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Cloud radar observations of precipitation

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Abstract. An innovative method for the observation of vertical air motion and raindrop size distribution in precipitation using a 94-GHz Doppler radar is demonstrated in this paper. The method is particularly appealing since it is based on fundamental physics, the scattering of microwave radiation by large particles (Mie scattering). Observations from stratiform rain are presented to illustrate the potential and accuracy of the method. The retrievals from this technique provide vertical air motion to an accuracy of 5–10 cm s^{-1}. The data revealed high-resolution kinematical and microphysical structures within the stratiform precipitation for the surface to the melting level. Such observations can enhance our understanding of physical processes that affect the final shapes of DSD in stratiform rain, like evaporation, turbulence and vertical air drafts. The observations were collected at the University of Miami's multi-frequency ground- based radar facility (W, S and UHF-band radars). The ensemble of radars at this facility can provide high temporal and spatial resolution profiles of vertical air motion and DSDs in stratiform and convective precipitation.

1 Introduction

Vertical air drafts in precipitation strongly impact the microphysics and influence the final shapes of the DSD (e.g. Kollias et al., 2001). Vertically pointing Doppler radars can provide excellent vertical and temporal resolution of over-passing precipitation. Furthermore, the mean Doppler velocity from these radars can be related to the sum of the air motion and raindrop's terminal velocity. The decomposition of the two contributions to the observed mean Doppler velocity is a difficult task. In the last 15 years, wind profilers that can detect both Bragg and Rayleigh scattering under certain conditions, have been used to decompose the velocity measurements (e.g. Wakasugi et al., 1986, Gossard et al., 1988). However, the retrievals from wind profilers are subject to many assumptions (e.g. wind shear induced Doppler spectra broadening and poor Doppler spectrum velocity resolution), therefore increasing the uncertainty of these measurements.

In this paper, a new technique using a 94-GHz Doppler radar in combination with as S-band radar is applied in stratiform rain (Lhermitte, 1988; Kollias et al., 1999, 2001; Firda et al., 1999). In the Mie scattering regime the backscattering cross section as function of the raindrop diameter oscillates due to resonant electromagnetic multi-poles effects. Under precipitating conditions at 94-GHz, these oscillations are apparent in the observed Doppler spectrum and can be used as reference points for the retrieval of the vertical air motion and subsequently the DSD. Using this 94-GHz technique, high spatial and temporal measurements of vertical air motion structures in stratiform rain from the surface to the melting layer were obtained. The collocated S-band profiler provided non-attenuated profiles of reflectivity and captured the entire depth of the precipitating clouds. The S-band observations were used to scale the 94-GHz Doppler spectra for DSD retrievals and attenuation studies.

2 Millimeter-wavelength radars and precipitation

Figure 1 shows the 94-GHz backscattering cross section as a function of raindrop diameter at 20°C for oblate spheroids and spherical particles. The first minimum is well defined and occurs at a raindrop diameter of 1.71 for oblate spheroids (Kollias et al., 2002). The air vertical velocity can then be deduced from the simple difference between that terminal velocity and the position of the minimum in the Doppler spectrum observed at vertical incidence with the millimeter wave Doppler radar.

Lhermitte (1988) first mentioned this innovative technique in the context of stratiform rain observations. Kollias et al., (1999, 2001); study a shallow convective cloud and revealed the interaction between a low-level updraft and the drop size distribution field. Figure 2 shows an example of a vertical

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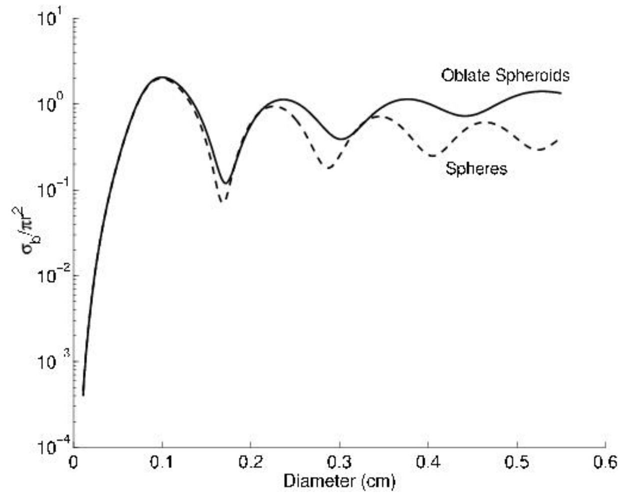

Fig. 1. Normalized backscattering cross-section as a function of the diameter for oblate spheroids (solid) and spherical raindrops (dashed) at 94-GHz and vertical incident.

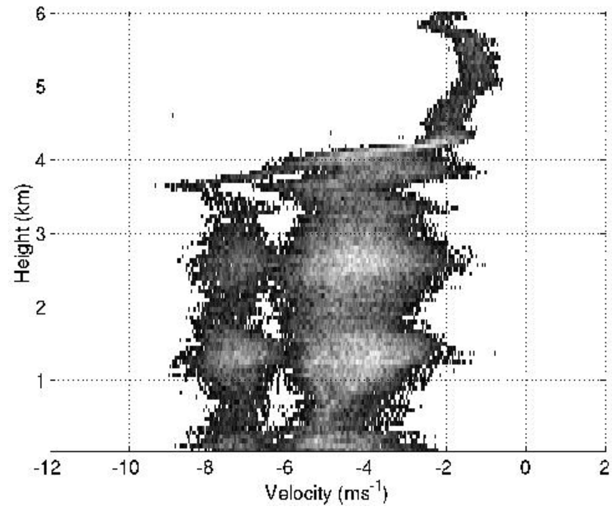

Fig. 2. Example of Doppler spectra with altitude from stratiform rain observed at vertical incidence with the University of Miami 94-GHz Doppler radar. The modulating affect of Mie scattering is illustrated on the Doppler spectrum. The velocity difference between the observed position of the 1st Mie minima and its theoretically calculated location in still air provides the air motion.

profile of Doppler spectra (spectrogram) in stratiform rain. The 1st backscattering minimum is visible from near the surface (200 m) to the base of the melting layer (4000 m). Following the location of the first minimum in the Doppler spectrum and correcting for the air density change with altitude, a profile of the vertical air motion is retrieved.

3 Observations

During the summer of 2001 the NOAA/ETL S-band profiler was operated on the RSMAS campus (Virginia Key), collocated with the 94-GHz and 915-MHz radars for precipitation studies. Several precipitating clouds were observed ranging from strong convective clouds to weak precipitating cirrus.

All the radars collected profiles of Doppler spectra. The S-band (to be replaced in the future by an X-band) provided accurate reflectivity measurements throughout the depth of the precipitating column. The W-band, observed the precipitation to some depth that depends on the rain intensity (usually above the melting layer for stratiform rain and the first 2 km for convective rain). This unique synergy of radars operating at different frequencies offers many opportunities for the study of precipitating clouds. Retrievals of air motion to an accuracy of 0.1 ms^{-1} (Kollias et al., 2002) and DSD will be performed using the profiles of Doppler spectra collected by the 94-GHz radar. The vertical profiles of reflectivity from the S-band radar will be used to scale the DSD retrieved from the 94-GHz Doppler spectra and to provide the vertical structure of the precipitating system. In addition to the main objective of small-scale precipitation studies, turbulence retrievals at different wavelengths and for different sampling volumes, Doppler spectra broadening effects, vertical air motion techniques (e.g. detection of Bragg peak versus Mie minima shift), and attenuation will be topics of research in an effort to assess the validity of retrievals when a single vertical pointing radar is used. In this paper, the retrievals of vertical air motion are presented.

The data for this case were collected on 8 September 2001, at the RSMAS (Rosenstiel School of Marine and Atmospheric Science) site. Figure 3a shows a time-height cross-section of reflectivity and mean Doppler velocity from the S-band profiler. Convective rain was observed before 19:20 UTC (15:20 local time) followed by stratiform rain that lasted for more than 2 h. The vertical lines correspond to the time period when the 94-GHz Doppler radar was operating. The melting layer is around 4.2 km and the cloud tops reached 12 km. The rainfall rate measured by the rain gauge during the stratiform period did not exceed 1–2 mm h^{-1}. Figure 4 shows a time-height mapping of reflectivity from the 94-GHz Doppler radar for the time period indicated by the vertical lines in Fig. 3. At the beginning signal attenuation is evident during the passage of the convective core. Later, as the rain intensity subsides, the mm-wavelength radar was able to observe the entire precipitating cloud. During that period Doppler spectra were recorded with a temporal resolution of 3 s and vertical resolution of 60 m. The PRF was 10 KHz, the number of FFT points 512 and the velocity resolution 3.2 cm s^{-1}. The top panel of Fig. 5 shows a vertical cross section of the retrieved air motion using the retrieval technique described above. The technique is applicable from near the surface to the base of the melting layer where the technique is not applicable due to the suppression (collapse) of the terminal fall velocities of the hydrometeors (see Fig. 2). The observed vertical air velocities are within ± 1 m s^{-1} Low frequency updraft-downdraft motions are observed and the wind structure tilts with height. The bottom panel of Fig. 5 shows the number of Mie scattering peaks detected in the

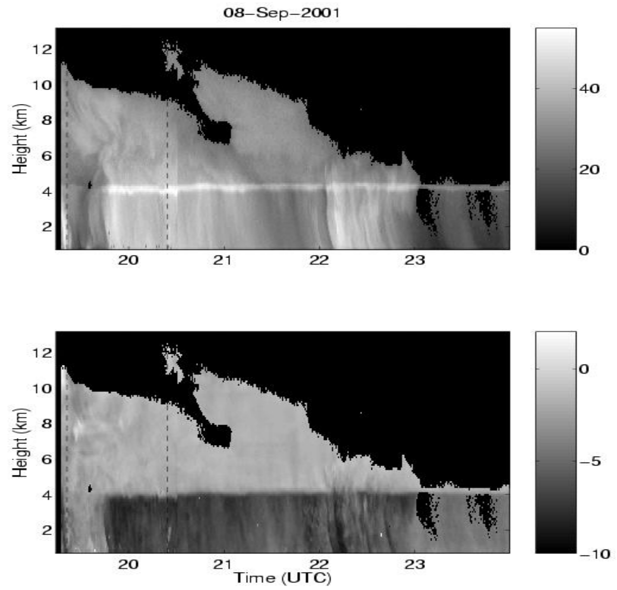

Fig. 3. **(a)** S-band radar reflectivity mapping of the precipitating system **(b)** S-band mean Doppler velocity observations.

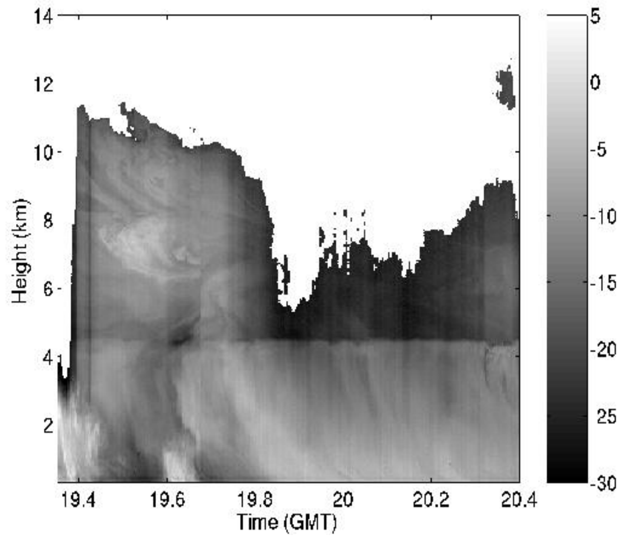

Fig. 4. **(a)** 94-GHz Doppler radar reflectivity mapping of the precipitating system.

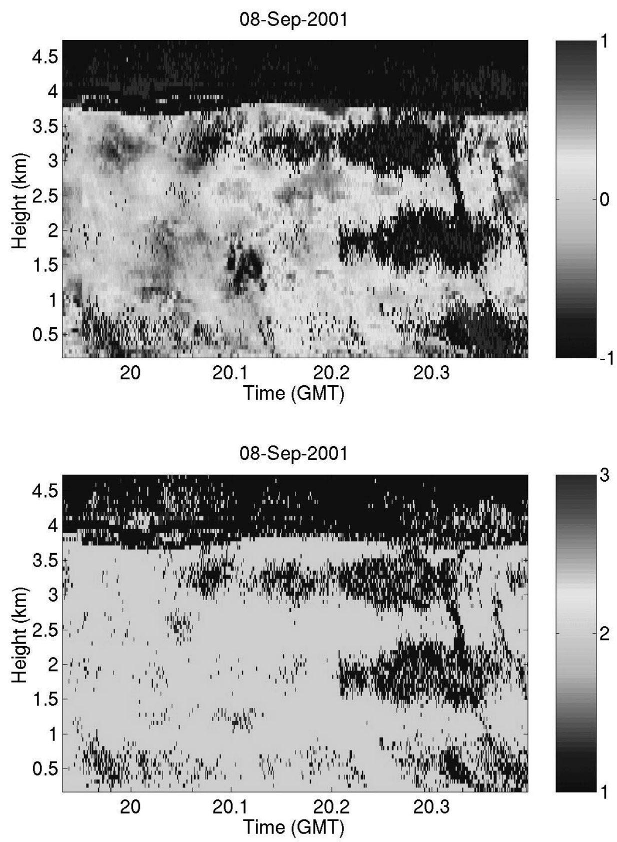

Fig. 5. **(a)** Vertical air motion field retrieved by the millimeter radar. **(b)** Number of Mie spectra peaks detected in the Doppler spectra.

94-GHz Doppler spectra at each time-height point. Above 3.8 km, there are very few multimodal Doppler spectra, while below 3.8 km the majority of the Doppler spectra have two Mie spectra peaks. There is a small number of points in the time-height cross section where three peaks where observed indicative of the presence of large raindrops with diameters larger than 3 mm. Around 20:20 UTC there are patches in the stratiform rain with only small raindrops (one spectral peak detected, diameters smaller than 2 mm). At these points the retrieval technique is not applicable and no retrieval of the air motion is performed.

4 Discussion and conclusions

In this paper, retrievals of vertical air motion in stratiform rain from near the surface to the base of the melting layer were presented for first time. The observations clearly demonstrated that a 94-GHz radar combined with lower frequency radar provides a useful means for studying the kinematics associated with stratiform rain. Such high resolution measurements of air motion from the base of the melting layer to the ground can be used for modeling studies of stratiform rain. The number of detected Mie peaks is correlated with the presence of large raindrops and can be used as indicator of ice crystals aggregation areas above the melting layer. The time-height retrieval of vertical air motion and the superior sampling (temporal and spatial resolution) relative to other remote sensors makes the cloud radar a unique instrument for resolving small-scale variability in stratiform rain when attenuation is not a major problem.

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