Vertical Velocity Statistics as Derived from 94-GHz Radar Measurements

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Introduction

Profiles of millimeter-wavelength radar Doppler spectra contain information about both the mean vertical velocities and cloud microphysics. In order to obtain this information, it is necessary to remove the effects of turbulence. Stratocumulus clouds often contain various species of ice and liquid, including graupel, crystals, columns, plates, liquid droplets, and drizzle drops. Most of the previous work to remotely determine microphysics of stratus clouds has largely ignored the presence of drizzle and ice, restricting applicability to only liquid clouds with no drizzle, a relatively rare event. Since mixed phase clouds have multimodal size spectra, it is essential to retain this information by using the measured Doppler spectra directly, rather than using only the moments.

A general technique has been developed, requiring no assumptions about the size distributions, that gives the quiet air fall spectrum of the entire population of cloud particles (Babb and Verlinde 1999a, 1999b). Assuming the smallest measured particles are tracers of the mean air motion, we determine the mean vertical velocity within the radar sampling volume. In this paper, we concentrate on the retrieval of vertical velocity fields to study the characteristics of lake-effect clouds. In particular, we discuss results from January 10, 1998, when weather conditions were particularly favorable for intense boundary layer convection.

Lake-Induced Convection Experiment

One of the goals of the Lake-Induced Convection Experiment (Lake-ICE) was the investigation of the effects of rapid airmass modification by lake-induced heat and moisture fluxes (Kristovich et al. 1999). The experiment took place during December 1997-January 1998, and was located in the area near Lake Michigan. In addition to The Pennsylvania State University (PSU) cloud radar used for this study, there were in situ instruments on board the University of Wyoming King Air, the Eldora dual Doppler radar on board the Electra, coordinated satellite overpasses, and multiple ground-based remote sensors. The PSU cloud radar was positioned on the downwind shore of the lake.

On January 10, 1998, the wind speed at ground level was about 15 m s^{-1} and the difference between the lake surface and air temperatures was about 10 °C. Bands of clouds, roughly parallel to the mean wind, were observed. These cloud bands are a common wintertime mesoscale structure in lake-effect events and play an important role in the vertical transport of heat and moisture from the surface layer to the top of the boundary layer (Etling and Brown 1993). Although analysis of Eldora data has not yet been completed, the ratio of the wavelength to vertical extent of cloud bands is most often observed to be between 4 and 6. Since the cloud depth was about 1 km, a typical value for the wavelength is 5 km. The orientation of the roll axis to the mean wind typically varies between –20° to 30° (Etling and Brown 1993). The wind speed throughout the cloud was variable, but the average in-cloud wind speed was about 15 m s^{-1}. A reasonable value for the wind speed perpendicular to the bands is, therefore, 3 m s^{-1}; it is this drift velocity that allows this phenomenon to be observed with a stationary radar. Figure 1 shows a two-dimensional (2-D) cloud probe image measured during Lake-ICE.

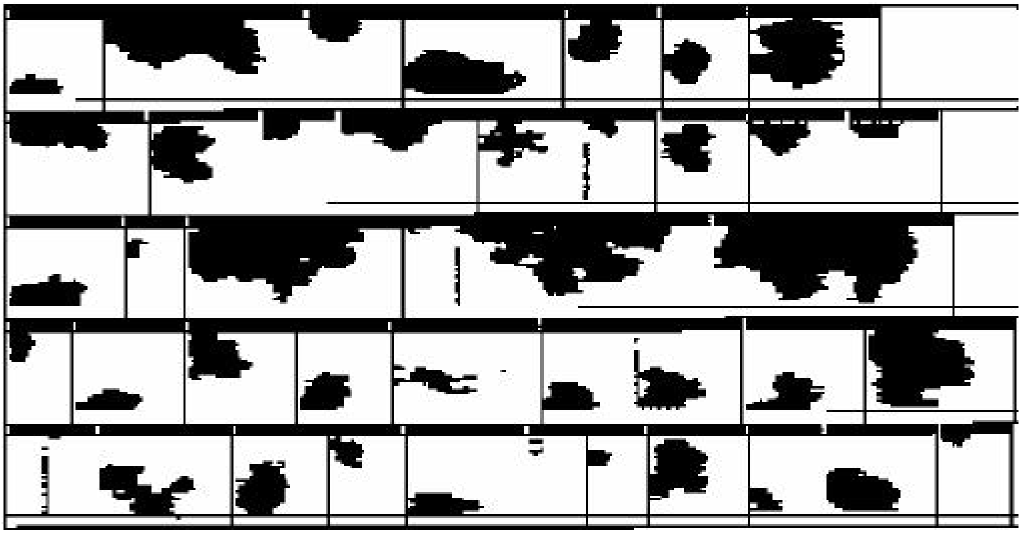

Figure 1. 2-D cloud probe image measured during Lake-ICE. Several different species are apparent including hexagonal crystals, graupel, aggregates, dendrites, and liquid drops.

Method

The Doppler spectrum measured by a cloud radar is the convolution of the quiet air spectrum (associated with cloud particles moving at their fall velocities plus the mean air motion) with the turbulent vertical velocities. This can be expressed, in matrix notation, as

$$S_M = K \bullet S_Q,$$

where S_M is the measured spectrum and S_Q is the quiet air spectrum. K is the turbulent probability function, where the element $K_{i,j}$ is the portion of the measured spectral reflectivity of the velocity interval i resulting from turbulent broadening of the quiet-air spectral reflectivity of the velocity interval j (Babb and Verlinde 1999a). Noise in the measured spectral reflectivity and the near singularity of K necessitate the use of an iterative method to invert the matrix. The quiet air spectrum is thus determined by solving iteratively for the matrix K that reproduces the measured spectrum. The method used is sub-optimal, meaning that a few non-physical solutions (e.g., negative reflectivity) are allowed in the set of possible solutions. With the assumption that the measured velocity of the drops/crystals at the positive end of the spectrum is due only to the mean air motion (thus, the fall velocities of these particles are negligible), we can determine the mean vertical velocity of the radar sampling volume. An advantage of this technique is that, unlike many other retrieval techniques, it does not require assumptions about the drop/crystal size distribution, which is crucial for mixed phase clouds.

Results and Discussion

The above method was applied for spectra at various heights within cloud for a period of 90 min. An example of measured and retrieved spectra is shown in Figure 2. Although the measured spectrum was not clearly multimodal, there are at least two modes apparent in the retrieved spectrum: a high reflectivity mode moving upward at about 0.8 m s^{-1} and a smaller reflectivity mode at 1.8 m s^{-1}. These modes likely correspond to different species. By assumption, the smallest detected particles are moving at the mean vertical velocity. The mean air motion for this example is, therefore, 2.0 m s^{-1}. Shown in Figure 3 are consecutive profiles of Doppler spectra at various heights in-cloud and below cloud base. Ceilometer cloud base height was about 500 m and radar cloud top height was about 1300 m.

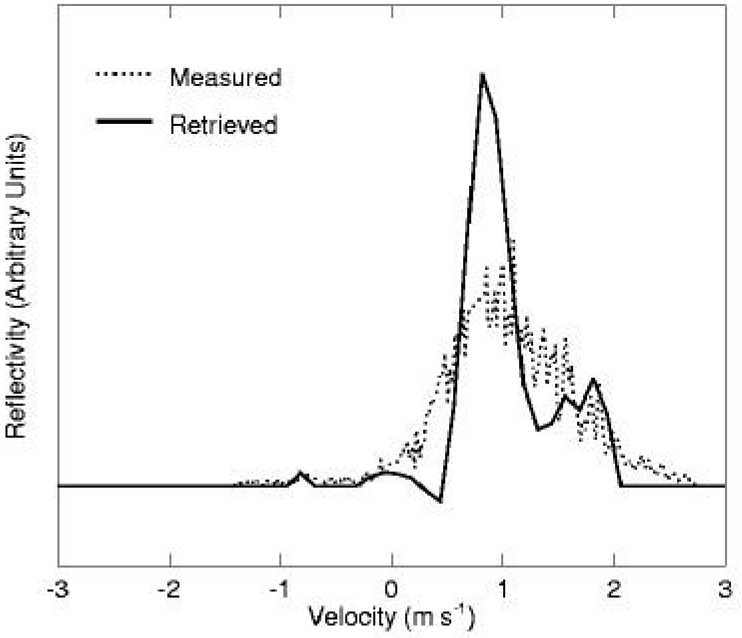

Figure 2. An example of a measured Doppler spectrum (dotted) and the corresponding retrieved, turbulence-removed spectrum.

Height profiles of mean vertical velocity are shown in Figure 4, for three consecutive profiles (each separated in time by 7 sec.). During data collection, noise is reduced by incoherently averaging spectra. In this case, data were collected for 5 sec., then processed for 2 sec. This averaging introduces an additional non-physical source of broadening, as is especially apparent for the light snow below cloud base.

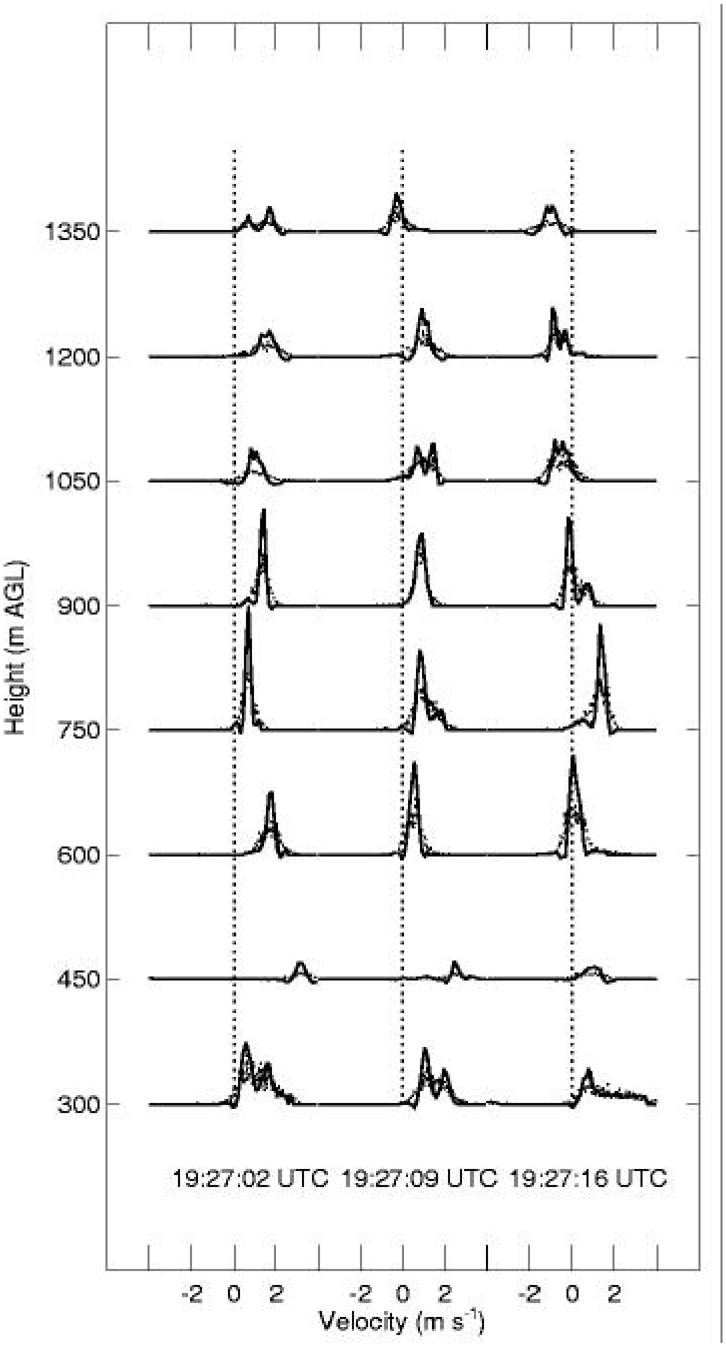

Figure 3. Consecutive profiles of measured (dotted) and retrieved (solid) Doppler spectra.

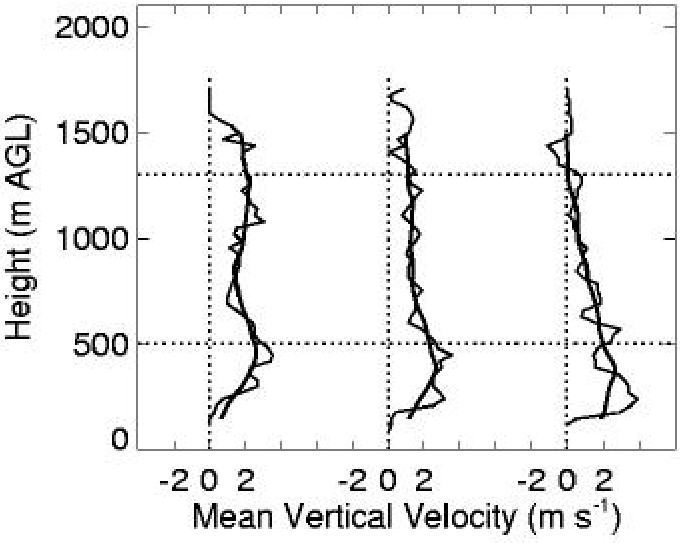

Figure 4. Consecutive (separated by 7 sec.) profiles of mean vertical velocity. Thick lines are smoothed. Ceilometer cloud base and radar reflectivity cloud top are indicated by horizontal dotted lines.

Time series of the retrieved mean vertical air motion are shown in Figure 5, for three different heights: in the light snow below cloud base (300 m), in mid-cloud (750 m), and near cloud top (1200 m). The thicker lines indicate the smoothed trend at each height. An oscillation of the vertical velocity, with period of about 30 min., is apparent throughout the depth of the cloud. Smaller scale variations, on the order of 10 min., are also apparent. With a 3.0 m s^{-1} drifting velocity, the corresponding horizontal scales are 5.4 km (cloud bands) and 1.9 km (thermals), respectively.

Conclusions

We apply a technique that removes turbulent broadening from cloud radar Doppler spectra to data collected during the Lake-Induced Convection Experiment. Multimodal spectra are retrieved, allowing the possibility of separating precipitation from radiatively important cloud particles, as well as separating the different species of ice. We determine mean air motion with temporal resolution of 7 sec. and vertical resolution of 30 m. Periodicity and vertical coherence of the mean air motion is apparent using this retrieval technique. Future work will include retrieval of longer time series, quantifying the vertical coherence, and analyzing the periodicity as a function of time using wavelet analysis.

Acknowledgments

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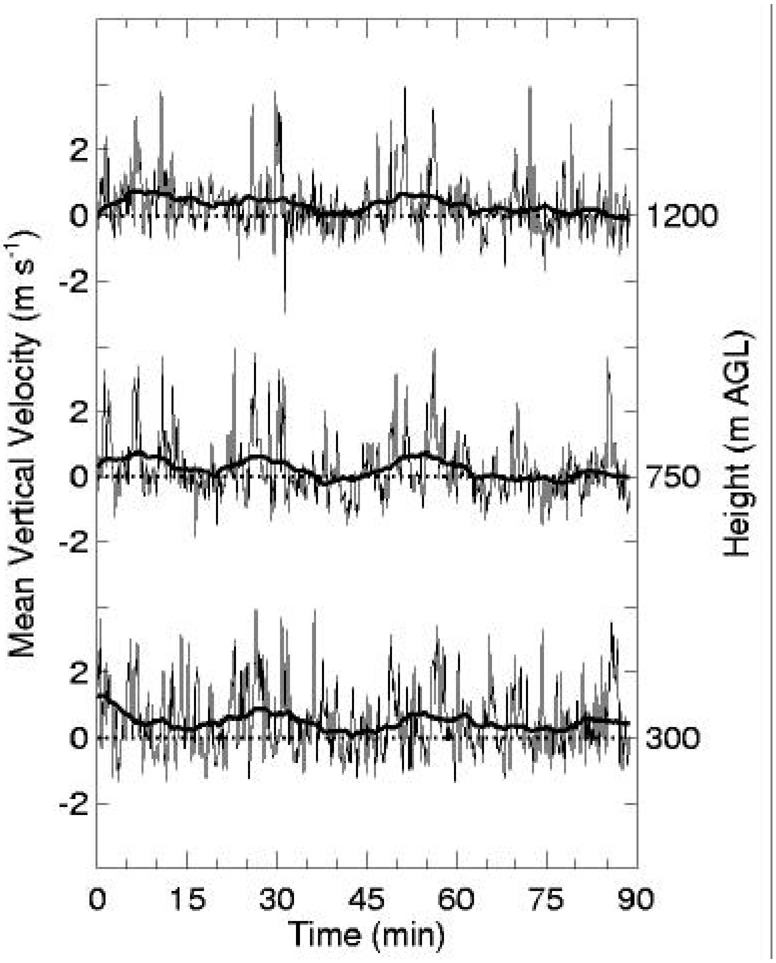

Figure 5. Mean vertical velocity as a function of time for various heights within cloud.

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