Mixed-Phase Cloud Retrievals Using Doppler Radar Spectra

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Introduction

The radar Doppler spectrum contains a wealth of information on cloud microphysical properties. Typically, radar-based cloud retrievals use only the zeroth or first moments of the Doppler spectrum – reflectivity and mean Doppler velocity – to derive quantities such as cloud water content and particle characteristic size (e.g., Liou and Sassen 1994; Matrosov et al. 2002). When using only the moments of the Doppler spectrum, important spectral information can be lost, particularly when the spectrum is multi-modal. Multi-modal spectra are possible when a mixture of two or more cloud particle phases, habits, or sizes exist in the same volume (e.g., Gossard et al. 1997). For example, the large difference in size between the liquid droplets and ice crystals in a mixed-phase cloud often causes these two phases to fall at different rates, thus producing a bi-modal spectral signature.

Mixed-phase clouds play an important role in global climate and aircraft safety. The identification and partitioning of phases in mixed-phase clouds is difficult yet has powerful implications in terms of the atmospheric and surface radiative balances (e.g., Sun and Shine 1994). In the Arctic, mixed-phase clouds are frequent (~41% of the time) and any changes in Arctic mixed-phase cloud composition and/or fraction are expected to strongly impact the surface energy balance in that region and feedback into global climate. In mid-latitudes, where mixed-phase clouds occur at higher altitudes and are somewhat less frequent than in the Arctic, super-cooled liquid drops are particularly important for aircraft icing hazard conditions (Cober et al. 2001). In general, we have only meager knowledge of mixed-phase cloud structure and formation/persistence mechanisms which has caused these clouds to be poorly represented in cloud and climate models.

Here, Doppler spectrum observations from ground-based radar are used to introduce a technique to identify and quantify both phases in a mixed-phase cloud. A case study on July, 29, 2002, from the National Aeronautics and Space Administration (NASA) Cirrus Regional Study of Tropical Anvils and Cirrus Layers - Florida Area Cirrus Experiment (CRYSTAL-FACE), is used to illustrate the method. The case of interest occurred from 1500 to 1530 Universal Time Coordinates (UTC) in a 2 km thick, mixed-phase altostratus layer at about 5 km above ground level (AGL).

Measurements

All measurements discussed here were made by ground-based remote-sensors at the CRYSTAL-FACE eastern ground site located in Miami, Florida (25° 39' N, 80° 26' W) on July, 29, 2002. Measurements of the radar Doppler spectrum were made by a vertically pointing, 35-GHz, millimeter cloud radar (MMCR). The MMCR has 45 m vertical resolution and resolves the Doppler spectrum over the range of -4.1 to +4.1 m s^{-1} to 0.064 m s^{-1} using 128 fast Fourier transform points. We utilize one of four alternating operational modes that samples for 1.8 seconds at 35-second intervals. The MMCR is similar to the 35-GHz radars in operation at the Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART) sites. Radar reflectivities for the half-hour long, July 29 case are shown in Figure 1a and example Doppler spectra are shown in Figures 1c-f.

Observations from a collocated microwave radiometer (MWR) and micro-pulse lidar are used to validate the information gained from the radar measurements alone. Microwave radiometer brightness temperature measurements at 20.6 and 31.65 GHz are used to derive column integrated condensed liquid water path (LWP) estimates (Figure 1b). The differential response of the lidar backscatter to liquid droplets and ice crystals is exploited to identify the base of the cloud liquid layer. Additionally, radiosonde temperature and humidity profiles from the nearby Miami International Airport are used to confirm below freezing temperatures within the cloud layer.

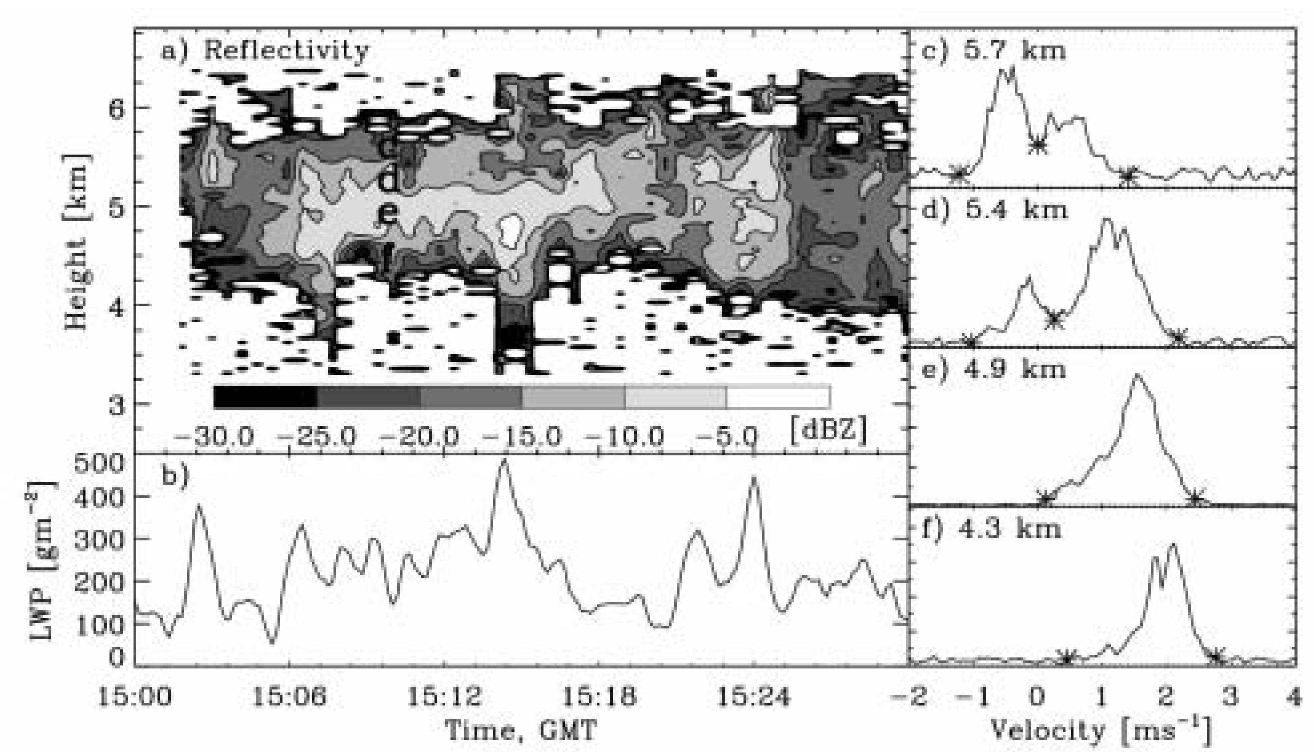

Figure 1. Observations from the July 29 case study of (a) radar reflectivity, (b) MWR-derived LWP, and (c) through (f) Doppler spectra at various heights annotated on panel (a).

The Mixed-Phase Doppler Spectrum

Doppler spectra from the July 29 case suggest distinct signatures from both cloud liquid and ice. Figures 1c-f show spectra at four heights within the cloud layer at 0510 UTC (locations are denoted on the cloud layer in Figure 1a). Near cloud top the spectra are clearly bi-modal. The mode at negative, or ascending, velocities suggests the presence of liquid droplets and an updraft. A cloud top updraft is crucial for liquid formation and persistence in mixed-phase clouds (e.g., Rauber and Tokay 1991). Coincident temperature soundings indicate that the cloud top temperature is about -11°C. Descending through the cloud layer, the spectral mode attributed to liquid decreases in relative magnitude and disappears all together below about 5 km. The second spectral mode, showing stronger downward fall speeds that suggest larger ice particles, increases in relative importance with descending depth in the cloud and is the only spectral mode in the lower half of the cloud layer. In summary, the Doppler spectra suggest that ice occurs throughout the depth of this cloud layer and that liquid exists only in the top portion of the cloud. This general mixed-phase cloud structure is similar to other mixed-phase clouds observed by aircraft (e.g., Hobbs and Rangno 1985).

Retrieval Method

The individual moments of the two distinct spectral modes of this mixed-phase cloud can provide quantitative information on both the cloud liquid and ice microphysical properties. Doppler spectra are averaged in time to increase the signal strength - here spectra were averaged over 5-minute intervals. In this case, averaging slightly broadened the spectral modes but did not significantly impact the first two spectral moments - reflectivity and mean Doppler velocity. The spectral noise level is computed using the Hildebrand and Sekhon (1974) method. A peak-picking algorithm is then applied to identify all significant spectral modes according to the following criteria:

1. The strongest peak must be greater than 135% of the spectral noise level,
2. Any secondary peaks must be greater than 115% of the spectral noise level,
3. Any spectral mode must be composed of at least seven continuous velocity bins (a width of at least 0.448 m s-1),
4. For two continuous modes above the noise to be considered distinct modes, the saddle point between the peaks must be lower than 60% of the lowest of the two peaks from the noise level.

The peak picking criteria used in this case were determined empirically by manual inspection of the peak picking results. The algorithm correctly determined the major peaks in about 95% of the 260 spectra in this case and made only minor errors in particularly noisy or non-uniform spectra. Once spectral peaks are identified, spectral mode ranges are determined by descending from each peak in both directions until either the noise level or an identified saddle point is reached. For the purposes of this mixed-phase cloud case, only two modes were allowed and the mode with the largest (smallest) fall speeds was assigned to be ice (liquid). If only one spectral mode was identified, it was assumed to indicate cloud ice. The boundaries of the spectral modes determined using this algorithm are indicated by stars in Figures 1c-f.

Once spectral modes have been distinguished by phase, the moments of each mode are calculated. The zeroth moment, reflectivity, is the total power for each mode, and the first moment, the mean Doppler velocity, is the power-weighted mean velocity over each spectral interval. Using the computed profiles of reflectivity and/or mean Doppler velocity, various moment-based retrieval methods can be applied to the liquid and ice components separately. Here, as an example, reflectivity power law regressions are used to relate radar reflectivity (Z_e) to cloud microphysical parameters. We will briefly summarize the specifics of these retrievals. For ice water content (IWC) a regression of the form.

$$IWC = aZ_e^b \tag{1}$$

is applied to the ice-only reflectivity profile. Using an assumed ice density-size relationship and an equation relating Z_e, IWC, and ice particle size (summarized by Matrosov et al. 2002), the characteristic particle size (D_o) is determined using the same coefficients as in Eq. (1).

$$D_o = 143a^{-0.526}\left(Z_e^{1-b}\right)^{0.526}. \tag{2}$$

Here values of a = 0.12 and b = 0.63 are assumed for Z_e in $mm^6\ m^{-3}$, IWC in $g\ m^{-3}$, and D_o in μm.

Similar reflectivity-based retrievals are used for liquid cloud microphysical parameters. For an assumed lognormal droplet size distribution, relationships between reflectivity and LWC and droplet effective radius (R_e) have the form,

$$LWC = (\pi/6)\rho\exp(-4.5\sigma^2)N^{1/2}Z_e^{1/2} \tag{3}$$

$$R_e = 0.5\exp(-0.5\sigma^2)N^{-1/6}Z_e^{1/6} \tag{4}$$

where ρ is the density of water, σ = 0.31 is the assumed spread of the droplet size distribution, and N is the droplet number concentration. Both σ and N are assumed to be constant with height. A perusal of in situ measurements by a Forward Scattering Spectrometer Probe flown on the North Dakota Citation during CRYSTAL-FACE showed that typical liquid droplet concentrations in mixed-phase clouds during the experiment were about 30 cm^{-3}. We use this concentration in Eqs. (3) and (4), although it is somewhat lower than typical liquid droplet concentrations measured in a marine environment.

Results and Assessment

Case-averaged profiles of radar reflectivity and mean Doppler velocity derived for the liquid and ice components of the 29 July mixed-phase cloud are shown in Figures 2a and 2b. For comparison, the moments of the "total" Doppler spectrum (not distinguishing bi-modalities) have also been plotted. One may assume that, due to size considerations, the ice particles in a mixed-phase cloud dominate the radar signal. To test this hypothesis, we will assume that the "total" spectrum moments characterize the ice component only and will then compare these "total" spectrum results to those from the individual ice spectral mode.

The first notable result of this retrieval method is that the radar measurements alone are able to accurately distinguish the base of the cloud liquid at 5 km. The relative normalized backscatter from the collocated micro-pulse lidar (Figure 2c) shows a marked increase in intensity between 4.9 and 5 km that corresponds to the base of the cloud liquid, and attenuation of the signal in the cloud liquid above 5 km. Also of interest is that the ice component does in fact dominate the radar reflectivity through the depth of this cloud. Where liquid is present near cloud top, the reflectivity from the ice mode is only 1-2 dBZ less than the “total” reflectivity observed by the radar. This difference is not drastically more than the uncertainty of the reflectivity measurements themselves. Thus, in terms of reflectivity, the assumption that the ice component of mixed-phase clouds dominates the radar signal is reasonable. However, in terms of the mean Doppler velocity, the contribution from the liquid component is important. As indicated by Figure 2b, the ice component in the upper portion of the cloud is falling approximately 0.5 m s^{-1} faster than the “total” mean velocity. Furthermore, in the absence of an updraft, liquid droplets should fall at less than 0.02 m s^{-1}, indicating that there is a 0.5 m s^{-1} updraft in the cloud top region. Thus, the actual ice fall speeds in the upper half of the cloud are significantly larger than would be expected if the ice component were assumed to dominant the “total” mean Doppler velocity. Using these offsets, more accurate ice particle fall speeds can be estimated, allowing for the use of retrievals based on particle fall speed and for the derivation of ice particle size distributions.

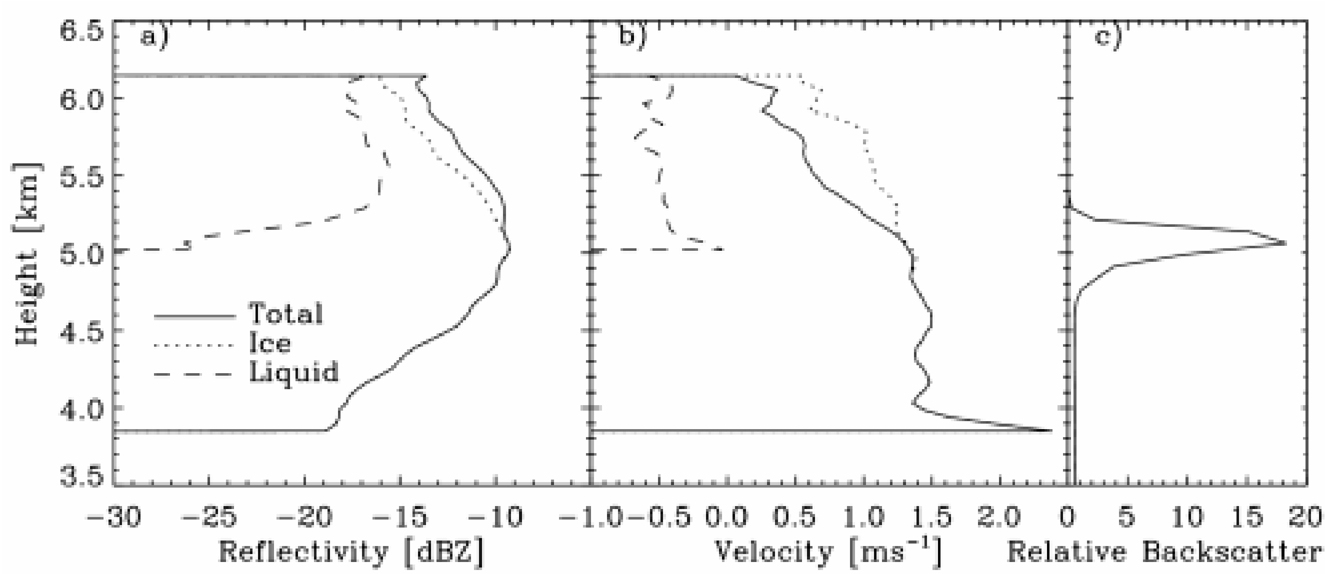

Figure 2. Derived profiles of (a) radar reflectivity and (b) mean Doppler velocity for the total Doppler spectrum and for the distinct liquid and ice spectral modes. (c) A profile of the micro-pulse lidar relative normalized backscatter.

Retrieved profiles of LWC and IWC, averaged over the half hour case study, are shown in Figure 3. A “total” IWC profile is also plotted that is derived from the “total” reflectivity under the assumption that the ice dominates the radar signal. Column integrated values of ice water path (IWP) and LWP are inset in the figure. By comparing the LWP that was independently derived from the collocated MWR (225 g m^{-2}) with the radar-based retrieval (240 g m^{-2}), we find the notable result that the

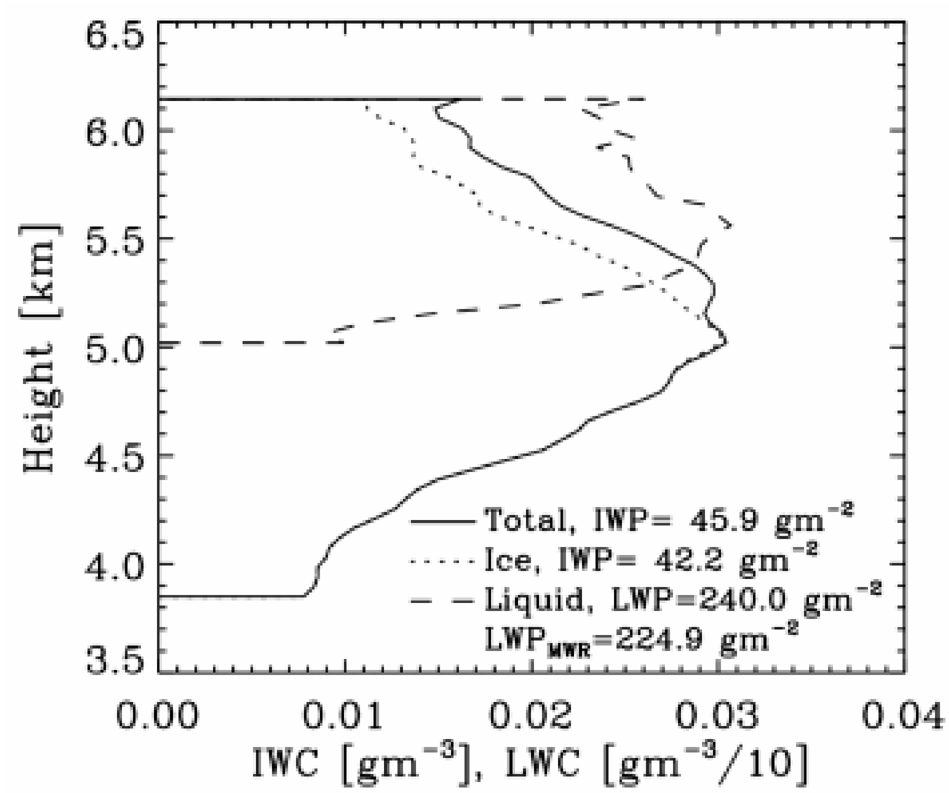

Figure 3. Profiles of retrieved LWC and IWC. Column integrated LWPs and IWPs are inset as well as the MWR-derived LWP. Note that the values of LWC are scaled by a factor of 10.

liquid component of mixed-phase clouds can be quantified, with reasonable accuracy, from radar measurements alone. Additionally, as was true with the reflectivities, there is little difference between the IWP computed from the ice spectral mode and the IWP computed from the "total" reflectivity.

Conclusions

A cloud case on July 29, 2002, from the CRYSTAL-FACE experiment is used to demonstrate a method to derive cloud microphysical properties for both liquid and ice components of mixed-phase clouds from radar Doppler spectra. Bi-modal Doppler spectra can occur when significant amounts of cloud liquid and ice simultaneously exist in mixed-phase clouds. By computing the radar moments for each spectral mode separately, moment-based cloud microphysics retrievals can be applied to characterize both cloud phases. The analysis presented here demonstrates the ability of the radar to distinguish the presence of mixed-phase cloud liquid and ice, to identify the vertical location of each phase, and to quantify the microphysical properties of each phase. Furthermore, by comparing the Doppler moments of the ice-only spectral mode with the moments of the full Doppler spectrum, we see that the ice component dominates the radar reflectivity but that the cloud liquid makes a significant contribution to the mean Doppler velocity. Thus, in the absence of Doppler spectra, the ice component of mixed-phase clouds can be derived, with a reasonable amount of certainty, from radar reflectivity measurements alone. As the mixed-phase cloud liquid water amount decreases, the ice dominance of the radar signal becomes stronger and the radar's ability to identify and quantify the liquid component decreases. Furthermore, there are likely situations when the distinction between liquid droplets and small ice crystals may not be possible in mixed-phase clouds. A Doppler spectrum method similar to the one presented here may also be useful for distinguishing the contributions to the radar signal from cloud liquid and drizzle drops.

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