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Turbulence and microphysical retrievals in boundary layer clouds using mm-wavelength Doppler spectra

P. Kollias and B. A. Albrecht

RSMAS/MPO, University of Miami 4600 Rickenbacker Cswy, Miami, FL, 33149, USA

Abstract. Due to their short wavelength, millimeter radars are capable of detecting very small droplets. This capability has established them as the ultimate observing systems for the study of weak meteorological targets undetectable by conventional weather radars. In this paper, some new ideas on the use of millimeter wavelength Doppler spectra for the retrieval of turbulence and microphysical parameters are injected in an attempt to emphasize the importance of recording the Doppler spectrum at vertical incidence. In particular, emphasis is given in the retrieval of turbulence intensity at resolvable and non-resolvable radar sampling scales and the removal of turbulence broadening for drizzle size distribution using the Doppler spectrum moments.

1 Introduction to Doppler spectra moments

The development and use of Doppler mm-wavelength radars during the past decade has advanced our capability to study non-precipitating clouds. The discussion is applicable only to vertically pointing mm-wavelength Doppler radars. Due to their short wavelength ($\sigma_b \approx \lambda^{-4}$), mm-wavelength Doppler radars are capable of detecting small cloud droplets (diameter D $\approx$ 1 to 40 μm), in stratocumulus and fair-weather cumulus clouds. The radar returns from cloud droplets contain information about their number density, sizes and radial velocities. The radar reflectivity Z (mm^{6}m^{-3}) relates to the droplet size distribution N(D) (mm^{-4}) through the expression

$$Z = \int_{D_{min}}^{D_{max}} N(D) D^6 dD. \quad (1)$$

The Doppler spectrum density $S(v) = dZ/dv$ (mm^{6}m^{-3}/ms^{-1}) is often recorded after Fast Fourier Transform processing of the radar I/Q signals. Although the Doppler spectrum is needed to capture the full radial velocity statistics of the targets and to identify spurious frequency components, spectral moments can provide a substantial part of the Doppler information needed for the assessment of the microphysical and dynamical properties in the cloud. The zeroth moment of the Doppler spectrum is the radar reflectivity Z. The first moment $< V >_{dop}$ (ms^{-1}) is the mean Doppler velocity and it is the reflectivity weighted mean radial velocity $< V >_{DSD}$ of the hydrometeors within the resolution volume in the absence of air motion. Often the mean vertical air motion $< w >_{vol}$ of the atmospheric volume sampled by the radar beam contaminates the observed mean Doppler velocity. Thus, the measured $< V >_{dop}$ is given by

$$< V >_{dop} = < V >_{DSD} + < w >_{vol} . \quad (2)$$

The second Doppler moment σ^2_{dop} (m^{2}s^{-2}) or Doppler spectrum variance is a measure of the spreading of the signal in the velocity domain. The presence of droplets with different terminal fall velocities and turbulence within the sampled radar volume are the main contributions to the Doppler spectrum variance. The occurrence of air turbulence creates a broadening of the droplets' velocity distribution in the scattering volume. This results in an increase of the spectrum width or second Doppler moment. Measurement of the spectrum width is thus essential for the interpretation of Doppler data in terms of cloud dynamics. The overall spectrum variance, σ^2_{dop}, is given by:

$$\sigma^2_{dop} = \sigma^2_{dsd} + \sigma^2_t + \sigma^2_s, \quad (3)$$

where σ^2_{dsd} is the variance relating to droplets' terminal velocity spread, σ^2_s is the variance due to velocity shear within the scattering volume, and σ^2_t is the variance due to air turbulence. The equation above is applicable only if the processes contributing to the variance are independent. The mean Doppler velocity and the Doppler spectrum variance along with the signal power or zeroth Doppler moment are often called the Doppler spectra moments.

Correspondence to: P. Kollias (pkollias@rsmas.miami.edu)

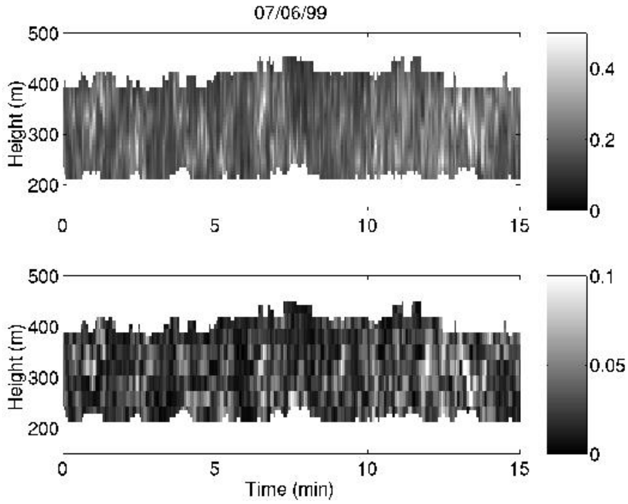

Fig. 1. Time-height mapping of Doppler spectrum width (ms^{-1}) in a marine stratocumulus cloud observed on the Monterey coast, CA in July 1999. The temporal resolution is 3 sec and the vertical resolution 30 m (top), and time-height mapping of the horizontal gradient of the mean Doppler velocity (ms^{-2}) for the same period.

2 Cloud properties retrievals using the Doppler spectra moments

In vertically pointing mode, mm-wavelength radars can provide detail mapping of the overpassing clouds (e.g. Kollias et al., 2001; Clothiaux et al., 1995; Syrett 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. Frisch et al., 1995; Matrosov et al. 1994). Such synergy of instruments is manifested at the Atmospheric Radiation Measurements supersites (Stokes and Schwartz, 1994) and several retrieval techniques have been proposed and demonstrated (e.g. Kato et al., 2001; Clothiaux et al., 2000; Mace and Sassen, 2000). The primary observations in these retrieval techniques are the Doppler spectra moments. While the reflectivity and mean Doppler velocity are often used, the second Doppler spectral moment or spectrum width is usually not included since it is difficult to decompose the various contributions shown in the equation of the spectrum variance. Often this is true for the mean Doppler velocity, especially when the fall velocities of the cloud droplets have magnitudes comparable to the vertical air motion in clouds. In this paper, we attempt a critical view of the usefulness of the Doppler spectra moments for microphysical and turbulence retrievals.

2.1 Non precipitating clouds

In the case of fair-weather cumuli and non-drizzling stratus layers, cloud droplets are the main source of backscattering. The terminal velocity of a cloud droplet is small, (0.3 cm s^{-1} and 7 cm s^{-1} for a 10 μm and a 50 μm droplet, respectively) so that the droplets' vertical velocity is primarily due to air motion and turbulence. The cloud droplets' inertia is small so they are good tracers of turbulent air velocity in the same way that smoke particles reveal turbulent eddies in a smoke filled room. 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 be used to analyze the internal dynamics and the interaction between the cloud and its environment. In such clouds, the mean Doppler velocity and Doppler spectrum width are not related to the microphysical properties of the DSD 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). For a typical cloud droplet distribution, the Doppler spectrum variance induced by the presence of droplets with different fall velocities will be only a few cm^2s^{-2}. As a result the observed Doppler spectrum width arises principally from turbulence and wind shear. The top panel of Fig. 1 shows high resolution (3 sec, 30 meters vertical) of Doppler spectrum width in a marine stratus layer. Several areas with enhanced spectrum width values are evident. The bottom panel shows the horizontal gradient of 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 finding in such clouds (non-drizzling), 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. Similar findings were 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).

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 $\lambda/2$ (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), but for the actual case of a finite dwell time of the signal from which the spectrum is calculated, it also includes large eddies traveling through the sampling volume.

We define the mean Doppler spectrum variance $< \sigma_{dop}^2 >$ as a time average (30-60 min) of Doppler spectrum variance away from shear zones and σ_v^2 as the variance of the mean Doppler velocity during the same time period. The ratio R

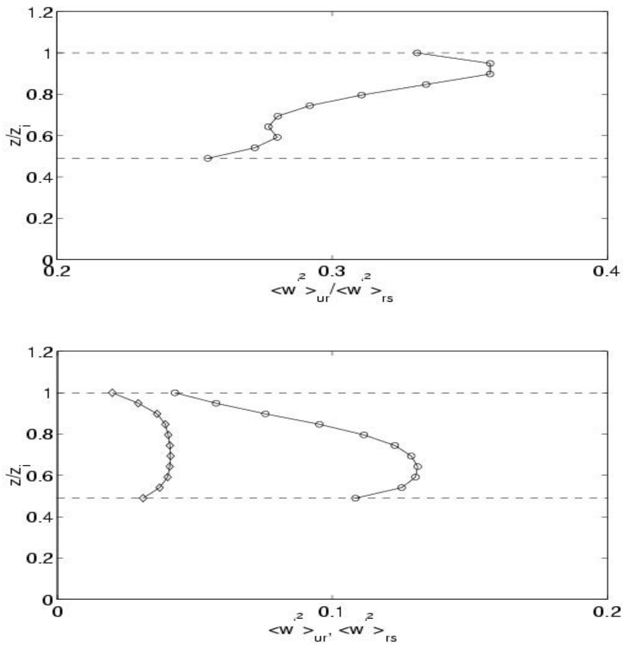

Fig. 2. Average vertical profile of the ratio R in non-precipitating marine stratocumulus cloud (top), and vertical profiles of the resolved (circles) and unresolved (diamonts) vertical component of the turbulent kinetic energy (bottom). The height is normalized to the depth of the marine boundary layer.

(Rogers and Tripp, 1964)

$$R = \frac{< \sigma_{dop}^2 >}{\sigma_v^2} \qquad (4)$$

indicates the turbulence kinetic energy partitioning between the radar-resolved (larger than L) and the radar-unresolved scales (smaller than L). Since L is variable with range (beam broadening) and radar dwell time, the ratio R will be different at various ranges from the radar even if the in-cloud turbulence field is invariant. If we account for the change of L with range we can estimate a profile of R in non-precipitating stratus layers. Fig. 2 shows such a profile (top panel) that is remarkably consistent with LES model results. The bottom panel shows the profiles of each individual term. The ratio R 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).

2.2 Drizzling stratus layers

When cloud and drizzle droplets coexist in the radar scattering volume, $< V >_{dop}$ and σ_{dsd}^2 induced by the drizzle size distribution are significant contributors of the first and the second moment of the Doppler spectrum. Furthermore, the dynamical contributions $< w >_{vol}$ and σ_t^2 are equally important. The contribution to the mean Doppler velocity from the radar sampling volume averaged air motion can be removed by time averaging of several mean Doppler velocity estimates at the same height (e.g. Frisch et al., 1995; Matrosov et al., 1994). Doppler spectrum models based on cloud and drizzle drop size distributions and convolution with turbulence filters have been used to account for the Doppler spectra broadening induced by turbulence (e.g. Gossard et al., 1994). However, these models have limited applicability and significant errors are introduced by the assumption of stationary air motion field during the radar dwell time. If the I/Q radar samples are recorded, such techniques can be revised and applied. Here we propose a simple decomposition technique of the Doppler spectrum width contributions from DSD and turbulence. As discussed previously, during non-precipitating periods we can define the ratio R. The turbulence induced Doppler spectrum broadening is given by $\sigma_t = R^{1/2}\sigma_v$. Assuming that the ratio R remains constant during non-drizzling and drizzling periods (typical drizzle patches in marine stratus last 5-10 min followed by non-precipitating periods) we can estimate the contribution from turbulence during the drizzle periods using the σ_v estimates during the drizzling period. Therefore we correct the Doppler spectrum width σ_{dop} for turbulence broadening using the equation:

$$\sigma_{dsd} = \sqrt{\sigma_{dop}^2 - R\sigma_v^2}. \qquad (5)$$

The σ_{dsd} can be used as input to drizzle microphysical retrieval models (e.g. Frisch et al., 1995) in which the assumed lognormal size distribution width σ_x is given at the ratio of the σ_{dsd} and the mean Doppler velocity. Thus far, a constant value was assumed to this lognormal distribution parameter (typically 0.35) based on aircraft measurements of drizzle size distributions. This modification to the original Frisch technique can lead to more realistic microphysical retrievals where the turbulence broadening is essentially removed.

3 Summary

Millimeter radar from boundary layer clouds returns reflect the microphysical content (cloud and drizzle size distribution). However, boundary layer clouds are highly turbulent and when the Doppler spectrum is recorded it contains both dynamical and microphysical information. To fully use this information, the observations data should be first classified as either non-precipitating or precipitating clouds. If the cloud is characterized as non-precipitating (contains only cloud droplets), the first and second moments can provide critical information on turbulence at various scales. The turbulence information can be used also to correct the Doppler spectrum broadening due to turbulence when drizzle droplets are present. Recording of the raw I/Q radar data is recommended for such small-scale studies since under strong signal to noise conditions can be used to resample the cloud at much higher resolution and to identify turbulence and wind shear induced spectral broadening.

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