High Resolution Doppler Radar Observations in Continental Stratus Clouds

P. Kollias and B. A. Albrecht
University of Miami
Miami, Florida

Introduction

Vertical mixing is a key factor in determining the macroscopic and microscopic structure of stratus clouds. The vertical velocities resolved from millimeter-wavelength radars can be used to define the turbulence structure within such clouds (Frisch et al. 1995). To illustrate the utility of such radar measurements for studying the turbulence structure of continental stratocumulus clouds, eight continuous hours of 2-second observations from the Doppler Pennsylvania State University (PSU) 94-GHz radar are analyzed. These observations are used to study the temporal evolution of the turbulence structure of the cloud and to evaluate how the turbulence statistics are affected by sampling strategies that degrade the temporal resolution. The results shown here focus on 2 hours of data that illustrate the evolution of the cloud as the boundary layer evolves from a fully coupled to a decoupled state.

Approach

Cloud turbulence measurements were made with an upward pointing 3-mm wavelength radar (Clothiaux et al. 1995) operating over central Pennsylvania in November 1994. Stratocumulus clouds varying in thickness from 400 m to 800 m were observed during the 8 hours of continuous operation with the radar. The clouds during this period formed in easterly flow associated with tropical storm "Gordon" located off the coast of North Carolina. The clouds observed were water clouds with temperatures above freezing at all levels in the boundary layer and 10° C to 13° C near the surface. In addition to the cloud radar, a laser ceilometer and microwave radiometer were in operation during this time to provide cloud base heights and cloud liquid water paths. During the first part of the observing period, the boundary layer was well coupled and the observed liquid water path from the radiometer was close to the adiabatic liquid water path calculated using the cloud base height from the ceilometer and the cloud top height from the radar reflectivity. During the second half of the observing period, the boundary layer becomes decoupled and the liquid water path was found to be substantially less than the adiabatic liquid water path.

Vertical velocities from the radar were estimated using a standard pulse-pair technique. Each 2-second radar sample is an average over 10,000 pulses and the vertical resolution is 28 m. Perturbation velocities were obtained at each level by calculating 1-hour means and then subtracting these means from the observed values.

Results

The perturbation vertical velocities obtained during a 1-hour segment of the first part of the observing period is shown in Figure 1a. These perturbations are shown for each of the gates in and slightly above the cloud. Cloud-top shown in this diagram is obtained objectively from the reflectivity using the technique described by Clothiaux et al. (1995). Cloud base is from the laser ceilometer. The perturbation velocities clearly show well-defined updrafts and downdrafts with some of these coherent structures extending through much of the depth of the cloud as relatively narrow updraft-downdraft couplets. These features are clearly on a scale that can be resolved by Large-Eddy Simulation (LES) models.

The effects of sampling strategies on the turbulence structure that can be resolved with the cloud radar were investigated by comparing the 2-second vertical velocity structures with those obtained by degrading the observations to what would be resolved using the current sampling strategy for the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) millimeter cloud radar (MMCR). This sampling strategy is a 10-second average every 40 seconds. Figure 1b shows the corresponding perturbation velocities using the degraded sampling strategy. Although some of the coherent updraft-downdraft features are still discernible in the degraded velocities, this is not always the case since 30-second blocks of data are not sampled using this strategy. In addition, the 10-second averaging removes most of the smaller scale perturbations.

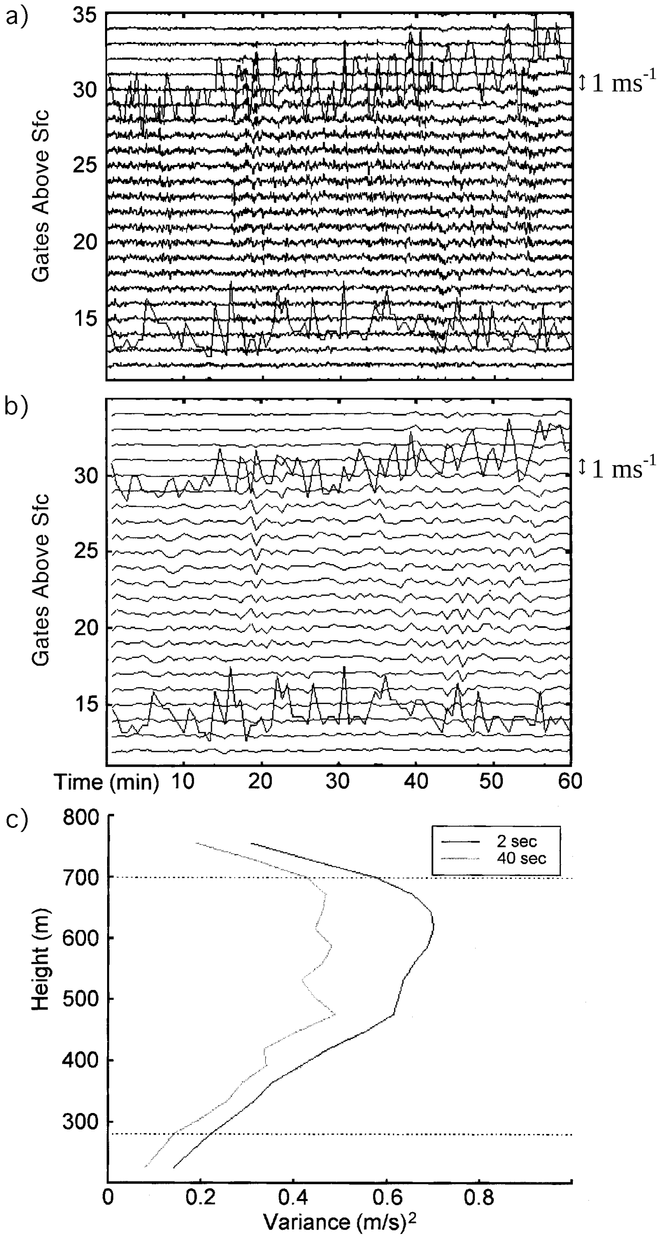

Figure 1. a) Vertical velocity perturbations in a solid stratocumulus cloud observed over central Pennsylvania starting at 0900 UTC using the PSU 94-GHz radar. Each level of data corresponds to gates spaced at 28 m. The upper solid line is the cloud top height from the radar reflectivity and the lower solid line is the cloud base from the ceilometer, b) vertical velocity perturbations obtained when the 2-second data shown above are degraded by making 10-second averages every 40 seconds, and c) vertical velocity variance calculated using both the 2-second and the degraded data. Straight horizontal lines indicate cloud base and cloud top.

The vertical velocity variance calculated using both the 2-second and the degraded vertical velocity perturbations are shown in Figure 1c. The 2-second values show a well-defined peak in the upper part of the cloud. This distribution is very similar to that observed in typical marine stratocumulus clouds. Although the degraded vertical velocities give a variance profile that is similar in shape, the profile is less smooth in the vertical than that from the 2-second data and the magnitude of the variance is reduced by about 40% using 10-second averages every 40 seconds.

The cloud perturbations observed near the end of the observing period when the boundary layer becomes decoupled is shown in Figure 2a. In this case, turbulence in the upper part of the cloud layer is substantially reduced compared with the well-mixed conditions observed during the first part of the observing period. The variance in the upper part of the cloud layer (Figure 2c) clearly reflects the changes in the structure of the perturbation velocity. The peak in the variance is reduced to about 0.5 $(m/s)^2$ and is now much lower in the cloud. The cloud at this time is about 600 m thick compared with the 400-m thickness for the results shown in Figure 1, although the cloud liquid water path is about the same for both cases.

Discussion

This radar study of continental stratocumulus provides a comparison of the vertical velocity statistics and macroscopic cloud properties for coupled and decoupled boundary layer conditions. In addition, these data provide a unique description of large-eddy structures that extend through the depth of the cloud. Observations of this type are of great potential importance for process studies and direct evaluation of LES models. The sampling strategy that has been implemented for the SGP MMCR may limit the application of this system for studies of the turbulence structure in clouds. Methods for improved sampling strategies should be considered if the full potential of the Doppler capability of the SGP MMCR is to be realized.

References

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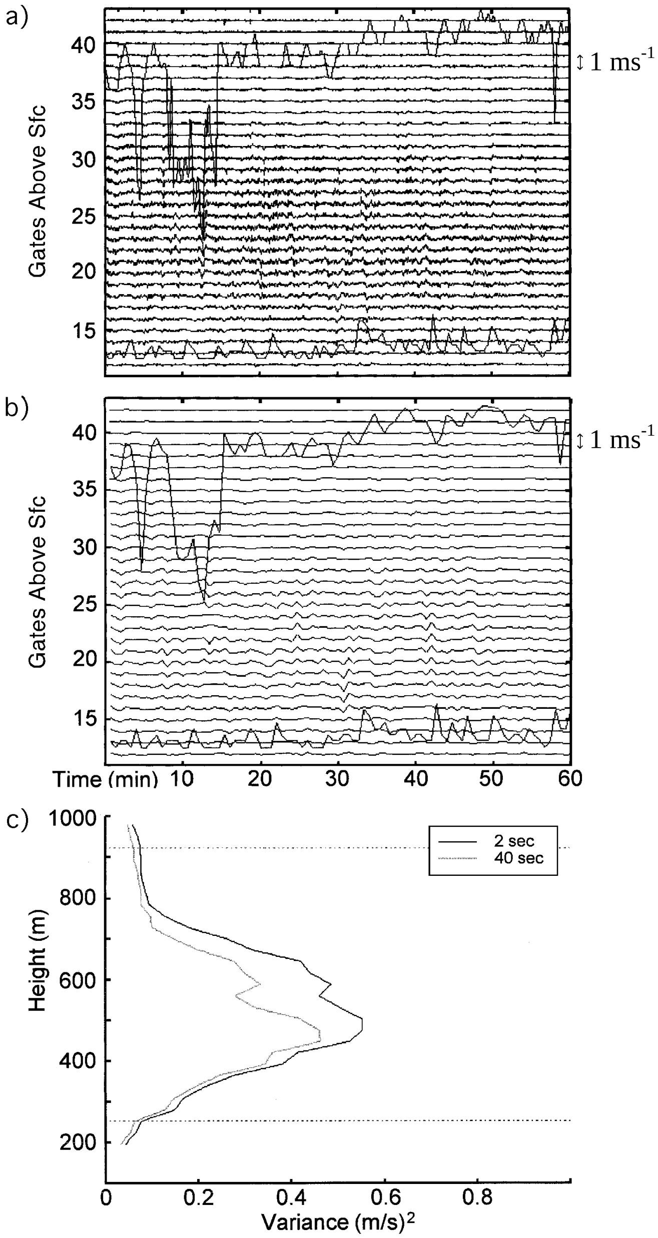

Figure 2. The same as Figure 1 except for the decoupled cloud observed at 1300 UTC.