Eddy-resolving Lidar Measurements and Numerical Simulations of the Convective Internal Boundary Layer

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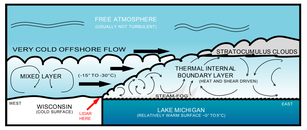
INTRODUCTION

Aerosol backscatter data from the University of Wisconsin Volume Imaging Lidar (VIL) are used to check the accuracy of large-eddy simulations (LES) of an internal convective boundary layer.

Wind speed and direction and eddy size and shape are obtained from cross-correlation of the aerosol backscatter data and simulated lidar aerosol backscatter in the LES.

The VIL was deployed in Sheboygan, Wisconsin, during the winter 1997-1998 Lake-Induced Convection Experiment (Lake-ICE).

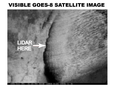
Sheboygan is located on the western edge of Lake Michigan. The lake does not freeze during the winter.



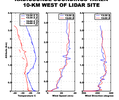
SPATIALLY RESOLVED 5-m WINDS FROM CROSS-CORRELATION OF AEROSOL BACKSCATTER STRUCTURE

10 JANUARY 1998

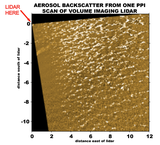
VISIBLE GOES-8 SATELLITE IMAGE



RADIOSONDE SOUNDINGS TAKEN 10-KM WEST OF LIDAR SITE

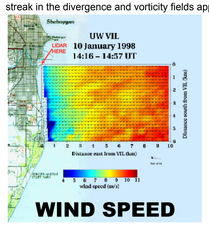


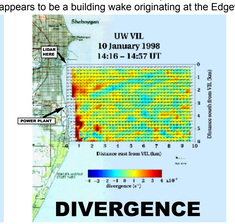
AEROSOL BACKSCATTER FROM ONE PPI SCAN OF VOLUME IMAGING LIDAR

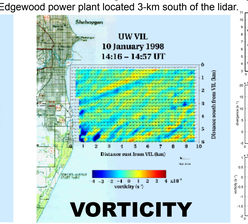


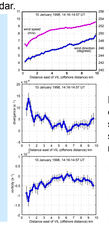
Minimum air temperature at the surface on the morning of 10 January 1998 was -16 C in Sheboygan. Winds were from the WSW at 5-10 m/s. The mixed-layer was about 1-km deep.

The 250-m resolution wind-field derived from PPI scans of the VIL on 10 January 1998 shows acceleration and veering of the offshore flow. The largest streak in the divergence and vorticity fields appears to be a building wake originating at the Edgewood power plant located 3-km south of the lidar.









Speed and direction as a function of offshore distance. These north-south averages of the wind speed and direction show acceleration and veering as the flow adjusts to changing surface friction, pressure-gradient, and vertical mixing over the water.

Divergence as a function of offshore distance. These north-south averages of the divergence show the effect of the acceleration near the shore.

Vorticity as a function of offshore distance. These north-south averages of the vorticity show the effect of veering near the shore.

Steam-fog near the VIL site from the NCAR Electra on 13 January 1998. Notice the cellular patterns of fog. Photo courtesy Dave Rogers (CSU).

Photograph of the VIL in Sheboygan, WI, during Lake-ICE. This was taken looking west before dawn with the moon setting. The bright light on the beam steering unit was used to prevent frost from forming on the windows.

This photograph was taken from the VIL site looking east over Lake Michigan. Notice the steam-fog and clouds offshore.

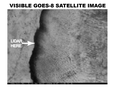
The VIL uses a Nd:YAG laser to transmit 400-mJ pulses at 1.064-micron wavelength at 100 Hz. The VIL resides in a semi-trailer van, employs 0.5-m optics, a beam-steering unit, log-amplifier and real-time-displays. Data are stored on write-once optical disks.

During cold-air outbreaks, steam-fog forms over the lake and is an excellent source of scattering for the lidar.

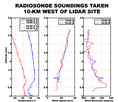
In this poster we present correlation functions and winds derived from horizontal (PPI) and vertical (RHI) scans of the VIL during Lake-ICE. The observations are used to check a large-eddy simulation of the internal boundary layer.

13 JANUARY 1998

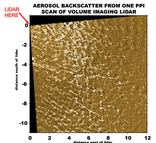
VISIBLE GOES-8 SATELLITE IMAGE



RADIOSONDE SOUNDINGS TAKEN 10-KM WEST OF LIDAR SITE

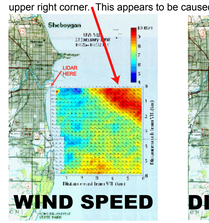


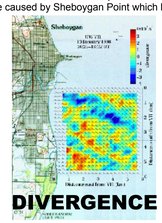
AEROSOL BACKSCATTER FROM ONE PPI SCAN OF VOLUME IMAGING LIDAR

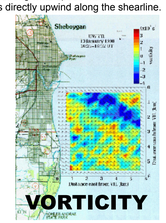


Minimum air temperature at the surface on the morning of 13 January 1998 was -21 C in Sheboygan. Winds were from the NW at 5-10 m/s. The mixed-layer was about 400-m deep.

The wind-field derived from PPI scans of the VIL on 13 January 1998 show a strong wind-speed maximum in the upper right corner. This appears to be caused by Sheboygan Point which lies directly upwind along the shearline.

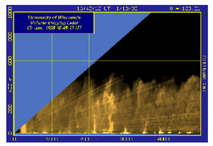




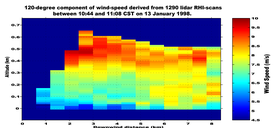


DOWNSTREAM WIND SPEEDS FROM RHI SCANS ON 13 JANUARY 1998

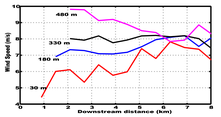
Consecutive RHI-scans at a constant azimuth angle (pointed downwind with respect to the mean surface wind direction) produced one vertical slice of the boundary layer every 2 s.



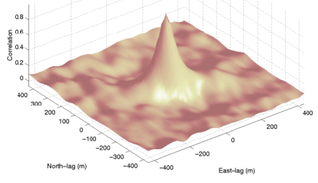
The cross-correlation technique was applied to the RHI scans to measure the downwind component of wind-speed as a function of altitude and downstream distance. Correlation functions were summed over 600-m horizontal bands to reduce noise.



The wind-speeds from the RHI scans show the air near the surface increasing speed while the upper-levels decrease in speed. The vertical gradient of wind-speed decreases offshore because of strong vertical mixing caused by convection.



CROSS-CORRELATION of aerosol backscatter data provide quantitative measurements of mean eddy shape, size, orientation, wind speed and direction.

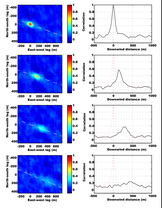


Autocorrelation using 40-scans

Cross-correlation using 24-second scan separation

Cross-correlation using 48-second scan separation

Cross-correlation using 72-second scan separation



LARGE-EDDY SIMULATION

LESs explicitly simulate the eddies & plumes in a turbulent boundary layer that are responsible for transporting heat, moisture, trace gases and momentum.

The University of Wisconsin Nonhydrostatic Modeling System

Solves the non-Boussinesq, Quasi-compressible, enstrophy conserving form of the Navier-Stokes equation.

Finite-difference with dynamic conservation principles enforced for enstrophy (vorticity squared), vorticity, kinetic energy, and entropy. (A 3-D extension of Arakawa & Lamb, 1981.)

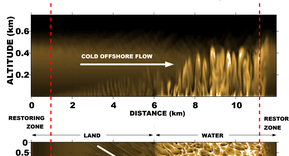
Subgrid turbulence parameterization uses a prognostic TKE equation that is equivalent to Lilly buoyancy enhanced formulation when TKE applied as a diagnostic. Equivalent to Smagorinsky formulation when TKE is applied diagnostically and shear is the only source of TKE.

Rayleigh damping layer at top of domain to prevent gravity wave reflection. Rayleigh restoring zones at east and west ends of the domain acting on U, V, W, T, and Q.

Periodic lateral boundary conditions

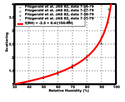
Bulk surface parameterization

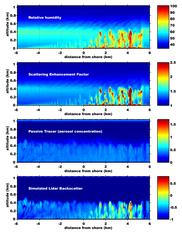
5-layer soil model (snow-covered land and water surface in our simulations)



For the simulations presented here:
DOMAIN SIZE: 800x120x69=6.6 million points
RESOLUTION: 15 m in all directions
TIME-STEP: 0.5 s
INITIALIZATION: horizontally homogeneous
SURFACE TEMPERATURE: -20 C (land)
5 C (water)

We simulate lidar aerosol backscatter by using the LES relative humidity (RH) and a passive tracer. First, the RH is used in a function to obtain an optical scattering factor. The scattering is multiplied by the tracer and then we take the log of their product to simulate the log amplifier used in the VIL.

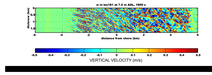




USING THE LIDAR DATA TO VERIFY LARGE-EDDY SIMULATIONS

The fundamental advantage of LES is its ability to explicitly calculate fluxes due to coherent structures. However, the modeled eddies can be sensitive to numerical methods. Conventional data lack the spatial and temporal resolution to evaluate the fidelity of the simulated structures.

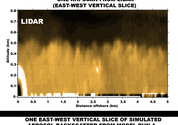
Here we present two simulations that differ only by the numerical advection scheme.



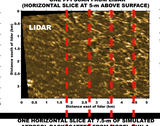
The images above show vertical velocity across the entire model domain at 7.5 m above the surface. The advection scheme used in Model Run A encourages fine-scale roll circulations to develop farther upstream than the advection scheme used in Model Run B.

LIDAR DATA

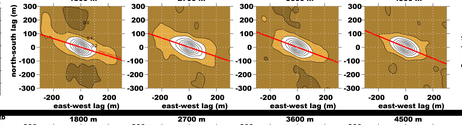
ONE RHI SCAN FROM LIDAR (EAST-WEST VERTICAL SLICE)



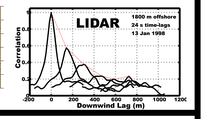
ONE PPI SCAN FROM LIDAR (HORIZONTAL SLICE AT 5-m ABOVE SURFACE)



TWO-DIMENSIONAL CROSS-CORRELATION FUNCTIONS OF AEROSOL BACKSCATTER ON HORIZONTAL PLANES AT GIVEN OFFSHORE DISTANCES

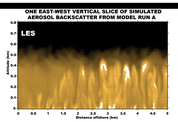


1800-m OFFSHORE CROSS-SECTION OF THE 2-D CORRELATION FUNCTION ALONG A DOWNWIND ORIENTED AXIS

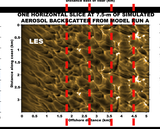


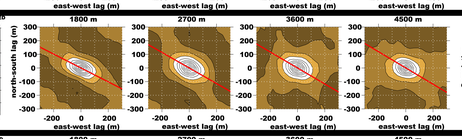
MODEL RUN A

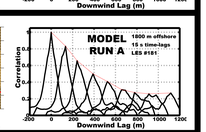
ONE EAST-WEST VERTICAL SLICE OF SIMULATED AEROSOL BACKSCATTER FROM MODEL RUN A



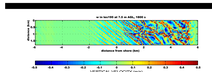
ONE HORIZONTAL SLICE AT 7.5-m OF SIMULATED AEROSOL BACKSCATTER FROM MODEL RUN A



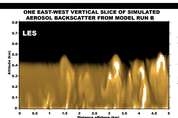




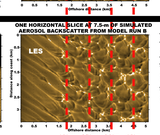
MODEL RUN B

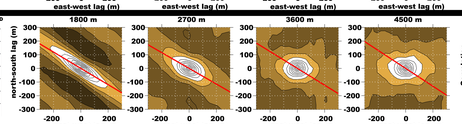


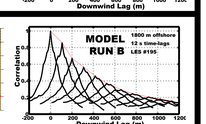
ONE EAST-WEST VERTICAL SLICE OF SIMULATED AEROSOL BACKSCATTER FROM MODEL RUN B



ONE HORIZONTAL SLICE AT 7.5-m OF SIMULATED AEROSOL BACKSCATTER FROM MODEL RUN B







SUMMARY OF COMPARISON OF OBSERVATIONS WITH SIMULATIONS

In general, both simulations show spatial and temporal eddy-structure which is remarkably similar to the lidar data. However, these two simulations differ markedly near the lake-edge. In particular, run B shows more elongated structures than the lidar data. The structures in both simulations are tend to orientations aligned with the domain rather than the wind direction as shown in the lidar data.

The wind accelerates too rapidly as it leaves the shoreline in both simulations. This may be related to lack of shoreline topography in the model or errors in the initialization of the pressure-gradient. Our current simulations show large-eddies of only about half the mixed-layer depth developing over the 6-km fetch of land in the model.

Acknowledgements: This work was made possible by NSF ATM9707165 and ARO DAAH-04-94-G-0195. Simulations were run on a J50 donated by IBM. Lidar measurements were made possible by Jim Hedrick, Patrick Ponsardin and Ralph Kuehn.