Boundary Layer Height Determination With the LIFT Dataset

S. A. Cohn
NCAR-Atmospheric Technology Division
Boulder, Colorado

C. L. Holloway
NTIA-Institute for Telecommunications Science
Boulder, Colorado

S. D. Mayor
University of Wisconsin, Department of Atmospheric and Oceanic Sciences
Madison, Wisconsin

Introduction

Surface fluxes of sensible and latent heat play a major role in the diurnal growth and decay of the continental convective boundary layer (BL). Measurements of BL height, z_i, are needed in calculations of derived quantities including heat flux and entrainment velocity. Study of the entrainment zone, where free atmosphere and BL air are mixed, is also necessary to understand the evolution of the BL. The Lidars in Flat Terrain (LIFT) experiment included collocated measurements with an ultra high-frequency (UHF) wind profiler and several lidars, from which z_i may be found and intercompared. Lidars and wind profilers make use of different backscatter mechanisms and it is important to check that each measures the same BL height. A technique using continuous wavelet transforms has been developed to objectively find z_i with time resolution of order seconds for the lidars and minutes for the profiler. The result from lidar data has enough detail to show entrainment of free atmosphere air into the BL. The z_i measurement using profiler data has less time resolution than that from lidar, but results using wavelets are considerably more detailed than previous techniques (about 1-hour resolution) and show a coupling between vertical motion and z_i. This wavelet technique will also be applied to lidar and profiler data collected during the Atmospheric Radiation Measurement (ARM)/Tropical Ocean Climate Study (TOCS) study.

Boundary Layer Definitions

The BL and entrainment zone are defined by properties that make them distinct from the free atmosphere. Definitions that have been used are as follows (Stull 1988):

- BL: "That part of the troposphere that is directly influenced by the presence of the earth's surface and responds to surface forcings with a timescale of about an hour or less."

- Entrainment Zone (Convective BL): That region where the buoyancy flux, $\overline{w'\theta'}$, is negative or the region where more than 5% and less than 100% of air on a horizontal plane has free atmosphere characteristics. z_i may be taken as the height at which 50% of the air has free atmosphere characteristics or when $\overline{w'\theta'}$ is minimum.

Lidar backscatter from aerosols is well suited as a tracer of BL air. Aerosols from the surface are well distributed through the daytime mixed layer and sharply decrease through the entrainment zone. A gradient in lidar back-scatter can be used to indicate z_i.

Profiler backscatter in clear air is proportional to the refractive index structure constant, C_n^2, which is a strong function of humidity gradients. An inversion at the height of the BL will often be seen as a peak in reflectivity that can be used to indicate z_i.

The LIFT Experiment

The LIFT dataset includes measurements from several instruments located at a site near the Flatland Atmospheric Observatory outside Urbana, Illinois. This site (Figure 1) was chosen because its very flat terrain eliminates the need to account for atmospheric structure and motions resulting from non-flat topography. Included among the instruments were a high-resolution Doppler lidar (HRDL, Grund 1996), a dual wavelength backscatter lidar [scanning aerosol

Figure 1. Aerial photograph of the LIFT site, near Urbana, IL. The lidars and wind profiler electronics are housed in the trailers. The wind profiler antenna surrounded by four Radio Acoustic Sounding System (RASS) speakers sits in the field. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/cohn(2)-98.pdf*.)

backscatter lidar (SABL)], and a UHF wind profiler. Radiosondes were launched from a site about 5 km away. More information on this experiment can be found in Cohn et al. (1998) and Angevine et al. (1998). Figure 2 shows a 20-minute time-height cross section of backscatter from the SABL infrared channel. Note the strong (3-dB) drop-off in strength above the BL, and the residual layers above. The 1-second resolution captures both plumes and entrainment through the BL top. Measurements below about 250 m are within the receiver recovery period and are invalid. Figure 3 shows 12 hours of wind profiler reflectivity. The reflectivity maximum indicates the BL top because of a humidity gradient between the moist BL air and the dryer air in the free atmosphere above.

Wavelet Analysis

We are developing algorithms based on a one-dimensional continuous wavelet transform (CTW) to objectively and automatically find the BL top from radar or lidar data. The CWT can be simply thought of as the inner product of a wavelet function with the backscatter profile. The inner

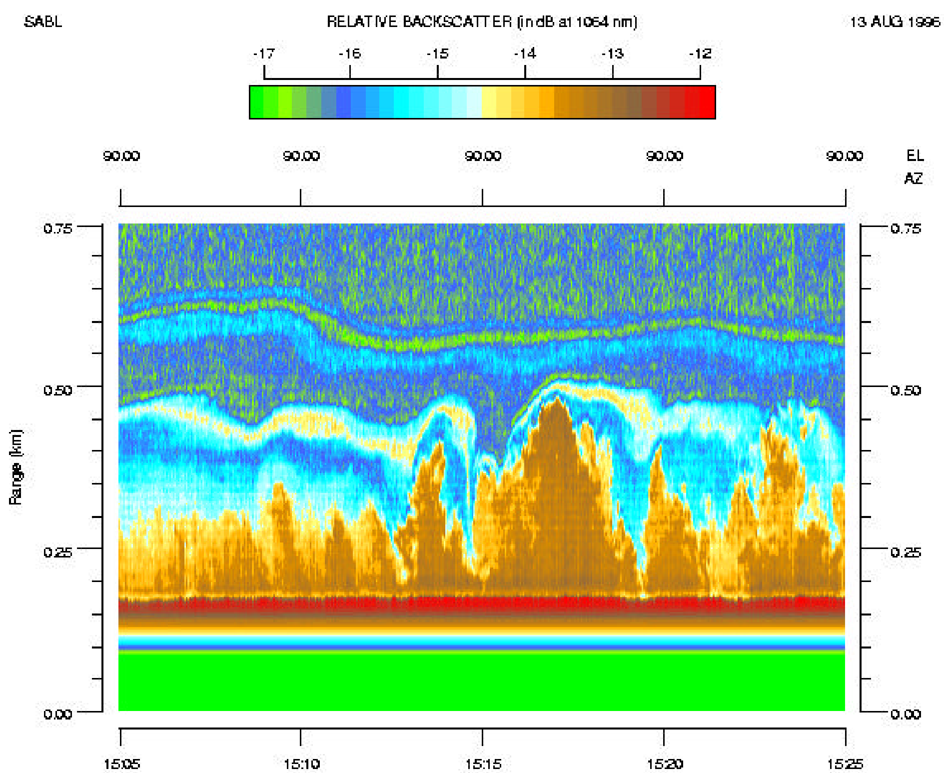

Figure 2. SABL infrared channel backscatter between 9:05 a.m. and 9:25 a.m. local time on August 13, 1996. Note the entrainment of clean free-atmosphere air (blue) into the aerosol laden BL air. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/ cohn(2)-98.pdf*.)

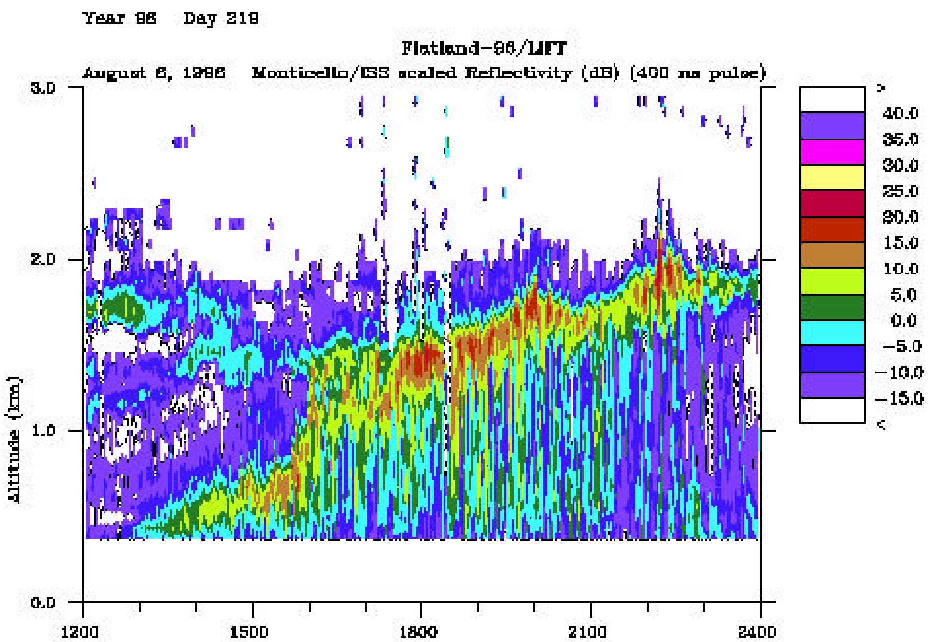

Figure 3. Wind profiler backscatter showing the growth of the boundary layer through the day (6 a.m. to 6 p.m. LT). The backscatter peak indicates mixing of moist (boundary layer) and dry (free atmosphere) air causing strong refractive index gradients. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/ technical/conf_9803/cohn(2)-98.pdf*.)

product is repeatedly carried out as the wavelet function is translated in altitude. In addition, the process is repeated for the same wavelet function at many dilations. Each dilation is, in effect, stretching the wavelet function in altitude. The result of the transform is a two-dimensional (altitude by dilation) field of transform coefficients. A Harr wavelet will return large coefficient values where a profile has large backscatter gradients, so this is used with lidar profiles. For profiler reflectivity, a Coif wavelet will highlight a local maximum in backscatter. The process is described in Cohn et al. (1997). A general reference for wavelet analysis is Foufoula-Georgiou and Kumar (1994).

Discussion

The upper plot of Figure 4 shows results of the wavelet algorithm applied to 2 hours of SABL reflectivity. Overplotted triangles represent the wavelet z_i determination. In this case, SABL backscatter profiles were averaged to 1 minute and the Harr wavelet algorithm was applied over a wide range of dilations. The maximum coefficient was taken to be at the altitude of the BL top.

The result clearly captures structure of the BL top. Similar results from HRDL (which also measures radial velocity) show correlations between local maxima in z_i and updrafts. With this correlation established, the skewness and kurtosis of z_i can be analyzed in the same way as a vertical velocity time series.

The lower plot of Figure 4 is the result for the same time period using wavelet analysis of the wind profiler reflectivity. In this case, a 10-minute average was used. This result is not as clean as the lidar result, but it is an improvement over previous techniques for profiler data that produce a value of z_i approximately every hour. With refinement, the profiler result can be improved. Wind profilers are much more common than lidars and this algorithm may be applied generally.

Many refinements are possible in interpreting the wavelet coefficients. The analysis may be used to identify a residual BL from the previous day, cloud boundaries, etc. Rather than simply taking the largest coefficient as the height of the BL, a weighted average can be used to interpolate between measurement heights. The dilation of the maximum coefficient could be used to indicate the thickness of the entrainment zone. Further sophistication is needed to ensure that the algorithm is not fooled by clouds, clutter, or interference, and is not biased by a sloping background reflectivity within the BL or the free atmosphere.

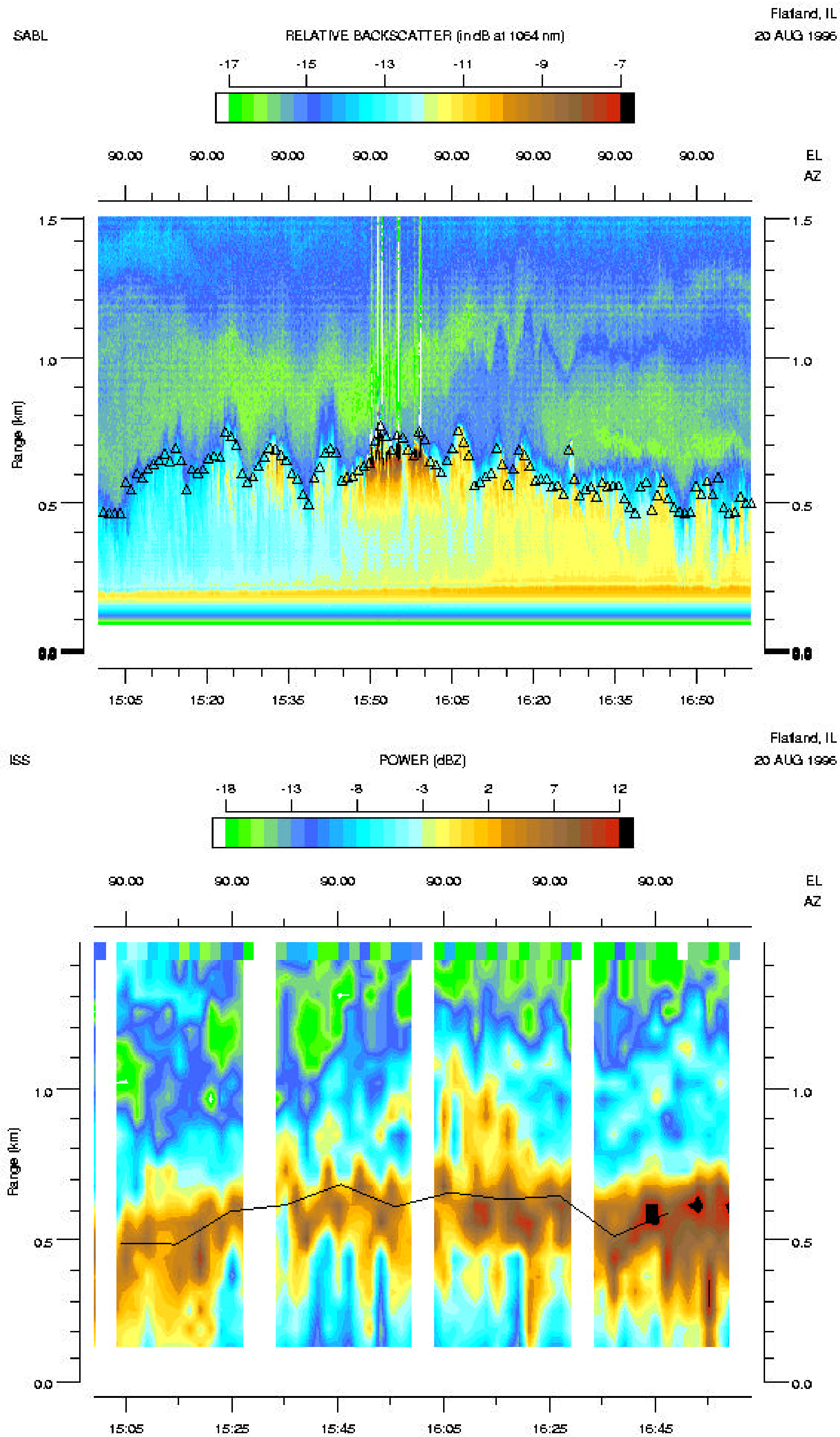

Figure 4. Two hours of backscatter from SABL (top) and the wind profiler (bottom) with the wavelet algorithm determination of BL height overplotted (triangles). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/cohn(2)-98.pdf*.)

Summary

Wavelet transforms can work well to find BL height from both lidar backscatter and wind profiler reflectivity profiles. The method presented is objective and automated and can be exploited to give a detailed view of the BL top. Growth and collapse of the BL, as well as information on convective plumes and entrainment, are available from lidar data and can be extracted using wavelet techniques. We plan to apply this method to measure BL height from the ARM/TOCS deployment of a wind profiler and SABL.

Acknowledgments

Support for the LIFT experiment and subsequent analysis came from the National Center for Atmospheric Research (NCAR) Atmospheric Technology Division Director's Office, the U.S. Department of Energy's (DOE's) Office of Health and Environmental Research, and DOE's ARM Program.

References

Angevine, W. M., A. W. Grimsdell, J. M. Warnock, W. L. Clark, and A. C. Delany, 1998: The Flatland boundary layer experiments. *Bull. Amer. Meteor. Soc.*, **79**, 419-431.

Cohn, S. A., C. J. Grund, S. D. Mayor, and W. M. Angevine, 1997: Boundary layer height and vertical velocity measurements at LIFT. In *12th Symp. on Boundary Layers and Turbulence*, Vancouver, BC, July 28-August 1, 1997, pp. 7-8.

Cohn, S. A., S. D. Mayor, C. J. Grund, T. M. Weckwerth, and C. Senff, 1998: The lidars in flat terrain (LIFT) experiment. *Bull. Amer. Meteor. Soc.*, in press.

Foufoula-Georgiou, E., and P. Kumar (Eds.), 1994: *Wavelets in geophysics*, Academic Press, San Diego, 373 pp.

Grund, C. J., 1996: High resolution doppler lidar employing a diode pumped injection seeded Tm:Lu, YAG transmitter. In *Advanced Solid State Lasers, 1996 Technical Digest (Optical Society of America, Washington D.C.*), pp. 204-206.

Stull, R. B., 1988: *An introduction to boundary layer meteorology*. Kluwer Academic Publishers, 666 pp.