JP2.6 RECENT ADVANCES IN THE USE OF MM-WAVELENGTH RADARS FOR CLOUD AND PRECIPITATION RESEARCH

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1. INTRODUCTION

The development and use of Doppler mm-wavelength radars during the past decade has advanced our capability for observing clouds and precipitation. In this paper we review some recent applications of 3-mm wavelength radars for studying dynamical and microphysical processes in fair-weather cumuli, marine stratocumulus clouds, cirrus anvils and convective and stratiform precipitation. The key to many of these studies has been the use of high temporal resolution Doppler spectra (and the associated Doppler moments) obtained from the radar operating in an upward-looking mode. This allows for not only a definition of the macroscopic structure of clouds, but also quantitative estimates of the vertical velocities in clouds on horizontal scales as small as 10-20 m at 1 km and 100-200 m at 10 km height and the turbulence characteristics at even smaller scales. The Doppler spectra from marine stratocumulus clouds observed along the coast of California during the summer of 1999 are used to examine drizzle characteristics and the turbulence variability these clouds. Observations made over South Florida are used to study the updraft-downdraft circulations and turbulence in fair-weather cumuli. The dynamical and microphysical characteristics of cirrus anvils are being made using radar observations made during the Cirrus Regional Study of Tropical Anvils and Cirrus Levels Florida Area Cirrus Experiment (CRYSTAL-FACE, 2002).

Although the development of 3-mm wavelength radars was motivated by the need for studying cloud properties, radars operating at this wavelength have characteristics that make them unique for studying air-motions and precipitation drop-size-distributions (DSDs) in convective and stratiform rain through the Mie signatures that are observed in the Doppler spectra. While attenuation limits the application of this technique under heavy rain conditions to the lowest 2-3 km, for stratiform rain, it is possible to obtain useful observations to the melting level and higher. A review of applications of the Mie technique for characterizing vertical air velocities and DSDs in convective and stratiform rain from a 3 mm wavelength radar will be presented. Recent applications provide new insight into key process associated with the effects of updrafts and downdrafts on DSDs and advance our understanding of processes operating at the melting level in stratiform rain. Future possible applications of 94 GHz radars for studying cloud and precipitation processes will also be discussed.

2. MM-WAVELENGTH RADARS

Since the early eighties (Lhermitte, 1981), very short wavelength Doppler radars (λ =3.2 mm or 94 GHz, W-band) are introduced to radar meteorology, primary for the observation of low radar reflectivity clouds. 94-GHz Doppler radars are about the shortest wavelength radars that are typically assembled for meteorological use. Their sensitivity results from the proportionality of the backscattering cross section in the Rayleigh regime (D ˙ λ) to $1/\lambda^{-4}$. Millimeter radars are capable of detecting very small droplets with diameters of tens of microns. In addition to their high sensitivity, millimeter radars can be configured to have excellent temporal and spatial resolution and can operate with antennas that have a very narrow beamwidth. These factors result in sampling volumes that are very small compared with those of longer wavelength radars. This reduced sampling volume decreases the effects of the Doppler spectrum broadening due to turbulence. The capability of 94 GHz radars for cloud detection and their portability make them a good tool for studying cloud microphysics and dynamics of boundary layer clouds and cirrus. Because of the deep Mie backscattering oscillations occurring in the raindrop particle size range (Lhermitte, 1988), the 94-GHz radar is also an attractive choice for vertical air motion and drop size distribution measurements, particularly when used in conjunction with an S-band or an X-band radar.

3. CLOUD AND PRECIPITATION RESEARCH APPLICATIONS OF MM-WAVELENGTH RADARS

In vertically pointing mode, mm-wavelength radars can provide detail mapping of the

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overpassing clouds (e.g. Kollias et al., 2001; Clothiaux et al., 1995). Collocated with other active (e.g. lidars) and passive (e.g. microwave radiometer) instruments the radar data can be used for the retrieval of cloud microphysical properties like liquid water content (LWC), ice water content (IWC) and N(D) (e.g. Gossard et al., 1994; Frisch et al., 1995; Mace and Sassen 2000). Finally, the 94-GHz can be used for precipitation research (Firda et al., 1999; Kollias et al., 1999; 2001) Here we provide a brief description of the University of Miami efforts on cloud and precipitation research using a 94-GHz Doppler radar. Several cloud radar groups in Europe and USA have worked on similar developments and applications (e.g. Danne et al., 1999; French et al., 2000; Hogan et al., 2000; Sekelsky et al., 1999).

3.1 Boundary Layer Clouds

In the case of fair-weather cumuli and non-drizzling stratus layers, cloud droplets are the main source of backscattering. The Doppler vertical velocity is primarily due to air motion and turbulence. The time-height mapping of the mean Doppler velocity reveals the cloud internal circulation structure in terms of updrafts-downdrafts (Kollias and Albrecht, 2000; Kollias et al., 2001), that can use to analyze the internal dynamics and the interaction between the cloud and its environment. In such clouds, the mean Doppler and Doppler spectrum width are not related to the microphysical properties and can be used only for turbulence retrievals. Although the first moments can provide Large-Eddies Observations (LEO) and estimates of the fractional area of updrafts and downdrafts, the Doppler spectrum width can be used to calculate the turbulence dissipation rate ε and to identify areas with sharp gradients of vertical air motion (Albrecht et al., 2001; Kollias et al., 2001). Similar findings where observed in fair weather cumuli clouds that are highly turbulent. We often observed Doppler spectrum bimodality that indicates the presence of sharp vertical velocity gradients such as those in the region between adjacent updrafts and downdrafts (Albrecht et al, 2001). The variance of the mean Doppler velocity is indicative of the turbulence kinetic energy at scales larger than the radar resolution volume and the Doppler spectrum width is indicative of the turbulence kinetic energy at radar-unresolved scales (smaller than the radar resolution volume). The ratio between these two quantities relates to the partitioning of the turbulent energy at small and large scales and can be estimated in non-drizzling stratus clouds.

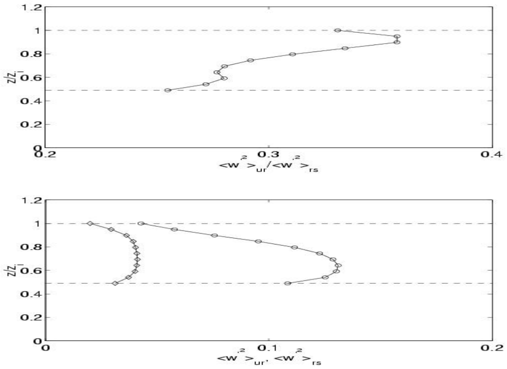

Fig. 1 Time-averaged (30-min) vertical profile of the ratio of large to small scale turbulence energy in non-precipitating marine stratocumulus cloud (top), and vertical profiles of the resolved and unresolved vertical component of the turbulent kinetic energy (bottom). The height is normalized to the depth of the marine boundary layer

Fig. 1 shows such a profile (top panel) that is remarkably consistent with LES model results. The bottom panel shows the profiles of each individual term. Such results can lead to useful applications (e.g. evaluation of LES sub-grid turbulence parameterization). The height is normalized to the depth of the marine boundary layer and the profile shown is the composite of more than 40 hours of data collected in non-precipitating stratocumulus clouds in Monterey Bay, California during the Drizzle and Entrainments Cloud study (1999).

3.2 Cirrus Anvil Clouds

The top panel of Fig. 2 shows high resolution (1.6 sec, 30 meters vertical) of Doppler spectrum width in a convective cirrus anvil at a single

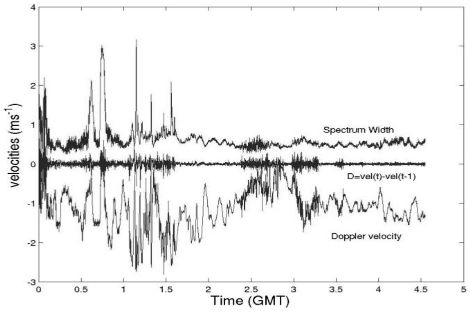

Fig. 2 Time series of mean Doppler velocity, horizontal gradient of mean Doppler velocity and Doppler spectrum width in a convective anvil at 7 km altitude.

altitude as a function of time. Several areas with enhanced spectrum width values (top line) are evident. The middle line shows the horizontal gradient of the mean Doppler velocity and the lower line is the mean Doppler velocity. There is strong correlation between areas with large horizontal gradient of the mean Doppler and spectrum width.

This is a typical velocity structure observed in such clouds, where for vertically pointing operations the most important contribution of shear to the spectral broadening is the air vertical velocity variation Δw moving horizontally across the beam. Away from shear zones, the variance due to air turbulence, σ_t^2, from small-scale variability, in both time and space, of the velocity field within the sampling volume is the main contributor to Doppler spectrum variance. Assuming that the in-cloud turbulence is a stochastic homogeneous process, the turbulent energy dissipation rate ε can be retrieved (Meischner and Baumann, 2001; Frisch and Strauch, 1976) for scales between λ/2 (λ is the radar wavelength), the smallest scale that can be probed by the Doppler radar and the larger scale L that relates to the scattering volume dimension (radar beam).

3.3 Precipitating Clouds

In precipitation, the scatterers (raindrops) have sizes comparable to the radar wavelength (Mie scattering). In the Mie regime, the backscattering cross section as a function of the raindrop diameter oscillates between fixed maxima and minima. These oscillations modulate the Doppler spectrum at vertical incident. 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 (Kollias et al., 1999; Kollias et al., 2001; Firda et al., 1999). The first minimum is well defined and occurs at a raindrop diameter of 1.71 mm 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. Using this 94-GHz technique, high spatial and temporal measurements of vertical air motion structures in stratiform and convective rain can be obtained.

Lhermitte (1988) first mentioned this innovative technique in the context of stratiform rain observations. Firda et al. (1999) study the retrieval of precipitation and vertical air motion in stratiform rain using mm-wavelength radar.

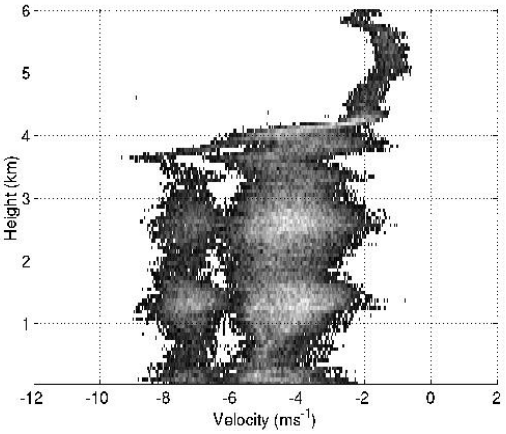

Fig. 3 Example of Doppler spectra with altitude from stratiform rain observed at vertical incidence with the University of Miami 94-GHz Doppler radar. The modulating affect of Mie scattering is illustrated on the Doppler spectrum. The velocity difference between the observed position of the 1st Mie minima and its theoretically calculated location in still air provides the air motion.

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. Fig. 3 shows an example of a vertical 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.

4. SUMMARY

In addition to providing reflectivities and mean Doppler motions in the clouds, mm-wavelength radars can provide full Doppler spectra that can be used to obtain critical information on physical processes and their interaction with updraft and downdraft structures. Recording of the raw I/Q radar data is recommended for such small-scale studies since under strong signal to noise conditions the raw data can be used to sample the cloud at much higher resolution and to identify turbulence and wind shear induced spectral broadening. Furthermore, a 94-GHz radar combined with lower frequency radar provides a useful means for studying the kinematics and microphysics associated with stratiform and convective rain. When used on a mobile platform (e.g. aircraft, pedestal or satellite) these radars have the potential for providing more on the three dimensional structure of non-precipitating clouds.

5. ACKNOWLEDGEMENT

This research was supported by the ONR Grant N 00014-99-1-0036, NSF Grants ATM9730119 and ATM 0210272, and DOE Grant DEFG0287ER62337.

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