99 POLARIMETRIC THERMODYNAMIC RETRIEVALS IN THE MELTING LAYER: ONE-DIMENSIONAL SPECTRAL BIN MODEL SIMULATIONS

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1. INTRODUCTION

With its discovery soon after the adoption of radar technology for weather surveillance, the so-called radar "brightband" has long been known to be emblematic of precipitation processes within the melting layer (e.g., Cunningham 1947; Austin and Bemis 1950). The melting layer is of significant interest to meteorologists due to its impacts on quantitative precipitation estimation (QPE; e.g., Giangrande and Ryzhkov 2008), aircraft icing conditions (e.g., Oraltay and Hallett 2005), sudden transitions of surface precipitation type (e.g., Kain et al. 2000), and cooling-induced dynamical responses including gravity wave generation (e.g., Szeto et al. 1988), turbulence and convection within the melting layer (e.g., Stewart et al. 1984), and mesoscale wind perturbations (e.g., Atlas et al. 1969).

Because of its importance, many studies have sought to model the melting layer and its effects. Bulk microphysics schemes generally struggle to reproduce the observed radar brightband (e.g., Iguchi et al. 2014) due to the lack of mixed-phase hydrometeors. As such, spectral bin microphysical models with a rigorous treatment of the melting process for individual particles have often been used (e.g., Matsuo and Sasyo 1981; Klaasen 1988; Mitra et al. 1990; Grim et al. 2009). These models can be coupled with electromagnetic scattering calculations to compute the simulated radar variables and compare them to observations (e.g., Planche et al. 2014).

Radar polarimetry offers enhanced insight into microphysical processes beyond that of reflectivity (Z) alone. As such, more recent studies have attempted to model the polarimetric characteristics of the melting layer (e.g., Giangrande 2007; Trömel et al. 2014). Observational studies of the polarimetric signatures of the melting level have existed for decades (e.g., Browne and Robinson 1952; Zrnić et al. 1993), but the adoption of quasi-vertical profiles (QVPs; Ryzhkov et al. 2016) of radar data has provided high-quality timeseries of vertical profiles of polarimetric variables through the melting layer. This has revealed interesting features such as "sagging" brightbands, sudden and transitory downward excursions of the melting layer signature hypothesized to be due to riming (Kumjian et al. 2016).

The goal of this study is to develop and present a one-dimensional model of the melting layer coupled to a polarimetric operator and use it to investigate the relationship between polarimetric signatures in the melting layer and the associated diabatic cooling profile.

2. MODEL DESCRIPTION

The one-dimensional melting layer model follows previous approaches and is very similar to that used in Trömel et al. (2014). In this approach, one raindrop at the surface corresponds to one snowflake above the melting layer, which precludes the inclusion of aggregation/collision and breakup processes. The snow particle size distribution is prescribed at the top of the model domain in 80 size bins. The default distributions used stem from rain particle size distributions at the surface measured from a disdrometer in Oklahoma (Schuur et al. 2001) associated with a specific Z and extrapolated to snow based on particle flux conservation and a diameter-density relationship. These distributions at the surface for various Z values are shown in Figure 1.

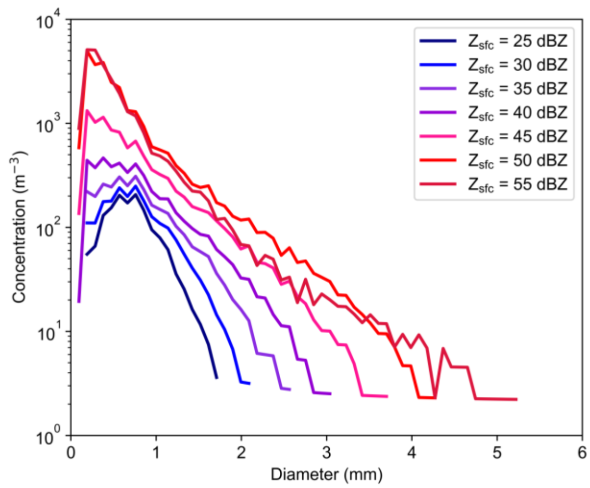

Figure 1: Surface particle size distributions used to initiate the 1-D model.

The terminal velocity of raindrops is given by the expression from Brandes et al. (2002), while the terminal velocity of snowflakes is given as a function of their fully-melted terminal velocity and their meltwater fraction (Szyrmer and Zawadzki 1999). The density of dry snow depends on the size and degree of riming following Brandes et al. (2007). The heat balance equation for the melting snowflake (Pruppacher and Klett 1978) is a function of temperature and vapor density deficits between the particle and the environment and incorporates the capacitance of the particle and ventilation effects, which are flow-dependent. The axis ratio of snowflakes was assumed to be 0.8, while the axis ratio of raindrops is given by Brandes et al. (2002). The axis ratio of melting snowflakes is linearly interpolated between the two based on meltwater fraction.

The polarimetric radar variables are calculated assuming Rayleigh scattering using the formulation of Ryzhkov et al. (2011) at S band. The scattering is calculated assuming a two-layer spheroid following Bohren and Huffman (1983), with the outer spheroid water and the inner spheroid snow calculated following Maxwell-Garnett (1904) assuming air as the matrix and ice as inclusions. Mean canting angles for both rain and snow are assumed to be 0˚, while the widths of the canting angle distributions are 10˚ and 30˚ for rain and snow, respectively, and changes linearly with meltwater fraction for melting snow.

In addition to melting, sublimation and evaporation (e.g., Rogers and Yau 1989) have been added to the model. At each height, feedbacks with the environment have been incorporated to reflect diabatic cooling and moistening as particles melt/evaporate, which subsequently impacts melting and evaporation rates. Since it is a simple one-dimensional model, no advection, mixing, or turbulence is included, which causes all of the microphysical processes to become self-limiting as the atmosphere approaches 0˚C and saturation.

3. RESULTS

The maximum *Z*, differential reflectivity (Z_{DR}), specific differential phase shift (K_{DP}), and cooling rate within the melting layer is shown for a wide range of environments in Figure 2. The model was run for each of the particle size distributions shown in Figure 1 and for a range of relative humidity profiles (values shown are for the surface, with 100% relative humidity assumed at the 0˚C level and a constant rate of decrease downward) at a constant lapse rate of 6 ˚C km^{-1}. As anticipated, the maximum cooling rate within the melting layer is a strong function of both the dryness of the environment and the precipitation intensity (flux), with the strongest cooling occurring in drier environments with heavier precipitation. In contrast, the maximum *Z*, Z_{DR}, and K_{DP} are all positively correlated with precipitation intensity and environmental humidity. These changes are fairly linear in *Z* but nonlinear for Z_{DR} and K_{DP}, with K_{DP} the most strongly affected by the relative humidity within the melting layer.

A comparison of model simulated polarimetric signatures compared to observations of a real data case is shown in Figure 3. The QVP on the left is from 10:00-12:00 UTC 20 May 2011 as the trailing stratiform region of an MCS passed over the KVNX radar site. A distinct melting layer signature is visible in all of the polarimetric variables, with enhanced *Z*, Z_{DR}, and K_{DP} that changes in time. The 1-D model environmental temperature and humidity was initialized with the 12:00 UTC sounding from the Southern Great Plains (SGP) Atmospheric Radiation Measurement (ARM) site, which was within the stratiform region at the time. The particle size distributions for the 1-D model were linearly interpolated from those shown in Figure 1 to match the observed *Z*

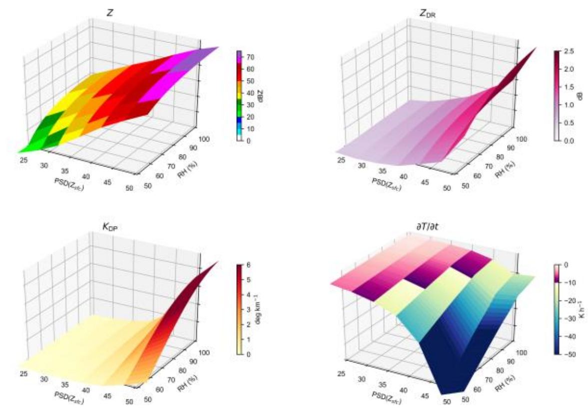

Figure 2: Parameter space of maximum (a) Z, (b) Z_{DR}, (c) K_{DP}, and (d) cooling rate in the melting layer for varying environmental (surface) relative humidity and precipitation intensity for a constant 6 ˚C km^{-1} lapse rate.

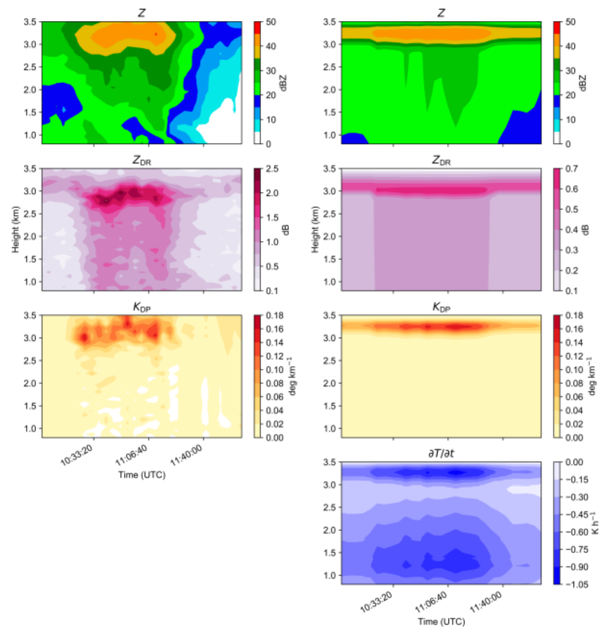

Figure 3: (Top) Z, (2nd row) Z_{DR}, and (3rd row) K_{DP} from (left) observed QVP from 20 May 2011 and (right) output from the 1-D model. The bottom right shows the corresponding cooling rate field from the 1-D model.

at the top of the 0˚C level. Because of the exclusion of processes that can keep the temperature profile and isothermal layer in a stratiform region steady-state (e.g., mixing, convective overturning, etc.), and because the sounding to initialize the model came from the end of the period, the environmental feedbacks were turned off.

The 1-D model is able to qualitatively reproduce the melting layer signature seen in the QVP. The melting layer signature is shallower than observed, and the largest disparity is in the Z_{DR} field, which is much lower than observed. However, both of these differences likely stem from the exclusion of aggregation in the model. Of note is the good replicability of the K_{DP} field, with models from the 1-D model quite close to those observed, despite the exclusion of aggregation and breakup processes. This result is encouraging and suggests the potential use of K_{DP} in the melting layer to estimate diabatic cooling.

It is well known that, absent restoring forces, melting snow creates a 0˚C isothermal layer, which should lower the height at which melting begins and subsequently the observed radar brightband signature. Sagging brightbands, which are frequently seen in QVPs, remain a mystery but have been hypothesized to be due to riming (Kumjian et al. 2016). Figure 4 shows a comparison of a sagging brightband reported in Kumjian et al. (2016) compared to the 1-D model. The 1-D model results were formed by keeping the riming fraction constant but instead varying the precipitation intensity from 25 dBZ (t = 0-30 min) to 40 dBZ (t = 50 – 130 min) and back to 25 dBZ (150 – 180 min). A similar descent in the melting layer signature by ~0.5 km is seen due to the growth of the 0˚C isothermal layer and the enhanced precipitation flux, which lowers the height of the maximum Z, Z_{DR}, and K_{DP}. More research is needed, but this result suggests there may be multiple mechanisms by which sagging brightband signatures can occur.

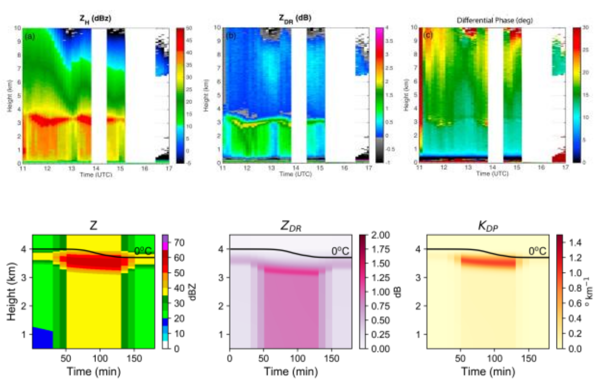

Figure 4: Comparison of (left) Z, (middle), Z_{DR}, and (right) K_{DP} in "sagging" bright bands (top) reproduced from Kumjian et al. (2016) hypothesized to be due to increased riming, and (bottom) produced in the 1-D model by varying precipitation intensity.

4. SUMMARY AND FUTURE WORK

In this study, a one-dimensional spectral bin model for the melting layer coupled to a polarimetric operator and with environmental feedbacks is presented. The model qualitatively reproduces observed polarimetric signatures as seen in QVPs and is able to qualitatively reproduce the descent of the brightband signature through cooling due to enhanced precipitation rates rather than due to riming.

With the increasingly widespread adoption of QVPs to study the melting layer, a large database of polarimetric melting layer signatures can be gathered and compared against the model for further validation. Quantitative relationships for possible use in thermodynamic retrievals should be examined between the polarimetric variables and the diabatic cooling profiles for a wide array of environmental conditions. Look-up tables may be generated for retrieving these profiles that employ all of the polarimetric variables rather than just Z alone. Further investigation of the sagging brightband and comparisons between those caused by riming and those caused by enhanced precipitation flux should be undertaken.

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