The Effect of Cumulus Cloud Formation on Boundary Layer Turbulence

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Introduction

The National Oceanic and Atmospheric Administration's (NOAA's) 35-GHz Doppler radar measured the turbulent motions in the planetary boundary layer (PBL) over the boreal forest as a contribution to the Boreal Ecosystem-Atmosphere Study (BOREAS) during the summer of 1994. The radar is sensitive enough to detect not only weakly and non-precipitating clouds (Martner and Kropfli 1993) but also small natural particulates that are commonly suspended in the clear PBL during warm seasons over land. These particles include insects, seeds, bits of vegetation, and giant aerosols, and are treated as passive tracers of boundary layer motions (Kropfli 1986). Thus, the radar provides an opportunity to study not only clear-air PBL dynamics, but also how cloudiness may affect PBL turbulence. It is capable of monitoring the scatter's instantaneous vertical motions (w) with an accuracy of 5 cms^{-1}, a spatial resolution of 75 m, and a temporal resolution of 6 s (gate spacing of 37.5m and sampling rate of 3 s).

There are several things that we can examine with these measurements. First of all, the small particulates need updrafts to stay airborne, which is provided by convection in the boundary layer. The particulates cannot be carried beyond the height where this vertical motion stops or slows to the particle fall speed. Above this height, there is neither a backscattered power or a Doppler shift measurement. As a consequence, this lack of radar echo can be used to determine the top of the PBL. This is a parameter for the measurement of the Deardorff velocity that is used to scale mixed layer turbulence measurements. The other important radar measurement is the Doppler shift. The small backscatter targets in the boundary layer can be used as air motion tracers to measure the vertical velocity as a function of height above the radar. The range of measurement is from the height of the antenna far field (~150 m), to the top of the PBL. We calculate vertical profiles of vertical velocity variance, skewness, and vertical velocity spectra. These quantities are important in understanding the convective PBL and are useful in the verification of various atmospheric and cloud models.

Sensible and latent heat flux measurements from the tower were used along with the radar PBL depth to calculate w*, the Deardorff velocity, which is used to make the variance dimensionless. The Deardorff velocity is given by

$$w^* = \left(\frac{g}{\overline{T}} \overline{w'T'} z_i \right)^{1/3}$$

where $\overline{w'T'}$ is the temperature flux, g is gravity, $\overline{T}$ is the mean temperature, and z_i is the PBL depth.

The vertical velocity spectra at each range gate were computed using an Fast-Fourier Transform, then logarithmically averaged over frequency. To further reduce scatter, the spectral variance was averaged over three range gates. The frequency was then normalized by our estimate of the inversion height and wind speed. This dimensionless frequency is given by

$$f = \frac{nz_i}{U}$$

where n is the frequency.

Figure 1 shows vertical profiles of vertical velocity variance and skewness along with the time-height plots of radar reflectivity and vertical velocity. Before the cumulus formation, the velocity variance shows a decrease with height at 0.4 z_i, decreasing to very small values near the boundary layer top. Above the boundary layer, the variance increases slightly. As the cumulus forms, the variance increases with height well above the boundary layer. The skewness also shows changes in its behavior with height. Initially, before the clouds form, the skewness is positive in the lower boundary layer, becoming negative above the boundary layer. Later, during cloud formation, the skewness is negative at the top of the boundary layer and at the third time interval, the skewness is negative down into the boundary layer. The dashed line is an empirical fit of measurements over the ocean for the convective boundary layer (Lenschow et al. 1980).

Figure 2 shows the vertical velocity power spectra (upper) and the frequency times the power spectra (lower) for different heights. While we can see some differences in the power spectra before and during cloud formation, the frequency power spectra product shows these differences in more detail. The peaks in the power spectra product during the cloud formation and after the clouds had formed correspond to periods of several minutes, similar to those observed in the cloud radar reflectivity.

Conclusions

From the radar and surface observations and the calculation of various turbulence parameters, we can see the influence of cloud development on the boundary layer. There are dramatic changes in the vertical velocity variance, skewness, and the power spectra. The results show the variance increasing with height in the upper 60% of the boundary layer after the clouds start to form. This is in contrast to the decrease observed in the clear-air convective boundary layer. The skewness at the upper part of the boundary layer changes from near zero to negative as the clouds start to form. The velocity spectra show peaks at about the same period as the observed clouds, well into the boundary layer, indicating that this increase in vertical velocity variance is correlated with the clouds.

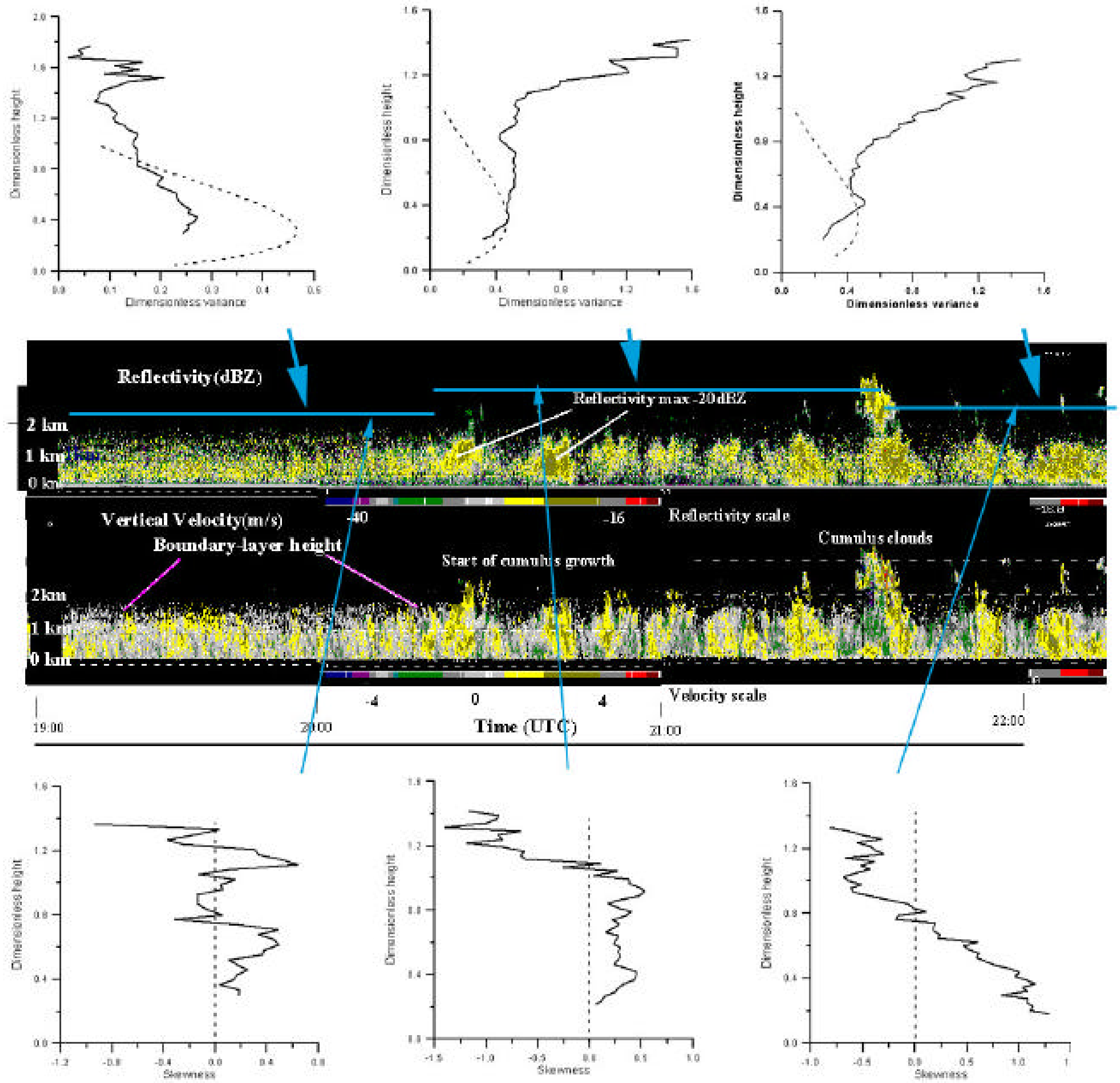

Figure 1. Vertical velocity and skewness profiles. Horizontal lines depict the averaging time for each corresponding calculation.

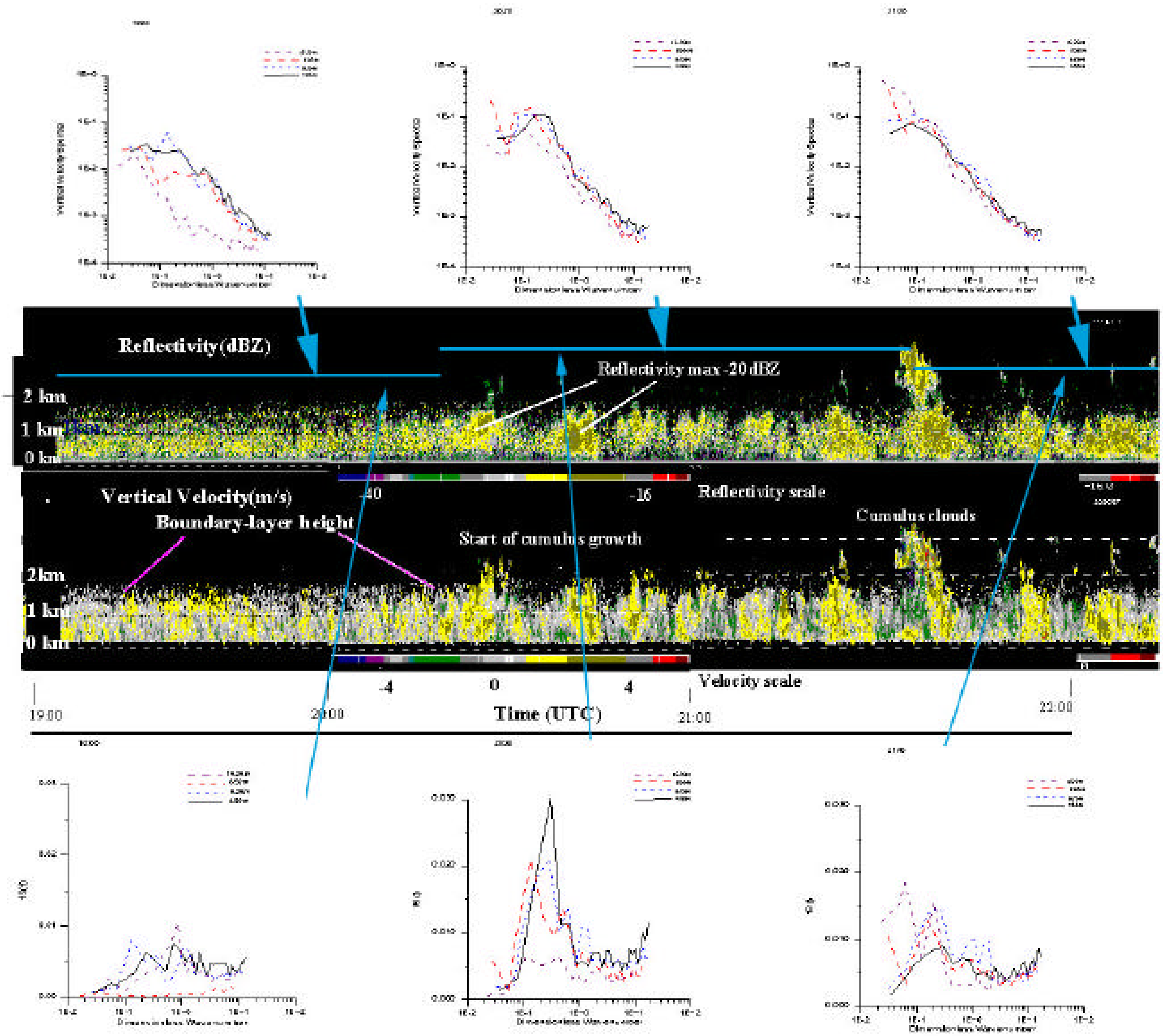

Figure 2. Vertical velocity power spectra (upper) and the product of power spectra times the dimensionless frequency (lower) for different heights.

Acknowledgments

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