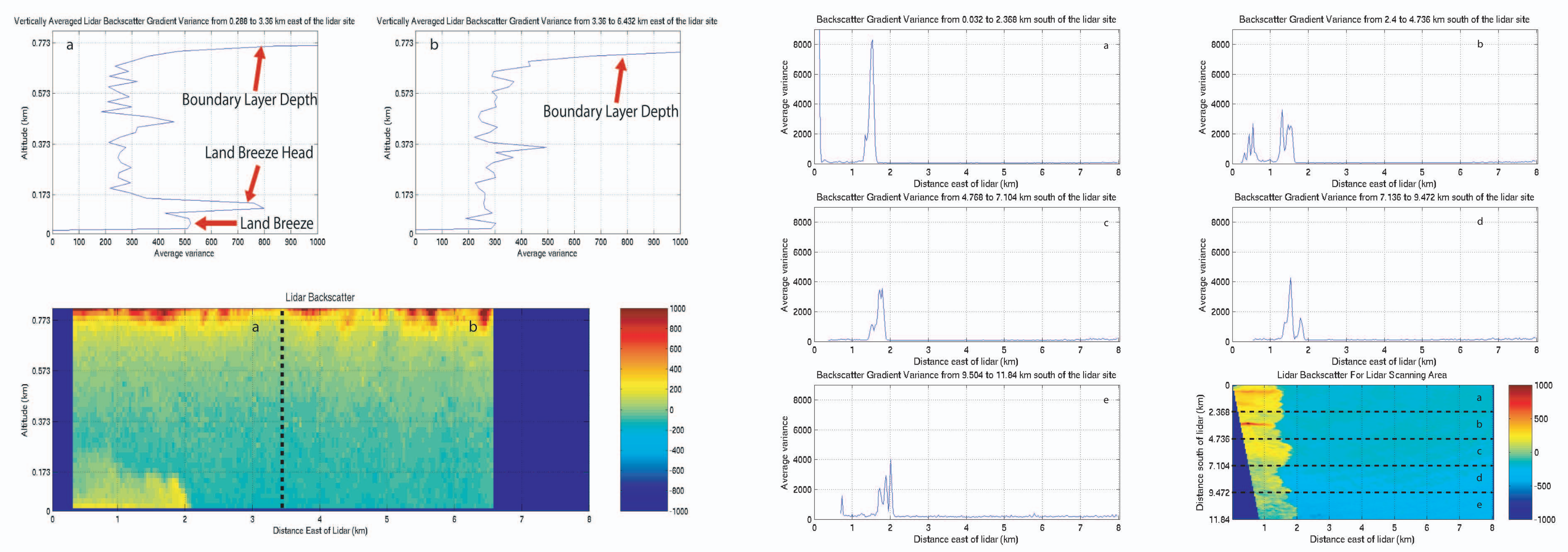
$$\alpha = -2.6 + \frac{8.41}{(100 - RH)^{0.2}}$$ (Fitzgerald , Hoppel; 1982)

$$scat = \tau\alpha$$

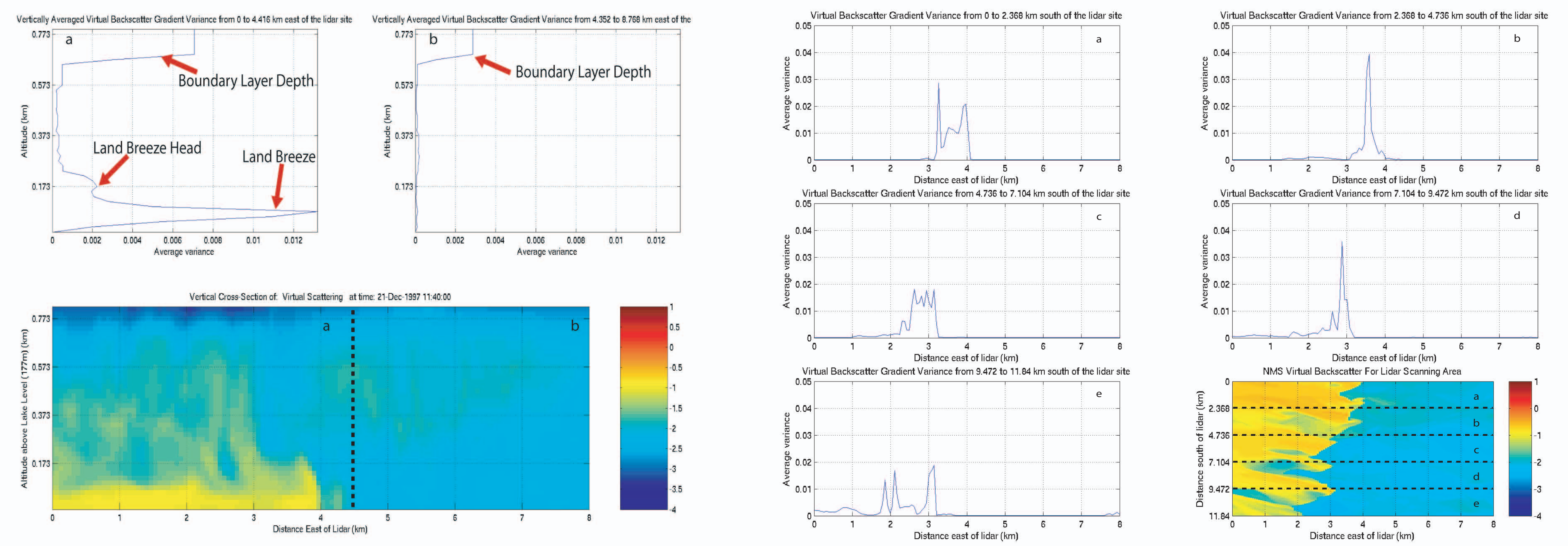
where:

$\tau =$ passive tracer concentration

Lidar Derived Scattering Gradient Variance



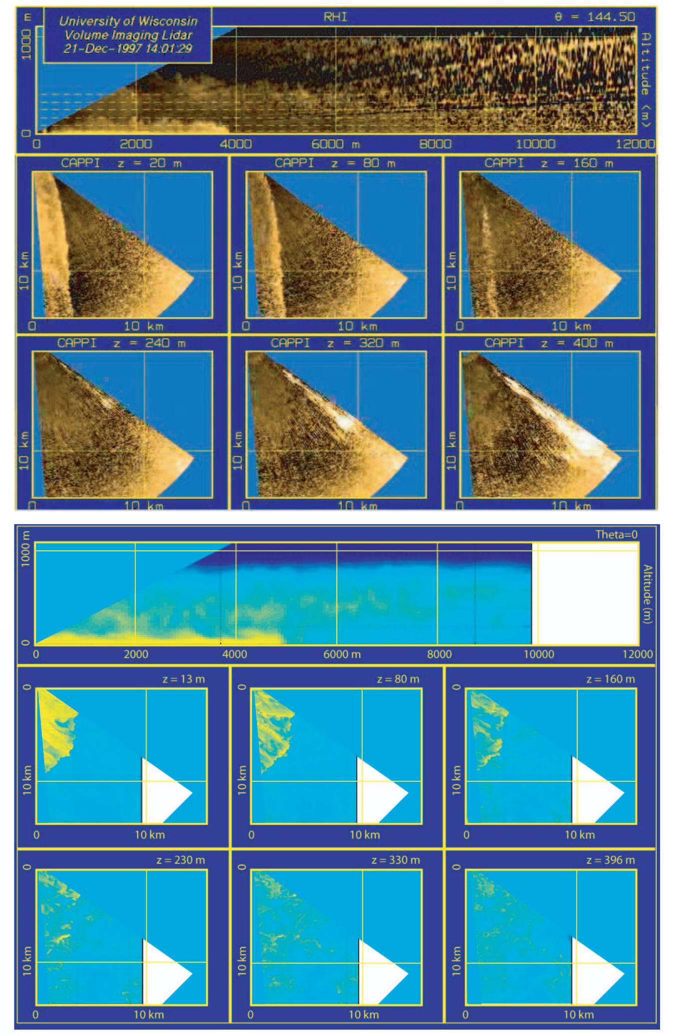
UW-NMS Derived Scattering Gradient Variance



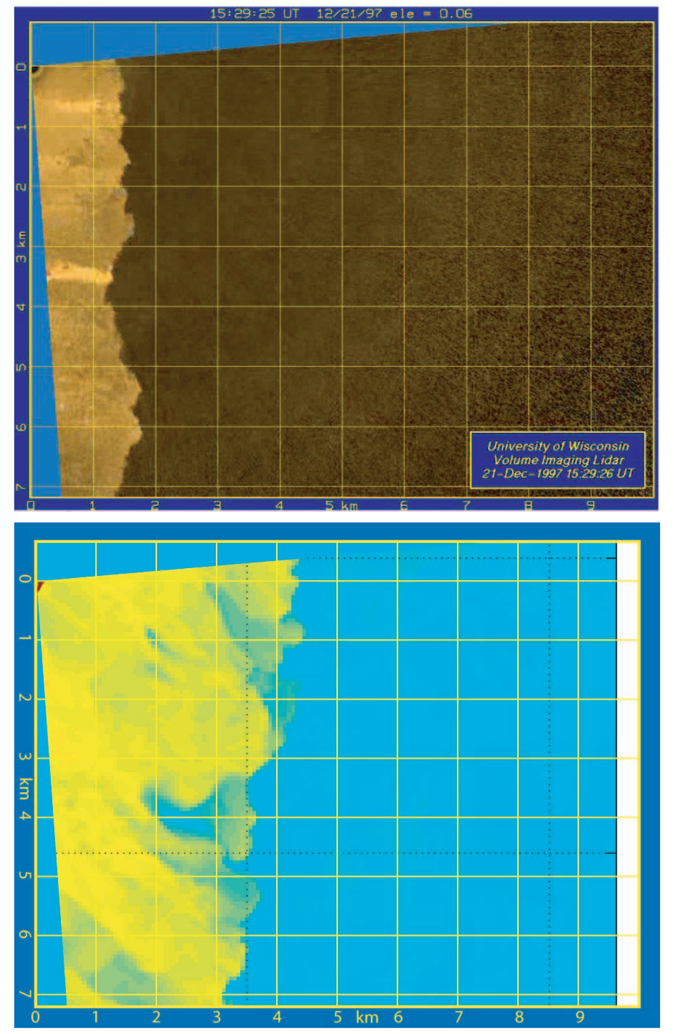
Shown above in color are plots of the lidar (above) and model (below) produced scattering, along with plots showing gradient variance fields for the observed area. Here, variance is defined as the square of the difference between the mean gradient in scattering between any two adjacent points in the domain and the actual gradient between the two adjacent points:

$$\text{Gradient Variance} = \frac{1}{y_n - y_1}\left(\sum_{y_1}^{y_n}(\overline{\Delta} - \Delta_x)^2\right)$$

Then, these values are averaged over a portion of the domain to reduce noise in the results. The body of the land breeze, land breeze head and top of the boundary layer show up clearly in the variance plots.



Lidar produced (top) and simulation produced (bottom) Range-Height Volume (RHI-Volume) scans over Lake Michigan from Sheboygan Point. In each, the top image is a vertical cross section, and the bottom images are constant elevation scans at approximately 20m, 80m, 160m, 240m, 340m, and 400m.



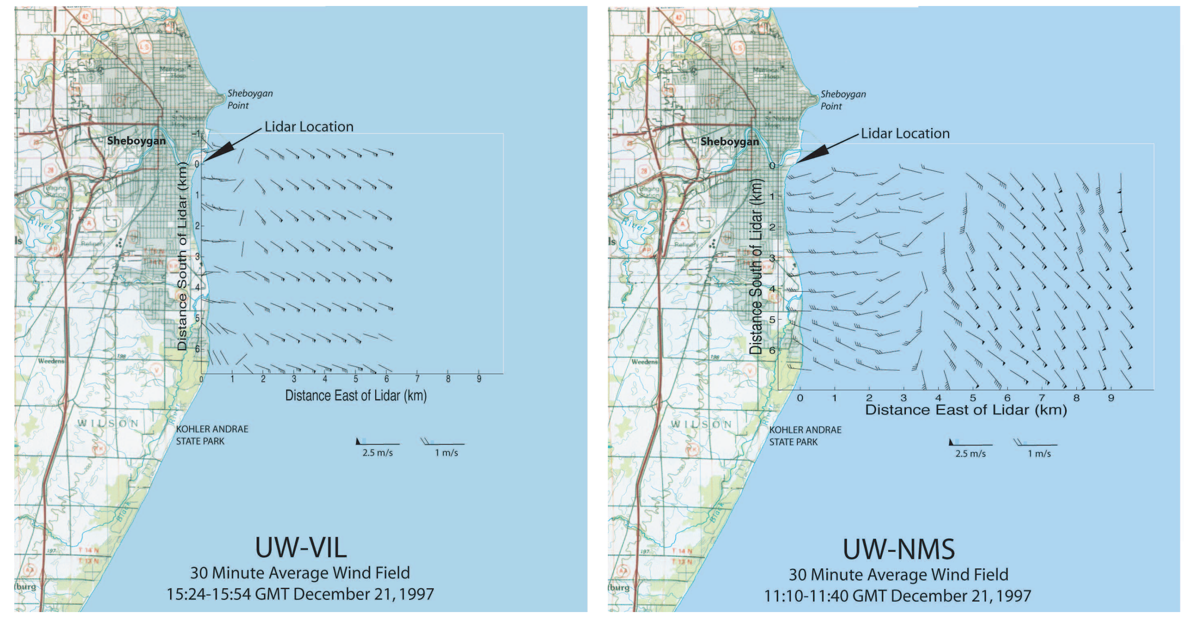
Lidar produced (top) and simulation produced (bottom) Plane-Parallel Indicator (PPI) scans over Lake Michigan from Sheboygan Point.

Lidar Derived Model Variables

An alternative to reproducing scattering in the simulation is to derive simulation variables, such as winds from the lidar data. Here, a cross-correlation technique is utilized in order to determine wind speed and direction within the lidar field of view. This data can then be compared to the simulation data as either a time averaged field (below), or as a time and area averaged field (right).

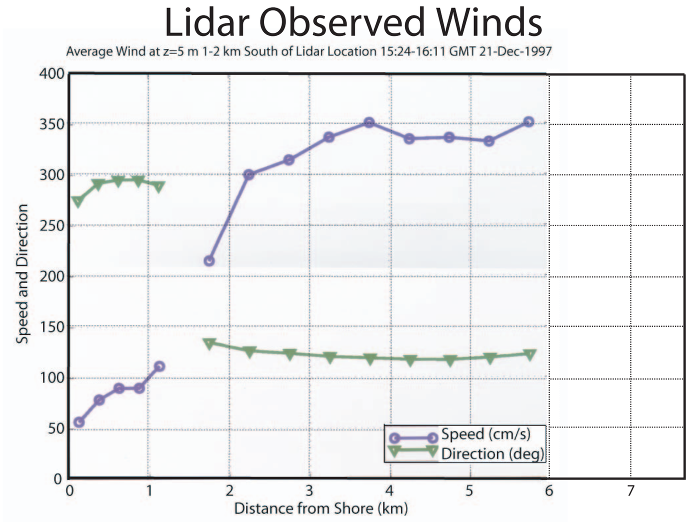
The time and area averaged winds are very helpful in determining the general characteristics of the flow. From the two right images, we can see that the simulation had a slightly stronger land breeze overall, and that the prevailing flow was not quite as strong. In addition, the simulation land breeze appears to be more westerly, and the prevailing flow less directly from the east. This would explain the simulated land breeze front being located further offshore.

The time averaged figure below gives us a more complete tool to evaluate the entire domain. Here we can compare individual points within the area seen by the lidar to see if the effects of a specific land feature may be misrepresented in the simulation.

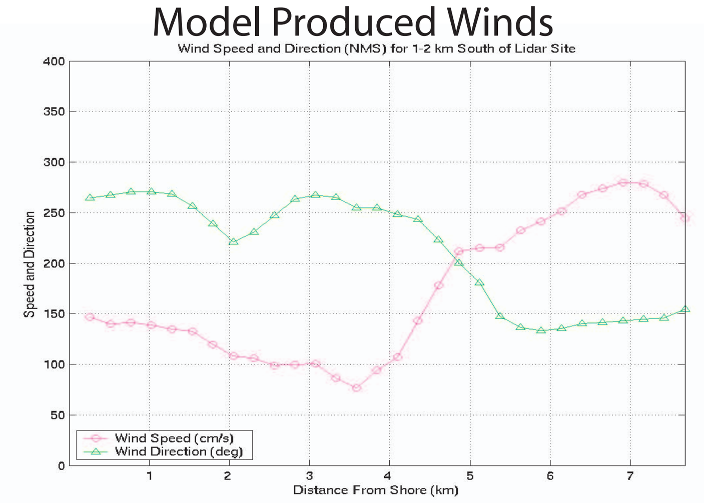


Wind fields derived from the Volume Imaging Lidar (left) and from the numerical simulation. Both time periods are chosen to represent relatively steady situations with the land breeze present. The observed land breeze front was noticably closer to shore than the simulated one, likely a result of the simulated prevailing flow being weaker than the actual flow.

Lidar Observed Winds



Model Produced Winds



Wind speed and direction for the area 1-2 km south of the lidar site as calculated by cross-correlation techniques applied to the lidar data (top) and by the UW-NMS simulation (bottom). Direction is shown in green and speed in pink/purple. The simulated land breeze was noticably stronger and more westerly, likely resulting in the land breeze extending farther offshore.

Conclusions

Data collected using the University of Wisconsin Volume Imaging Lidar is of great value in validating high resolution numerical simulations. Comparison of the simulation and VIL data reveals several relatively small errors in the simulation that lead to significant differences in the extent and strength of the simulated land breeze. Point measurements simply would not have shown with the same effectiveness the differences between the atmospheric volumes compared. Direct statistical analysis likely would have lead to several of the features of the land breeze, such as the undulating frontal zone being lost. The visual confirmation provided by the VIL is one that is difficult to obtain utilizing any other means. Additionally, the high resolution of the VIL data set allows us to closely examine individual parts of the simulated domain, rather than simply the statistics of the entire domain.

In this particular simulation, it becomes clear that although the simulation captures the land breeze with amazing detail, there are some differences between the simulated circulation and the observed circulation. The land breeze extends farther offshore in the simulation, and a comparison of the lidar derived and simulation produced wind fields reveals why that may be. Point measurements may have lead to a similar discovery, but there is no guarantee that this will be true, and extreme care has to be given to the point chosen for comparison in order to avoid localized influences. These errrors in the simulation are likely the result of very small errors in the synoptic flow pattern, which then grow in magnitude and importance at the microscale.

As for the ability of a nested simulation to accurately reproduce microscale structures through a dynamical downscaling technique, this work shows that this is possible to a certain extent. Through comparison with the lidar data, we can see that the land breeze is recreated with respectable accuracy. The seemingly major differences are likely the result of small errors in the inital and boundary conditions (the large scale flow). This issue can be partially addressed through the use of an ensemble system to derive the initial state. Without the information gathered from the VIL data, however, it is unlikely that these differences would be as readily detected.

Acknowledgements

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