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A HIGH RESOLUTION HYDROMETEOR PHASE CLASSIFIER BASED ON ANALYSIS OF CLOUD RADAR DOPPLER SPECTRA

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6A.2 A HIGH RESOLUTION HYDROMETEOR PHASE CLASSIFIER BASED ON ANALYSIS OF CLOUD RADAR DOPPLER SPECTRA

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1. INTRODUCTION

The lifecycle and radiative properties of clouds are highly sensitive to the phase of their hydrometeors (i.e., liquid or ice). Knowledge of cloud phase is essential for specifying the optical properties of clouds, or else, large errors can be introduced in the calculation of the cloud radiative fluxes. Current parameterizations of cloud water partition in liquid and ice based on temperature are characterized by large uncertainty (Curry et al., 1996; Hobbs and Rangno, 1998; Intriery et al., 2002). This is particularly important in high geographical latitudes and temperature ranges where both liquid droplets and ice crystal phases can exist (mixed-phase cloud). The mixture of phases has a large effect on cloud radiative properties, and the parameterization of mixed-phase clouds has a large impact on climate simulations (e.g., Gregory and Morris, 1996). Furthermore, the presence of both ice and liquid affects the macroscopic properties of clouds, including their propensity to precipitate.

Despite their importance, mixed-phase clouds are severely understudied compared to the arguably simpler single-phase clouds. In-situ measurements in mixed-phase clouds are hindered due to aircraft icing, difficulties distinguishing hydrometeor phase, and discrepancies in methods for deriving physical quantities (Wendisch et al. 1996, Lawson et al. 2001). Satellite-based retrievals of cloud phase in high latitudes are often hindered by the highly reflecting ice-covered ground and persistent temperature inversions. From the ground, the retrieval of mixed-phase cloud properties has been the subject of extensive research over the past 20 years using polarization lidars (e.g., Sassen et al. 1990), dual radar wavelengths (e.g., Gosset and Sauvageot 1992; Sekelsky and McIntosh, 1996), and recently radar Doppler spectra (Shupe et al. 2004). Millimeter-wavelength radars have substantially improved our ability to observe non-precipitating clouds (Kollias et al., 2007) due to their excellent sensitivity that enables the detection of thin cloud layers and their ability to penetrate several non-precipitating cloud layers. However, in mixed-phase clouds conditions, the observed Doppler moments are dominated by the highly reflecting ice crystals and thus can not be used to identify the cloud phase. This limits our ability to identify the spatial distribution of cloud phase and our ability to identify the conditions under which mixed-phase clouds form.

2. ARM CLOUD RADARS

The United States Department of Energy Atmospheric Radiation Measurement (ARM, www.arm.gov) program operates millimeter-wavelength cloud radars (at 35- and 94-GHz radar frequencies) in several climatologically distinct regions. The digital signal processors for these radars were recently upgraded (completed in 2006). A comprehensive evaluation of the performance of the ARM millimeter-wavelength cloud radars (Kollias et al., 2005) lead to a new operational sampling strategy and modes. The new sampling strategy for the ARM profiling clouds radars (Kollias et al., 2007) includes significant improvement in temporal resolution (i.e., less than 1 s for dwell and 2 s for dwell plus processing), wider Nyquist velocities, operational de-aliasing of the recorded spectra, removal of pulse compression while sampling the boundary layer, and continuous recording of 128 and 256-point FFT Doppler spectra from the 35- and 94-GHz Doppler cloud radars. The post-processing of the recorded Doppler spectra

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from the vertically pointing cloud radars is essential for the mitigation of insect radar returns in the boundary layer (Luke et al., 2007) and spurious artifacts such as DC signal components, spectral image due to I/Q phase and amplitude imbalance and aliasing (Kollias et al., 2007).One of the main advantages of the new operational scheme was the minimization of Doppler spectral broadening due to turbulence. While the improvement on the interpretation of the mean Doppler velocity in non-precipitating clouds is small due to the overwhelming air motion contribution at any observable scale, we significantly isolate the effect of turbulence on the Doppler spectrum and relate the Doppler spectra shape (or morphology) to microphysical characteristics of the scatters.

3. DOPPLER SPECTRA MORPHOLOGY

Careful analysis of Doppler spectra collected from mm-wavelength radars at the ARM sites revealed that the shape of the Doppler spectrum is highly non-Gaussian. Furthermore, multi-modal Doppler spectra from non-precipitating clouds, especially mixed-phase clouds were frequently observed at the North Slope of Alaska (NSA) ARM site. Examples of Doppler spectra from ice and mixed-phase clouds from the ARM NSA site are shown in Fig. 1. The liquid spectrum exhibits a weak spectral peak power. The ice Doppler spectrum shows a strong narrow Doppler spectra peak and the mixed-phase Doppler spectrum shows strong non-Gaussian shape and a “bump” on the left side of the primary Doppler peak indicating the presence of liquid droplet size distribution. Finally, snow spectra exhibit high spectral peak power and larger spectrum width. Although large difference are observed in the shapes of the Doppler spectra and particularly in parameters such as the skewness and the left and right slope, radar returns from hydrometeors with different phases (e.g., liquid, solid or mixed) have often overlapping distributions of the first three Doppler moments of the Doppler spectrum (radar reflectivity, mean Doppler velocity and Doppler spectrum width) and thus it is difficult to use the standard Doppler radar moments to extract information about the phase of the hydrometeors in the atmospheric volume observed by the radar.

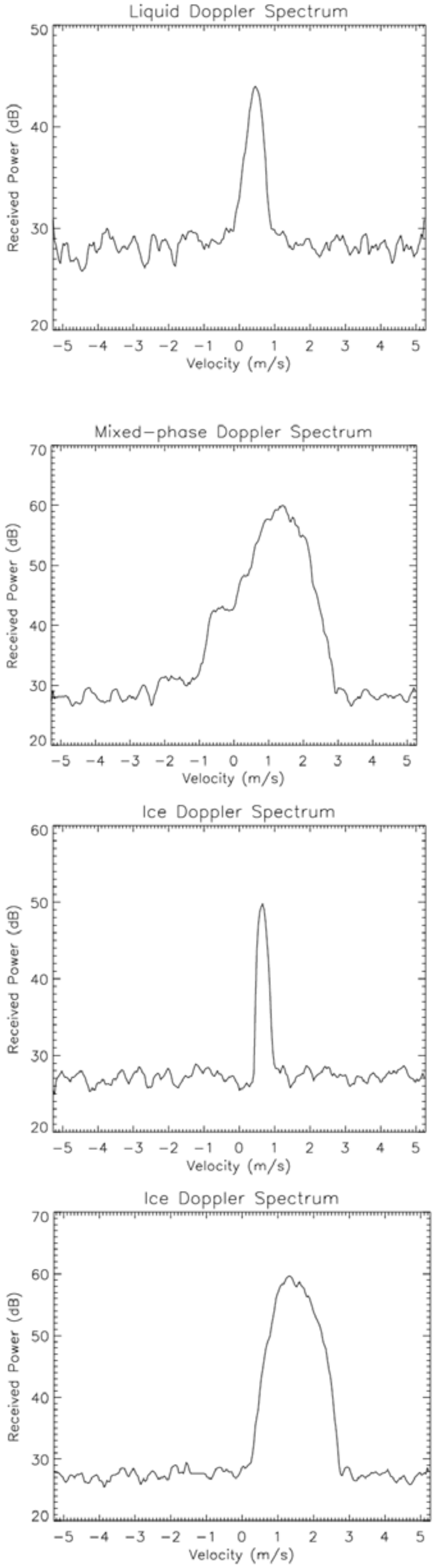
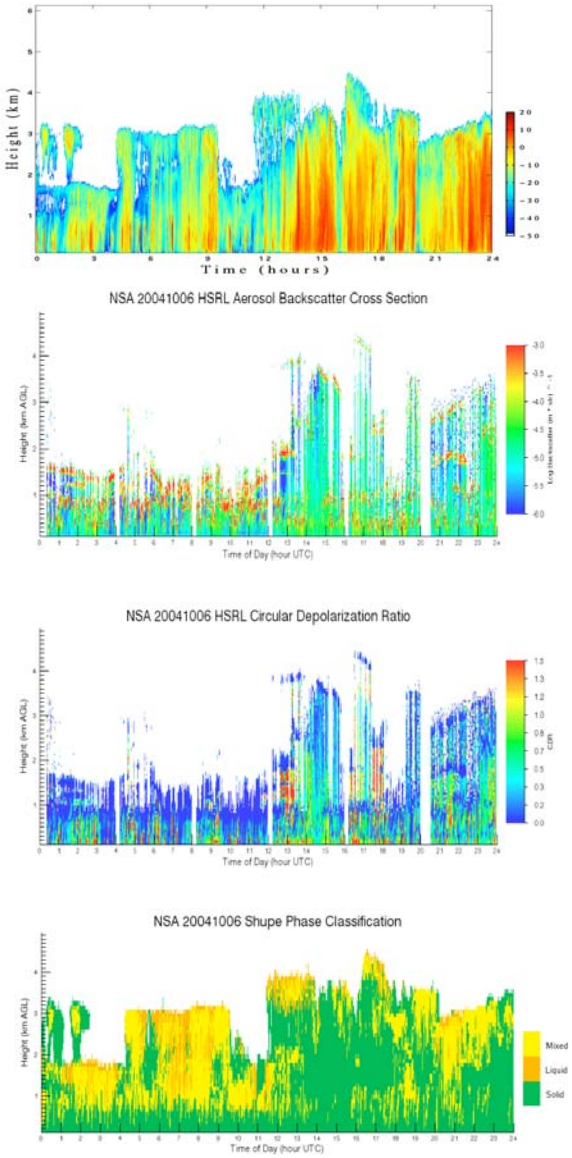


Figure 1: Examples of 256-point FFT MMCR Doppler spectra: (a) liquid particles, (b) mixed-phase particles, (c) and (d) ice particles. The Doppler spectra were collected during the Mixed-Phase Artic Clouds Experiment (MPACE).

Retrieving hydrometeor phase using remote sensors is challenging and often accomplished using a combination of measurements from cloud radar, depolarization ratio lidar, microwave radiometer and radiosondes. During MPACE, a High Spectral Resolution Lidar (HSRL) was deployed at the NSA site. This 532-nm system provides profiles of calibrated backscatter and depolarization ratio, which are both crucial for determining cloud phase, through aerosols and clouds up to an optical depth of ~4, above which the lidar beam is attenuated. HSRL measurements provide information about cloud shape and density. In particular, cloud liquid is identified by high lidar backscatter and low depolarization ratio (e.g., Sassen 1984; Intrieri et al. 2002; Shupe 2007), which indicate numerous, spherical particles. On the contrary, nonspherical ice crystals highly depolarize the lidar signal. Since the lidar beam is attenuated by optically thick (often liquid) cloud layers, only single-layer clouds are considered here. Microwave radiometer retrievals of a positive LWP (see below) also support the presence of liquid water in this case. Radiosonde profiles showing saturation from the base of the liquid cloud identified by the lidar up to the top of the cloud identified by the radar, also indicate liquid water in this layer. Radar reflectivities, which respond to the particle size to the sixth power, are dominated by cloud ice signals since ice crystals are typically much larger than liquid droplets. Fig. 2 shows examples of time-height mapping of cloud radar reflectivity, HSRL backscatter and circular depolarization ratio and our best estimate of hydrometeor phase when all measurements are incorporated in a phase retrieval algorithm. However, this instrument synergy is unique and only possible in the context of a field experiment.

4. HYDROMETEOR PHASE RETRIEVAL

Our objective is to attempt to retrieve the hydrometeor phase if only the recorded Doppler spectra are available. It is well known that when large ice-crystals are present, the difference in fall velocity between the liquid and ice particles is enough to produce bi-modal Doppler spectra. Shupe et al., (2004) developed a technique using bimodal Doppler spectra from both 35- and 94-GHz Doppler radars for the retrieval of liquid and ice water content, ice crystals effective radius and vertical air motion if presented. The Doppler spectra bimodality is induced when the liquid and ice particles fall velocities are such that they produce distinct Doppler spectra signatures.



NSA 20041006 HSRL Aerosol Backscatter Cross Section

NSA 20041006 HSRL Circular Depolarization Ratio

NSA 20041006 Shupe Phase Classification

Figure 2: Time-height mapping of: (a) MMCR reflectivity, (b) HSRL backscatter, (c) HSRL depolarization, (d) Instrument-synergy hydrometeor phase classification

However, we are interested in a more general retrieval algorithm that does not require the presence of a bimodal Doppler spectrum for the retrieval of hydrometeor phase. Detailed inspection of a large number of Doppler spectra in mixed-phase clouds lead to the conclusion (our hypothesis) that the shape of the Doppler spectrum hints information about the presence of a liquid and solid particle size distribution coexisting in the radar volume. Thus, the first step is the extraction of information about Doppler spectrum beyond the three basic Doppler moments.

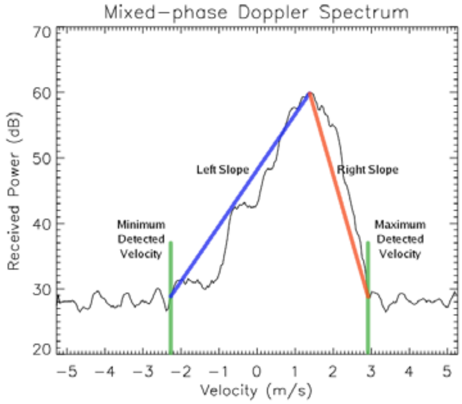


Fig. 3: Definition of Doppler spectra boundaries, left and right slope

The technique hinges on a neural network-based algorithm that extracts information from the morphology of primary Doppler spectrum peaks (gradient, curvature, and integral parameters) and uses a training dataset based on lidar depolarization measurements. Input Doppler spectra morphological parameters to the neural network include: reflectivity, spectral width, mean Doppler velocity, primary peak skewness, primary peak kurtosis, minimum detected velocity, maximum detected velocity, primary peak left slope, primary peak right slope and range gate altitude.

The phase retrieval results (liquid, ice and mixed) from two different days during the MPACE, are presented in Fig. 4. The top panel shows the retrieved hydrometeor phase using only the cloud radar Doppler spectra as input during a multi-layer cloud situation. When compared with the hydrometeor phases derived by the combination of all the remote sensors at NSA during MPACE (Fig. 2, last panel), the Doppler spectra-based technique show remarkable ability to identify the location of mixed phase conditions. The lower panel shows a single cloud layer with liquid only observed near the top, mixed-phase conditions up to the cloud base and precipitating ice particles below the cloud base. It is noticeable that the Doppler spectra-based technique is capable of detecting the level of the cloud base (transition from solid to mixed-phase conditions). The ceilometer cloud base (black line) is shown for comparison only and it was not an input to the neural network for the identification of the hydrometeor phase.

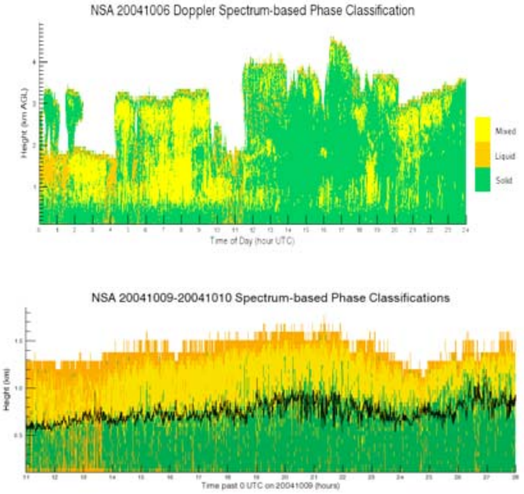


Fig. 4: Retrieved hydrometeor phase using the cloud radar Doppler spectra.

5. SUMMARY

A new retrieval technique for the identification of cloud phase that uses Doppler spectra measurements from profiling millimeter-wavelength radars, such as those operated continuously at the U.S. Department of Energy Atmospheric Radiation Measurements (ARM) program Climate Research Facilities (e.g., Ackerman and Stokes, 2003) is presented here. The new technique is based on the extraction of morphological features related to cloud particle phase from the shape of the recorded Doppler spectra. The phase retrieval results (liquid, ice and mixed) from the recent Mixed-Phase Arctic Clouds Experiment (MPACE, Harrington and Verlinde 2003) in the fall of 2004 at the North Slope of Alaska (NSA) ARM site are presented. The accuracy of cloud phase retrievals is assessed using coincident lidar depolarization and microwave-radiometer measurements. This Doppler spectra-based cloud phase retrieval technique is immune to the limitations of laser systems, exhibits great coherency in time and space and highlights the vertical distribution of cloud phase.

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