Microphysical Characteristics of Squall-Line Stratiform Precipitation and Transition Zones Simulated Using an Ice Particle Property-Evolving Model

ANDERS A. JENSEN
National Center for Atmospheric Research, Boulder, Colorado

JERRY Y. HARRINGTON
The Pennsylvania State University, University Park, Pennsylvania

HUGH MORRISON
National Center for Atmospheric Research, Boulder, Colorado

(Manuscript received 24 July 2017, in final form 22 January 2018)

ABSTRACT

A quasi-idealized 3D squall-line case is simulated using a novel bulk microphysics scheme called the Ice-Spheroids Habit Model with Aspect-ratio Evolution (ISHMAEL). In ISHMAEL, the evolution of ice particle properties (e.g., mass, shape, maximum diameter, density, and fall speed) are predicted during vapor growth, sublimation, riming, and melting, allowing ice properties to evolve from various microphysical processes without needing separate unrimed and rimed ice categories. ISHMAEL produces both a transition zone and an enhanced stratiform precipitation region, and ice particle properties are analyzed to determine the characteristics of ice that lead to the development of these squall-line features. Rimed particles advected rearward from the convective region produce the enhanced stratiform precipitation region. The transition zone results from hydrometeor sorting; the evolution of ice particle properties in the convective region leads to fall speeds that favor ice advecting rearward of the transition zone before reaching the melting level, causing a local minimum in precipitation rate and reflectivity there. Sensitivity studies show that the fall speed of ice particles largely determines the location of the enhanced stratiform precipitation region and whether or not a transition zone forms. The representation of microphysical processes, such as rime splintering and aggregation, and ice size distribution shape can impact the mean ice particle fall speeds enough to significantly impact the location of the enhanced stratiform precipitation region and the existence of the transition zone.

1. Introduction

Interest in squall-line microphysics has been motivated by the desire to determine what controls the organized, robust, and long-lived features of these systems (Rotunno et al. 1988; Houze et al. 1989; Parker and Johnson 2000) that produce a significant fraction of the warm-season precipitation in the central United States (Fritsch et al. 1986). A common organizational mode is the leading-edge, trailing-stratiform squall line [Houze et al. (1989), see their Fig. 1]. It is characterized by a convective line (or bow) often followed rearward by a transition zone of relatively low precipitation rate and radar reflectivity, and then by stratiform precipitation (sometimes called enhanced stratiform precipitation, relative to the transition zone).

This type of squall line has been studied extensively through observations (Zipser 1977; Leary and Houze 1979; Smull and Houze 1985; Houze et al. 1989; Biggerstaff and Houze 1991, 1993; Braun and Houze 1994; McFarquhar et al. 2007; Jensen et al. 2016). However, a challenge of inferring the impact of microphysics from observations is that they cannot directly reveal microphysical process rates; measurements of hydrometeor properties such as size, shape, and fall speed represent the net effects of many interacting processes (e.g., vapor growth, riming, aggregation, and melting). Microphysical models can therefore be useful as a way to augment observations since they can directly simulate the impact of microphysical processes on the structure and evolution of squall lines.

DOI: 10.1175/MWR-D-17-0215.1
© 2018 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).
Studies using microphysical models in conjunction with observations, including those from radar, sounding, surface mesonet, and wind profiler, have been used to explain the existence of the stratiform precipitation region. These studies have shown that trailing stratiform precipitation results from ice grown in the convective updraft, by vapor growth and riming, and advected rearward (Leary and Houze 1979; Smull and Houze 1985; Rutledge and Houze 1987; Braun and Houze 1994). Therefore, microphysical growth processes and the evolution of ice particles within the convective region and along their rearward trajectories are believed to be important in controlling the general structure of the stratiform region. The existence of the transition zone is also thought to depend on the sorting of ice particles advected rearward from the convective region; if ice particles that comprise the stratiform precipitation region advect far enough rearward from the convective region before reaching the melting level, a transition zone of relatively low precipitation rate and low-level radar reflectivity may occur (Biggerstaff and Houze 1993). While the stratiform region and transition zone depend on ice growth in the convective region and the properties of this ice as it is transported rearward, the intensity of the stratiform region has also been shown to depend on additional ice growth locally through vapor deposition and aggregation (Rutledge and Houze 1987; Houze et al. 1989; Braun and Houze 1994). On the other hand, it has been suggested that a low-reflectivity transition zone, which requires relatively small particles, exists because of sublimation in convective downdrafts, which keeps ice particles small and limits aggregation (Biggerstaff and Houze 1993). In general, these studies have led to significant advances in understanding the role of microphysics on squall lines, but uncertainties remain. In particular, there are questions concerning the role of microphysical versus dynamical processes in driving the occurrence of the trailing stratiform region and transition zone, especially given the inability of most models to reproduce these observed squall-line features with fidelity as noted below. This provides the basic motivation for the current study.

Overall, the studies outlined above indicate that ice particles within squall lines have a wide range of physical properties, and the evolution of these properties has an important influence on squall-line structure. However, traditional microphysics models that represent ice using only a few categories (e.g., snow, graupel, hail) with fixed property parameters (see Ferrier 1994) have a limited ability to capture the wide range of ice properties observed within squall lines. Moreover, different traditional microphysics models produce substantially different squall-line features (Van Weverberg et al. 2012; Morrison et al. 2015). For example, models produce significant spread in stratiform region characteristics including precipitation rate, areal size, and location (Morrison et al. 2009; Bryan and Morrison 2012; Van Weverberg et al. 2012; Adams-Selin et al. 2013; Wu et al. 2013; Morrison et al. 2015), and they also generally have difficulty simulating a coherent transition zone (Morrison et al. 2015). This large model spread is in part due to variations in the assumptions made about ice particle properties in different schemes. Specifically, the parameterization of fall speeds for rimed ice in the convective region (by assuming it is graupel or hail, or by representing both as separate categories) controls how far rearward it will advect before reaching the melting level (Morrison et al. 2015). Thus, assumptions made about rimed ice properties affect stratiform precipitation intensity, location, and width, as well as the cold-pool strength and system dynamics (Smull and Houze 1985; Rutledge and Houze 1987; Fovell and Ogura 1988; Bryan and Morrison 2012; Wu et al. 2013; Morrison et al. 2015).

In contrast to traditional schemes that assume a few ice categories with fixed ice property parameters, recent work has developed microphysical models that predict the evolution of ice particle properties (Chen and Lamb 1994; Hashino and Tripoli 2007; Harrington et al. 2013a; Morrison and Milbrandt 2015; Jensen and Harrington 2015; Jensen et al. 2017). These models can smoothly and physically evolve the properties of ice particles grown in the convective region and transported rearward, and they do not assume constant fall speed parameters for “rimed ice,” which contributes to the large spread of simulated squall-line characteristics using various traditional schemes (Morrison et al. 2015). In the current study we use a particle property-evolving model to investigate the microphysical processes impacting squall-line structure and evolution. The bulk microphysics model used in this study was developed by Jensen et al. (2017) and is called the Ice-Spheroids Habit Model with Aspect-ratio Evolution (ISHMAEL). In ISHMAEL, bulk ice properties such as mass, shape, maximum diameter, density, and fall speed evolve freely in time because of vapor growth, sublimation, riming, and melting. Predicting shape evolution during vapor growth and riming allows various habits to be modeled and allows the properties of those habits to evolve during riming without needing to parameterize unrimed and rimed ice using separate categories. Rime density is also predicted such that rimed ice can evolve to be graupel-like or hail-like depending upon the environmental conditions and growth history. The benefit of this model is that ice properties can evolve smoothly from nucleated to vapor grown to rimed, allowing squall-line features to be explored when ice particle properties freely evolve.
Specifically, this study explores the ice particle properties and processes that produce coherent stratiform precipitation regions and transition zones as well as the impact of aggregation on squall-line features. As will be shown, the baseline simulation of an observed squall-line case produces enhanced trailing stratiform precipitation and a low-reflectivity transition zone consistent with the observations, and therefore is used to analyze the microphysical and dynamical processes that drive these squall-line features. This baseline simulation is contrasted with microphysical sensitivity tests that do not produce a transition zone, thereby allowing us to isolate processes and properties in the model necessary for it to produce this structure. These simulations also provide a test of ISHMAEL using an observed case study that was also used previously to evaluate bulk scheme simulations.

2. The squall-line case and the simulation setup

a. The squall-line case

Midafternoon on 19 June 2007 a leading-edge, trailing-stratiform squall line was observed by the dual-polarization S-band Weather Surveillance Radar-1988 Doppler (WSR-88D) in Norman, Oklahoma (KOUN). Observations made with the KOUN radar were used to determine reflectivity (Fig. 1), precipitation rate, and raindrop distribution properties. Reflectivity was obtained from the KOUN radar (Fig. 1), while radar and disdrometer measurements were used to determine precipitation rate and raindrop distribution properties. For a detailed description of how these quantities were obtained from the observations, see Morrison et al. (2012). These observations reveal a classic squall-line structure with high reflectivity at the leading edge, a transition zone with local minima in reflectivity and precipitation rate, and enhanced reflectivity in the stratiform precipitation region (e.g., Houze et al. 1989, see their Fig. 1). This case has been used previously to study microphysical and dynamical sensitivities to squall lines (Morrison et al. 2012; Lebo and Morrison 2014; Morrison et al. 2015).

b. The simulation setup

This study uses the Advanced Research version of the Weather Research and Forecasting (WRF) Model, version 3.8.1 (Skamarock et al. 2008). The WRF Model employs fully compressible and nonhydrostatic dynamics. The time stepping uses a third-order Runge–Kutta method. Advection is monotonic and turbulence is parameterized using a 1.5-order closure. Radiation, surface flux, and boundary layer parameterizations are ignored in this quasi-idealized case to focus on the microphysical sensitivities.

The domain is 612 km × 122 km in the horizontal directions and has 100 vertical levels. The horizontal grid spacing is 1 km and the vertical grid spacing is slightly stretched with the domain top at 25 km. The domain is open in the direction of propagation of the main convective line (along-line direction) and periodic in the direction parallel to the squall line. Both the top and bottom domain boundaries are rigid with Rayleigh damping applied to the top 5 km. The model is run for 7 h using a 2.5-s time step.

Model initialization (temperature and humidity) comes from the 0000 UTC Norman, Oklahoma, sounding at pressures less than or equal to 700 hPa and from Lamont, Oklahoma, at pressures greater than 700 hPa. The Norman sounding is used at mid- and upper levels because of possible contamination in the upper-level sounding at Lamont caused by the anvil from the squall line. This sounding (their Fig. 2) is
smoothed using a 1–2–1 moving average (Morrison et al. 2015). Initial model wind shear is 0 m s$^{-1}$ parallel to the squall line and 12 m s$^{-1}$ from 0 – 5 km in the direction perpendicular to the squall line. This wind shear profile is based on data from a wind profiler located in Purcell, Oklahoma. The most unstable parcels have 5900 J kg$^{-1}$ of convective available potential energy (CAPE). Convective motion is initiated using forced horizontal convergence at the center of the domain with a maximum at the lowest model-domain level and decreasing with height for the first hour of the simulation (Morrison et al. 2015).

3. ISHMAEL microphysics

ISHMAEL, described in detail in Jensen et al. (2017), models ice particle shape using two dimensions. The two dimensions are rooted in the $a$- and $c$-axis lengths ($a_i$ and $c_i$, respectively) of hexagonal ice with the overall shape represented by an aspect ratio, $\phi_i = c_i/a_i$. Spheroids are used to approximate the general shape of atmospheric ice because the complexity of naturally occurring ice cannot be explicitly modeled. Planar and columnar single ice particles are represented as oblate ($\phi_i < 1$) and prolate ($\phi_i > 1$) spheroids, respectively. While it should be possible to represent “irregular” ice and rosettes with spheroids (Sheridan 2008), the model currently lacks parameterizations for these particles.

To track the evolution of two axis lengths during growth a mass-distribution hypothesis is used (Chen and Lamb 1994; Jensen et al. 2017), which relates changes in mass to changes in aspect ratio and effectively distributes mass over two axes, for every microphysical process in which shape evolves (vapor growth, sublimation, riming, and melting). The relationship between the axis lengths is based on an analytical power-law relationship derived from the mass-distribution hypothesis:

$$c_i = \alpha_\phi d_i^{\delta_\phi}. \hspace{1cm} (1)$$

Each microphysical process causes changes in the power-law exponent $\delta_\phi$, effectively modifying the shape of the ice particles (see Jensen et al. 2017). The prefactor $\alpha_\phi$ is determined by integrating the mass-distribution hypothesis under the assumption that ice is initially spherical (Harrington et al. 2013a). Tracking $c_i$ as a function of $a_i$ allows spheroidal mass $m_i$ to be written as a function of one axis only,

$$m_i = \frac{4}{3} \pi a_i^3 c_i = \alpha_m d_i^{\beta_m}. \hspace{1cm} (2)$$

where $\beta_m = 2 + \delta_\phi$, $\alpha_m = \rho_i (4/3) \pi \alpha_\phi$, and $\rho_i$ is the effective particle density. Mass has the form of a mass–size relation as is often used in traditional models; however, in ISHMAEL, both $\alpha_m$ and $\beta_m$ change as particle shape and density evolve. Density evolution is parameterized using a vapor depositional density that accounts for crystal branching during planar growth and hollowing during columnar growth and a rime density that accounts for air pockets among the frozen drops (Jensen et al. 2017).

Currently, three ice species are used in ISHMAEL. Two of these ice species (ice-1 and ice-2), their mass mixing ratios being $q_1$ and $q_2$, respectively are used to separately track ice nucleated at temperatures where planar and columnar ice typically grow. Two species are used so that particle shapes are not diluted through mixing. In bulk models, dilution occurs when mixing causes particle properties to become less distinct (Milbrandt and Morrison 2016). For example, mixing large hail with small ice (by advection of nucleation) will result in particles with a mean size smaller than the original size of the hail. In ISHMAEL, mixing oblate and prolate ice will cause the shape of the resulting ice to be more spherical, thereby diluting the aspect ratio. During nucleation, ice is initiated as ice-1 or ice-2 depending on temperature: nucleation produces ice-1 at planar vapor growth temperatures (e.g., $-15^\circ C$) and ice-2 at columnar vapor growth temperatures (e.g., $-7^\circ C$). After nucleation the shapes of ice-1 and ice-2 evolve based on process rates and both species can become either oblate or prolate. Aggregates are parameterized as a separate ice species ($q_3$) because aggregation causes abrupt changes to ice shape and density, whereas shape transitions during vapor growth, riming, and melting are more continuous and smooth.

In ISHMAEL, mass and number mixing ratios are predicted for all three ice species; however, to track changes in density and aspect ratio, the volume and volume times aspect ratio mixing ratios are also predicted for ice-1 and ice-2. Predicting two volume mixing ratios for ice-1 and ice-2 allows two axis lengths, and therefore shape, to evolve for these ice species. These prognostic variables are analytically linked to $\delta_\phi$, $\alpha_m$, and $\beta_m$, and allow ISHMAEL to track the evolution of shape and density. Therefore, conversion between ice categories, for example, cloud ice to snow and snow to graupel is not needed, although conversion to an aggregate species is used as described below. Mass mixing ratio and distribution-averaged shape, density, maximum dimension, and fall speed evolve naturally as a result of vapor growth, sublimation, riming, and melting. Ice particle size distributions for each species follow a gamma function, written as
where $N_I$ is the number concentration, $\Gamma$ is the gamma function, $\nu$ is the shape parameter, and $a_n$ is the characteristic $a$-axis length, which is related to the inverse of the slope parameter. ISHMAEL, like most numerical models, uses a constant shape parameter. A value of $\nu = 4$ is chosen here based on comparisons with bin microphysical model calculations (Harrington et al. 2013b; Jensen et al. 2017). Equation (2) along with other ice properties (e.g., $f_I$) are integrated over the size distribution [Eq. (3)] to calculate, for example, mass mixing ratio $q_I$ (Harrington et al. 2013a; Jensen et al. 2017), where the subscript $I$ can equal 1, 2, or 3 to denote ice-1 (subscript 1), ice-2 (subscript 2), or aggregates (subscript 3). Other bulk properties include mass-weighted terminal fall speed $v_I$, mass-weighted maximum diameter $D_I$ (which is double the larger of the mass-weighted axis lengths), volume-weighted density $\rho_I$, and number-weighted aspect ratio $f_I$. Aggregates are parameterized as oblate spheroids using a constant density and aspect ratio of $\rho_3 = 50$ kg m$^{-3}$ and $f_3 = 0.2$ (Jensen et al. 2017). Aggregation, which is described in Jensen et al. (2017), is summarized here because sensitivities to aggregation rate are explored. In ISHMAEL, aggregation efficiencies $E_{II}$ depend on temperature, ice density, and ice shape. The dependence of $E_{II}$ on density and shape is parameterized by multiplying $E_{II}$ by two corrective factors, $f_o$ and $f_s$, respectively, which both vary from 0 to 1. These corrective factors ensure that high density, isometric ice particle (i.e., graupel-like and hail-like ice) do not produce abundant aggregates. Self- and cross-collection are parameterized following Jensen et al. (2017). Aggregation is a mass and number mixing ratio source for $q_3$ and $n_3$, respectively, when self- or cross-collection of ice-1 and ice-2 occurs. Aggregates can also grow by vapor deposition and riming. Aggregation causes a decrease in number mixing ratio $n_3$, only when self-collection of aggregates occurs.

### 4. Squall-line simulation using ISHMAEL microphysics

#### a. Baseline simulation overview and comparison with observations

The baseline simulation using ISHMAEL microphysics produces a mature leading-edge convection, trailing-stratiform squall line, apparent in the reflectivity field (Fig. 2) and line-averaged precipitation rate (Fig. 4a). The line-averaged precipitation rate from the baseline simulation is used to define the squall-line regions in this study. The convective region encompasses the maximum in the system line-averaged precipitation rate and extends from $x = 0$ to $x = -40$ km. The transition zone encompasses a local minimum in line-averaged precipitation rate rearward of the convective region and extends from $x = -40$ to $x = -47$ km. The enhanced stratiform precipitation region encompasses a local maximum in the line-averaged precipitation rate rearward of the transition zone and extends from $x = -47$ to $x = -200$ km.

The line-averaged, system-relative $u$ and $w$ winds plotted at 6 h (Fig. 3) show the general system dynamics. Line-averaged values are calculated with respect to the $\theta < -2$ K lowest model-domain value. This perturbation temperature is assumed to be the leading edge of the cold pool. Air parcels lifted along the cold pool form an upshear-tilted convective updraft (Fig. 3, darker red shaded region). The dominant dynamical features of this
simulated squall line are consistent with the conceptual model of Houze et al. (1989). Both a mesoscale updraft (Fig. 3, lighter red shaded region at \( x = -100 \text{ km} \)) and downdraft (Fig. 3, blue shaded region at \( x = -150 \text{ km} \)) reside rearward (with respect to the system-relative front-to-rear flow at midlevels) of the cold pool. A rear inflow jet develops (Fig. 3, blue arrow) because of the buoyancy gradient between the cold pool and higher-level warming from hydrometer growth as well as the convective heating in a sheared environment (Fovell 2002). Typical squall-line cloud features including a shelf cloud and rear and forward anvils can also be seen. Quasi-idealized simulations (such as this one) are necessarily limited because feedbacks with the larger mesoscale environment are not possible, and for example, the impact of vertical vorticity [bookend vorticities, see Markowski and Richardson (2010), p. 261] on the simulated squall-line structure is unknown. Nevertheless, model output is compared to observations, and the system is analyzed as if it were strictly linear.

The reflectivity field at \( z = 1.1 \text{ km} \) and at 6 h from the simulated storm includes a region of convective reflectivity as high as 55 dBZ, a transition zone (TZ) where reflectivity drops to 30–35 dBZ, and an enhanced stratiform precipitation region (ESPR) with reflectivity of 35–45 dBZ (Fig. 2a). Reflectivity values are diagnosed based on hydrometeor properties and are not directly simulated. These features are quasi steady and do not depend on the chosen simulation time. These features match the retrieved reflectivity field (Fig. 1), although the TZ in the simulated squall line is narrower than the retrieved one. The width of the line-averaged ESPR reflectivity (>35 dBZ) at the surface is approximately 50 km for both the simulated and retrieved fields. In ISHMAEL, melted ice size distributions (with \( v = 4 \)) have a different shape than rain size distributions (with \( v = 1 \)), and if this change in size distribution shape were unphysical it would produce a high bias in reflectivity values (Ferrier 1994). We assume that the microphysical processes that produce and act on rain (e.g., collection, breakup, autoconversion, melting, and shedding) generally cause the size distributions of rain to become inverse exponential, which provides a physical basis the change in distribution shape during melting.

The simulated line-averaged reflectivity field has a high bias of 10 dBZ in the TZ above \( z = 6 \text{ km} \) (Fig. 2b) and a low bias of 10 dBZ in the convective region from \( z = 5.5 - 8 \text{ km} \). The high bias in the TZ is likely from ice particles being too large on average as they advect rearward from the convective region. The low bias in the convective region is due to the way in which ice initiation occurs: ice initiation in ISHMAEL depends on temperature and not size. A simulation (not shown) where ice initiation is based on size (i.e., frozen cloud droplets are nucleated to ice-1 and frozen raindrops are nucleated to ice-2) produces reflectivity values of 30–35 dBZ up to \( z = 10 \text{ km} \), but this simulation also produces an ESPR that is too narrow and too intense. When ice is sorted based on size at nucleation ice-2 sizes are larger and ice-1 sizes are smaller compared to CTRL. Initiating ice based on temperature works to moderate mean ice sizes compared to initiating ice based on size. Even though initiating ice based on temperature leads to a weak convective region on average compared to the observations, the method can capture relatively deep and strong convective regions along certain cross sections of the system (see Fig. 4a, red solid line and Fig. 8a).

Compared with the line-averaged radar-retrieved precipitation rate, the simulation underestimates the intensity of the ESPR at its rear, from 100 to 150 km behind the leading edge (Fig. 4a, gray and blue lines). The model underpredicts precipitation rate, which coincides with reflectivity values that are smaller than observed, which is also seen in all of the bulk simulations of Morrison et al. (2015). ISHMAEL also underestimates the breadth and magnitude of the convective precipitation region on average (Fig. 4a). The simulation does capture the general spatial distribution of precipitation rate that includes a local minimum in the TZ and enhanced stratiform precipitation.
with a maximum of 7 mm h\(^{-1}\). ISHMAEL overestimates the median volume diameter for rain \(D_0\) at \(z = 0.57\) km in the TZ and at the spatial location of the simulated maximum enhanced stratiform precipitation rate (Fig. 4b, gray and blue lines). Similar to the spatial precipitation rate, ISHMAEL captures the trend of decreasing \(D_0\) going rearward in the stratiform region, even though the precipitation rate is underestimated.

The simulated reflectivity field produces a region where the transition-zone reflectivity drops to 20–25 dBZ, in better agreement with observations. Through this region referred to as a low-reflectivity transition zone (LRTZ) (Fig. 2a, solid red line) \(D_0\) decreases rapidly as seen in the radar-derived values of \(D_0\) (Fig. 4b, solid red line through the light gray shaded region). Along a cross section where the simulated transition-zone reflectivity is 35–40 dBZ (Fig. 2a, dashed red line), referred to as a high-reflectivity transition zone (HRTZ), the TZ is still apparent in the precipitation rate (Fig. 4a, dashed red line), although \(D_0\) is larger in the TZ (Fig. 4b, dashed red line). Both cross sections have convective precipitation rates that are larger than the line-averaged value.

b. Microphysical controls of the simulated squall-line features

The squall-line simulation using ISHMAEL microphysics produces both a transition zone and an enhanced stratiform precipitation region, which is noteworthy because other microphysics schemes have trouble simulating at least one of these features for this case (Morrison et al. 2015, see their Figs. 4 and 5). Both the TZ and the ESPR are maintained in the simulation once the squall line becomes mature (Fig. 5). Here we explore the microphysical processes and the ice properties that lead to the development of these simulated regions, and we compare how ISHMAEL produces these regions to previous modeling studies, retrievals, observations, and theories. The predicted physical ice properties
(Fig. 6) along with time- \( (6 - 7 \text{ h}) \) and line-averaged microphysical process rates (Fig. 7) are used to help reveal the dominant microphysical controls on squall-line features simulated by ISHMAEL.

A vertical cross section through the simulated squall line (Fig. 2a, black line) reveals the bulk properties of ice within the system. Ice-1 (Figs. 6a,d,g) is dominated by homogeneous nucleation at upper levels that produces relatively small \( (D_1 < 0.5 \text{ mm}, \text{ Fig. } 6g) \), high density \( (\rho_1 > 500 \text{ kg m}^{-3}, \text{ Fig. } 6d) \), and numerous \( (N_1 > 100 \text{ L}^{-1}, \text{ Fig. } 6d) \) ice particles. This ice has the properties of what would traditionally be cloud ice, and this ice comprises both the front and rear anvils. In the convective region \( (x = 330 \text{ km}) \), ice-1 has hail-like properties characterized by relatively large maximum diameters \( (D_1 > 1 \text{ mm above the melting level and } D_1 > 5 \text{ mm near the surface}) \), densities \( \rho_1 > 800 \text{ kg m}^{-3} \), and fall speeds \( \nu_f > 2 \text{ m s}^{-1} \). This small hail-like ice is produced because rain frozen at temperatures between \( 0^\circ \text{C} \) and \( -5^\circ \text{C} \) is initiated as ice-1.

Ice-2, into which ice is initiated at temperatures between \( -5^\circ \text{C} \) and \( -9^\circ \text{C} \), has a maximum in mass mixing ratio of \( q_2 = 2 - 5 \text{ g kg}^{-1} \) centered near \( z = 10 \text{ km} \) (Fig. 6b). The mass-weighted maximum diameters for this ice are \( D_2 = 1 - 2 \text{ mm} \) (Fig. 6h), mass-weighted fall speeds are \( >2 \text{ m s}^{-1} \) (Fig. 6h), volume-weighted densities are \( 200 - 300 \text{ kg m}^{-3} \) (Fig. 6e), and number-weighted aspect ratios are nearly isometric \( (0.8 < f_2 < 1.25, \text{ not shown}) \). Thus, the properties of this ice have evolved to become distinctly graupel-like.

The mass mixing ratio of aggregates (Fig. 6c) is the smallest of all ice species \( (q_3 < 0.5 \text{ g kg}^{-1}) \), with maximum diameters becoming as large as \( 5 \text{ mm} \) (Fig. 6i). Aggregation efficiencies remain small in this simulation because the shapes of ice-1 and ice-2 are mostly isometric throughout the domain. The properties of ice-1 and ice-2 in this simulation are significantly influenced by riming in the convective updraft, homogeneous ice nucleation, and the freezing of raindrops. These processes produce isometric ice, and because aggregation
rates in ISHMAEL depend on shape, aggregation is suppressed. The maximum in aggregate mass mixing ratio is rearward of the mesoscale updraft, where convergence of the rear-inflow jet and the system-relative front-to-rear flow occurs. At this location, self-collection of aggregates causes $D_3$ to increase. Negligible precipitation is produced by melted aggregates in this simulation, because of the low values of $q_3$, though aggregates in this simulation contribute to enhanced radar reflectivity.

The complete microphysical picture of the simulated squall line is shown in Fig. 7a: significant riming occurs in the updraft above the melting level, a region of sublimation exists rearward of the convective updrafts, vapor growth dominates the mesoscale updraft region, and sublimation again occurs along the rear-inflow jet. The maximum in total ice mass mixing ratio occurs near $z = 10$ km in the convective updraft region, extending rearward toward the ESPR.

1) CONVECTIVE PRECIPITATION

While this paper focuses on the enhanced stratiform precipitation region and the transition zone, we first describe the controls of the simulated convective precipitation region because ice produced in the convective region influences both the ESPR and the TZ. Vertically integrating the microphysical process rates (process rates have units of kg kg$^{-1}$ s$^{-1}$), where the results are converted to units of mm h$^{-1}$, reveals that on average in the convective region ($x = 0$ to $-40$ km) more total growth (vapor growth plus riming, Fig. 7c, black and...
magenta lines) occurs than melting (Fig. 7b, blue lines). This means that there is a net flux of vapor-grown and rimed ice out of the convective region. Small hail-like ice (mostly ice-1) melts in the convective region (before reaching the surface), adding a total of about 7 mm h\(^{-1}\) of precipitation at \(x = -25\) km (Fig. 7b, blue lines). Note that along the LRTZ cross section, where precipitation rates better match observations, a wider and more pronounced hail shaft (ice-1) extends toward the surface, and vertically integrated ice-1 melting rates (not shown) are significantly larger than the line-averaged maximum in the convective region. Thus, the line-averaged convective precipitation rate low bias is likely from ISHMAEL producing spottier small hail-like ice compared to observations, though we note that several other bulk microphysics scheme show a similar result including schemes that parameterize rime density and hail (Morrison et al. 2015).

2) THE TRANSITION ZONE

The existence of the transition zone has been proposed to occur from both hydrometeor sorting, where the trajectories of ice particles lead to a local minimum in precipitation rate in the transition zone, and from sublimation in convective downdrafts (Biggerstaff and Houze 1993), where sublimation reduces the downward vertical ice flux in the transition zone. Lack of aggregation in the transition zone has also been proposed as a reason for the reduced reflectivity values there (Biggerstaff and Houze 1993). The TZ in the simulated storm is apparent as a local minimum in the line-averaged reflectivity field between the convective region and the ESPR (Fig. 2b, dashed gray lines), collocated with a local minimum in line-averaged precipitation rate (Figs. 4a and 5).

As already shown, aggregate mass mixing ratios are small in the baseline simulation, and the TZ still exists when aggregation is turned off (not shown). Thus, the baseline simulation results are not in agreement with the hypothesis that significant aggregation causes the ESPR and lack of aggregation causes the TZ, at least for this squall-line case. Sensitivities to increases in aggregation rate will be shown later. The TZ as simulated by ISHMAEL occurs where there is a local minimum in total line-averaged melting rate (Fig. 7b, blue lines), a region of net line-averaged sublimation (Fig. 7c, black lines), and a local minimum in rain evaporation rate (Fig. 7b, thin gray line). This region is located between where the ice-1 melting rate increases going forward toward the convective region and the ice-2 melting rate increases going rearward toward the ESPR. The region of average sublimation is broader than the TZ itself, but it peaks around the location of the minimum in surface precipitation. Sublimation occurs on average in the TZ, and less ice is melted and less rain is evaporated in the TZ compared to the surrounding regions.

In addition to hydrometeor sorting, there is evidence that the dynamical structure is important for the TZ characteristics. Along the LRTZ cross section, convective reflectivity values are higher (Fig. 8a) and the strongest region of the convective updraft (Fig. 8a, thick black contour) is vertically deeper than along the HRTZ cross section (Fig. 8b). Reflectivity values above \(z = 7\) km in the TZ are also smaller along the LRTZ cross section than along both the HRTZ cross section and the system line average (Fig. 2b) in better agreement with the observations. Deeper updrafts along the LRTZ cross section may lead to a more realistic representation of ice particles sizes advected rearward from the convective region through the TZ compared to the system line average, possibly from deeper updrafts producing more homogeneously frozen cloud droplets, reducing the mean size of ice advected rearward.
Along the HRTZ cross section, a second, weaker convective updraft exists behind the leading edge, and overall, a more disorganized updraft structure is apparent. The HRTZ is associated with more up- and downdraft couplets, which are reflected by the vertically integrated vapor growth and sublimation rates, which have a higher amplitude and frequency of variability than along the LRTZ cross section (Fig. 9b). The less organized updraft structure is associated with larger ice-1 and ice-2 melting rates in the TZ (Fig. 9a, blue lines). Variations in updraft strength, width, and spatial location impact both the height and the properties of ice-2 advected out of the convective region, causing a spatial shift in where precipitation from ice-2 reaches the surface. The HRTZ is caused by a merger of the stratiform region, which shifts forward, and the convective region, which widens and shifts rearward (Fig. 9a). This result suggests that coherent convective organization is crucial for TZ formation: both the horizontal and vertical spatial locations where ice is exported out of the convective region and the properties of that ice determine the spatial location where ice melts (or reaches the surface) and therefore the strength of the TZ. Note that the LRTZ retains its approximate spatial locations along the y direction for about an hour of simulation time, which also suggests that coherent convective updrafts are important for maintaining an LRTZ.

3) THE ENHANCED STRATIFORM PRECIPITATION REGION

The maximum in enhanced stratiform region precipitation rate at \( z = 1.1 \) km (Fig. 7b, thick gray line) coincides with the maximum in ice-2 melting rate (Fig. 7b, dashed blue line). Ice-2 grows preferentially by riming in the convective updraft (Fig. 7c, dashed magenta line) and sublimates (Fig. 7c, dashed black line) as it advects rearward. As this ice melts around \( z = 4 \) km it continues to advect rearward (Fig. 3) until it falls into the cold pool, at which point it advects forward in the low-level rear-to-front flow. This rain, the source of which is ice-2, composes the enhanced stratiform precipitation region. The spatial location of the ESPR in the baseline simulation is determined by ice fall speeds that depend on the mean size and density of ice produced in the convective updraft where riming is the dominant growth process.

The formation mechanism of the ESPR in our simulation aligns with the hypothesis of Smull and Houze (1985): ice originating from the convective region (at \( z \approx 10 \) km) and falling between 1 and \( 4 \) m s\(^{-1}\) explains the width of the ESPR. Without vapor growth in the mesoscale ascent, the spatial extent of the ESPR would be less in this particular case, but the ESPR would still exist as a result of ice-2 advection out of the convective updraft. The partitioning of ice-1 and ice-2 out of the convective updraft is nearly even: 51% of the flux of ice into the stratiform region above the surface is ice-2. Consistent with the properties of ice-2 being graupel-like, only 2% of this ice source comes from vapor growth. A majority of this ice precipitates out forward of the mesoscale updraft. On average, 62% of the stratiform surface precipitation rate results from melting ice-2.

In contrast, 40% of ice-1 comes from vapor growth in the mesoscale updraft. This growth leads to the broad region of \( 2 - 3 \) g kg\(^{-1}\) of ice in the mesoscale updraft region (Fig. 7a, solid black contoured region labeled “vapor growth”) as well as the maximum in ice-1 melting rate centered at \( x = -150 \) km (Fig. 7b, solid blue line).
While ice-1 produces a significant source of rain at the rear of the system, this rain evaporates (Fig. 7b, thin gray line) in the relatively dry and descending rear-inflow jet. The vapor growth of ice-1 in the mesoscale updraft produces approximately 2 mm h\(^{-1}\) of surface precipitation from 100 to 150 km behind the leading edge (Fig. 7c, solid black line). Averaging where total ice mixing ratio aloft is greater than 0.001 g kg\(^{-1}\), the domain average of ice rearward of the convective region is 0.76 g kg\(^{-1}\), with 85% being ice-1, most of the rest being ice-2, and 1% being aggregates. Clearly, ice-2 evolves to be mostly precipitating ice, and ice-1 evolves to form the cloud ice and a majority of the stratiform anvil. Averaging from 6 to 7 h, the horizontal flux of ice out of the transition zone (rearward of x = −48 km) accounts for the majority of the mass (66%) in the stratiform region above the surface. Vapor growth of ice accounts for a smaller portion of the stratiform mass (26%) with the remainder being caused by riming of ice within the stratiform region near x = −48 km. This mass budget is in line with the analysis of Gamache and Houze (1983) who used radar, rawinsonde, aircraft data, and satellite imagery to determine that 60%–75% of the stratiform cloud in a tropical MCS [observed during the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE)] was advected from convective towers and 25%–40% of the stratiform cloud was produced in the stratiform region by the mesoscale updraft. While the GATE case occurred in the tropics as opposed to the midlatitudes, the systems observed during GATE were dynamically (or perhaps “structurally”) similar to the case simulated here. Leary and Houze (1979) determined that graupel was likely the producer of stratiform precipitation in GATE cases, which aligns with our results. They hypothesized that riming occurs in situ in the mesoscale region, although our results indicate that graupel-like ice advects from the convective region.

5. Sensitivities of the enhanced stratiform precipitation region and transition zone

The baseline simulation (CTRL) results support the hypothesis that the properties of the ice (i.e., size, mass, density, and fall speed) advected out of the convective region exert a dominant control on features of the enhanced stratiform precipitation region and transition zone. Here we explore the sensitivities of these regions to changes in the ice properties and ice process rates in ISHMAEL as outlined in Table 1. Some sensitivity study results are discussed here, while others are explained in detail in the following subsections.

For the first sensitivity simulation we turn off rime splintering (RS-OFF). We do this because the location of the ESPR in the baseline simulation coincides with a relatively large production rate of rain from melting of ice-2, and a large source of ice-2 is rime splinters produced near −7°C in the convective updraft. The addition of numerous small ice splinters into the ice-2 distribution causes the mean size and fall speed to decrease. This sensitivity highlights the relative importance of secondary ice production on the reflectivity and precipitation properties of the TZ and ESPR.

For the second sensitivity test (\(\nu^1\)) inverse-exponential distributions are used for all ice species. Bulk microphysics models must make assumptions about the ice-size distribution shape, which is determined by the shape parameter \(\nu\) for the three-parameter gamma function used here. Many microphysics schemes employ inverse-exponential distributions (\(\nu = 1\)) for precipitating ice in agreement with some observations (Marshall and Palmer 1948). For example, aggregation often causes the distribution shape to become inverse-exponential over time (Westbrook et al. 2004). Although observations of ice distributions that fit a gamma distribution with \(\nu = 4\) exist, they are generally for distributions with relatively smaller observed mass-weighted sizes (Heymsfield 2003). The choice of \(\nu\) impacts microphysical process rates and size sorting, a process by which the mass-weighted fall speed of ice is larger than the number-weighted fall speed allowing larger ice to sediment out faster than smaller ice, which increases with decreasing \(\nu\) (Milbrandt and Yau 2005a).

The third sensitivity simulation explores the role of aggregation on squall-line features. The potential role of aggregation in squall-line evolution has been hypothesized based on both retrievals and in situ observations (Churchill and Houze 1984; Biggerstaff and Houze 1993; Fridlind et al. 2017). For example, lack of aggregation has

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Abbreviation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline simulation</td>
<td>CTRL</td>
<td>Two free ice species (ice-1 and ice-2) and aggregates</td>
</tr>
<tr>
<td>Rime splintering off</td>
<td>RS-OFF</td>
<td>CTRL simulation with rime splintering off</td>
</tr>
<tr>
<td>Inverse exponential</td>
<td>(\nu^1)</td>
<td>CTRL simulation with (\nu = 1) for all ice species</td>
</tr>
<tr>
<td>Increased aggregates</td>
<td>AGG</td>
<td>CTRL simulation with increased aggregation rates by setting (f_a = 1)</td>
</tr>
<tr>
<td>One free ice species</td>
<td>1SP</td>
<td>One free ice species (ice-1) and aggregates</td>
</tr>
<tr>
<td>1SP increased aggregates</td>
<td>1SP-AGG</td>
<td>1SP simulation with increased aggregation rates by setting (f_a = 1)</td>
</tr>
</tbody>
</table>
been hypothesized to cause the TZ (Biggerstaff and Houze 1993). Aggregates have also been hypothesized to be important for the production of enhanced stratiform precipitation (Churchill and Houze 1984; Braun and Houze 1994). Because of the weak influence of aggregates on the baseline simulation, in this sensitivity (AGG) aggregation rates are increased by assuming that they do not depend on shape (setting $f_s = 1$).

A fourth sensitivity simulation (not shown, but discussed) sets the vapor-growth density to $900 \text{ kg m}^{-3}$ for $D_I < 0.1 \text{ mm}$ and otherwise to $100 \text{ kg m}^{-3}$, similar to what is done in some bulk models using cloud ice and snow categories with different densities. This is done because ice in CTRL evolves to become mainly isometric and thus, the density evolution should have some control over the squall-line evolution. This simulation produces a squall line with a similar precipitation rate and reflectivity to CTRL, but with the evolution of these quantities delayed by about one hour. The time the squall line takes to become mature depends on the chosen vapor-growth density (confirmed by using a few different assumed vapor-growth densities); ice precipitates more slowly with a lower density causing the cold pool to develop more slowly. Predicting ice habit evolution (through both predicted shape evolution and vapor-growth density) and rime density produce the variability in ice properties, particularly density, that allow the model to simulate squall-line features without the sensitivities that arise from choosing unrimed and rimed ice densities and habit types.

A fifth sensitivity simulation (1SP) uses one free ice species such that all ice is initiated to the same species (ice-1) and is briefly summarized here. Simulating the squall line using one free ice species is done to determine the impact of separating ice at the nucleation stage into one versus two free ice species. Using one free ice species will inevitably cause particle property dilution (Milbrandt and Morrison 2016), as mixing columnar and planar ice, for instance, will cause the ice to become more isometric. Since the ESPR and TZ depend on the properties of ice, in principle the characteristics of these features can change depending on the number of ice species used.

In 1SP, the larger upper-level rimed ice is mixed with the smaller homogeneously nucleated ice in the convective updraft. The mean size, density, and fall speed of this ice as it advects rearward from the convective region are approximately a mass-weighted average of those of ice-1 and ice-2 in CTRL; therefore, the spatial location of the maximum in stratiform-region melting rate in 1SP (Fig. 10, dashed blue line at $x = -130 \text{ km}$) falls between the locations of maximum ice-1 melting rate ($x = -150 \text{ km}$) and maximum ice-2 melting rate ($x = -75 \text{ km}$) in CTRL. Using one ice species produces a TZ with a lower average reflectivity (Fig. 10, dashed black line), though the ESPR is narrower and the maximum in ESPR reflectivity is less. The ability of this simulation to capture all three squall-line regions implies that separating ice species may not be necessary in this squall-line case. Both ice species evolve to become quasi spherical in this case, and therefore, the evolution of size and density and the impact of those properties on fall speed seem to be the important ice properties to capture, which can be done using one ice species. In fact, one ice species alone can predict unrimed ice, partially rimed ice, and graupel particles with a variety of densities and fall speeds (Jensen et al. 2017). This result may not apply more generally to all cases, however.

Finally, the cloud droplet number concentration is increased (from $N_C = 200 \text{ cm}^{-3}$ in CTRL) to $600 \text{ cm}^{-3}$ which causes a decrease in cloud droplet mean size (for the same liquid water content) and a reduction in both riming and warm-rain autoconversion rates. This results in a maximum in convective precipitation rate that is approximately $5 \text{ mm h}^{-1}$ less than in CTRL (not shown). A simulation using a constant cloud droplet number mixing ratio ($n_C = 200 \times 10^6 \text{ kg}^{-1}$) causes an increase in cloud droplet mean size compared to CTRL at mid- and upper levels. This produces more rain aloft ($z = 6 \text{ km}$) in the TZ, from warm-rain autoconversion, widening the convective region and narrowing the TZ (not shown).

### a. Rime splintering off simulation

When rime splintering is turned off in ISHMAEL, large numbers of small splinters are not initiated into
ice-2 causing ice-2 number concentrations to decrease. This coincides with an increase in average particle size and fall speed. Thus, the ESPR merges with the convective region, as seen by the shift in the spatial location of the ice-2 melting rates (Fig. 11c), which completely fills in the TZ in both the reflectivity field (Fig. 11a) and surface precipitation rate (Fig. 11c, dashed gray line). The spatial location of the maximum value of ice-2 melting rate shifts approximately 25 km forward in the RS-OFF simulation compared to in CTRL. This sensitivity to rime splintering suggests that ice multiplication is an important process that can impact the properties of ice advected rearward from the convective region. Adding numerous ice splinters, the rate of which is parameterized using data from Hallett and Mossop (1974), to ice-2 (which has graupel-like properties) will cause some dilution of the splinter properties. However, we argue that it is reasonable to expect the mix of particles to behave in a physical manner. Splinters produced in the vapor-rich environment of a convective updraft would grow rapidly to sizes where riming can begin, at a particle maximum diameter of 70 \( \mu \text{m} \) (Wang and Ji 2000), and could also freeze supercooled lofted raindrops, a process that has been attributed to increased graupel number concentrations (Lasher-Trapp et al. 2016). Thus, the reduction of ice-2 mean size that occurs from the addition of rime splinters may be partially offset by the rapid growth of those splinters, and the expected increase in graupel concentrations is captured by the model. In nature, larger graupel number concentrations also imply a greater riming rate for a given water content and hence reduced water content, which would lead to a smaller mean graupel size. The reduction in ice-2 mean size associated with increased number concentration in ISHMAEL may capture the production of relatively larger concentrations of smaller graupel through rime splintering and allow for better representation of the ice particles that eventually produce stratiform precipitation. In weaker updrafts, rime splintering would produce particles that could grow predominately by vapor deposition (e.g., needles and columns) and those particle properties would become diluted if mixed with graupel-like particles in ISHMAEL.

b. Inverse-exponential size distributions

Employing inverse-exponential size distributions for all ice species leads to the loss of the transition zone in
the reflectivity field, but a local minimum still remains in the precipitation rate (Figs. 11b,d). A large region of high reflectivity (>35 dBZ) extends from the leading edge rearward as ice-2 in the $n=4$ simulation sediments faster than with $n=5$, thereby merging the convective line and the stratiform region. Thus, the existence of the simulated TZ depends critically on the assumed shape of the ice size spectrum, which determines particle properties such as mass-weighted fall speeds as well as bulk growth rates. The dependence of cloud evolution on distribution shape was noted in previous studies (e.g., Milbrandt and Yau 2005b); the impacts of assumed shape on process rates can be substantial even for layered cloud systems (Ovchinnikov et al. 2014). Because $n=1$ causes the TZ to disappear (for reflectivity), it is possible that in real systems the collection processes that drive $\nu \rightarrow 1$ occur minimally in the TZ for ice that will eventually become stratiform precipitation, as suggested by Biggerstaff and Houze (1991). Another possibility is that excessive size sorting is occurring in the TZ in the $n=1$ simulation (Milbrandt and Yau 2005a, 2006), which could be controlled numerically (Milbrandt and McTaggart-Cowan 2010). Note that turning off size sorting by setting the number-weighted fall speed to equal the mass-weighted fall speed (corresponding to a mono-disperse size distribution) reduces the maximum in enhanced stratiform precipitation by $1 - 2$ mm h$^{-1}$ and eliminates the ESPR in the line-averaged reflectivity field (not shown). Thus, some size sorting is needed to produce the ESPR.

**MICROPHYSICAL DIFFERENCES BETWEEN SIMULATIONS WITH AND WITHOUT TRANSITION ZONES**

While CTRL produces a TZ in both the reflectivity field and precipitation rate, the TZ vanishes in the reflectivity field in the $n=1$ simulation and in both the reflectivity field and precipitation rate in the RS-OFF simulation. Here we explore the microphysical differences between these simulations.

As shown in Fig. 12a, the height of the maximum rearward total ($q_1 + q_2 + q_3$) ice flux from the convective region is similar for all three simulations. The CTRL simulation produces the largest rearward flux of ice out of the convective updraft (near $z=8$ km) and at this height ice-2 mass-weighted fall speed and maximum diameter are the smallest of the three simulations (Figs. 12b,c, solid black lines). The mass-weighted fall speeds of ice-2 in CTRL, at the location of the maximum ice-2 flux out of the convective updraft ($z=7$ km), span the range given by Smull and Houze (1985) to produce an ESPR (1-4 ms$^{-1}$), whereas the same analysis of RS-OFF and $n=1$ reveal that ice-2 mass-weighted fall speeds are larger than this range. When rime splintering is turned off, more ice mass remains in ice-1 leading to a larger flux of ice into the forward anvil and less ice-2 mass overall (Fig. 12a, opaque red line). This leads to significantly less ice-2 mass flux out of the convective region, but that ice is larger with a greater fall speed (Figs. 12b,c) and therefore the height of maximum rearward ice-2 flux ($z=6$ km) is lower than in CTRL. The $n=1$ simulation produces a slightly weaker convective region and less convective ice mass compared to the CTRL simulation.
simulation, likely a result of both the impact of $\nu$ on growth rates, which affects the vertical location of ice mass and hence water loading and buoyancy.

Frequency plots of vertical velocity $w$ in the TZ region ($x = -41$ to $-47$ km for every $y$ cross section and produced from both $z = 4 - 6$ and $z = 6 - 10$ km) reveal dynamic similarities among the three simulations in both vertical regions (Fig. 13b). Ice-2 in the CTRL simulation has, on average, smaller sizes and fall speeds than the other simulations (Figs. 13c,d), with sizes and fall speeds most narrowly distributed. The smaller and slower falling ice is more likely to be advected horizontally out of the TZ, thus producing the distribution of lower surface reflectivities (Fig. 13a).

This result corroborates the hypothesis of Braun and Houze (1994), who used retrievals from a midlatitude squall line along with trajectory calculations with assumed inverse-exponential ice size distributions to determine that the flux of precipitating ice from the convective updraft (maximum at $z = 7$ km) would fall into the TZ. They suggest that the size distribution of ice particles advected rearward from the convective region is more important than the rearward flux of ice, and we show this to be the case in our simulations. Along with the ice particle properties, the distribution shape is also important for modeling transition zones and stratiform precipitation regions. If ice size distribution shape is transformed into an inverse exponential, that

---

**Fig. 13.** Frequency plots in the transition zone of (a) lowest model-domain reflectivity, (b) vertical velocity, (c) ice-2 mass-weighted maximum diameter, and (d) ice-2 mass-weighted fall speed. Solid lines are from $z = 4$ to 6 km and dashed lines are from $z = 6$ to 10 km. The simulations shown are CTRL (black), RS-OFF (red), and $n1$ (blue).
transformation should occur rearward of the transition zone. Otherwise, as our simulations suggest, ice would sediment into the region immediately behind the line of deep convection effectively removing the transition zone. Moreover, if size spectra take on an exponential shape rearward of the transition zone, then some microphysical process (e.g., aggregation) is likely responsible for the size distribution transition, which would provide evidence of microphysical processes that are important to the squall-line stratiform region.

c. The role of aggregation

Turing off aggregation (not shown) as mentioned has little effect on the simulated squall line because aggregation rates are low in CTRL because of the isometric shape of ice. Observations suggest that isometric and irregular ice can aggregate in the ESPR (Churchill and Houze 1984; Fridlind et al. 2017). In ISHMAEL, we can allow isometric, low-density ice to aggregate (AGG) by setting \( f_a = 1 \). This effectively allows isometric ice to aggregate as efficiently as particles with highly anisotropic shapes (see Jensen et al. 2017). Allowing isometric ice to aggregate significantly increases the mass-mixing ratio of aggregates in the domain and allows aggregates to be produced in the updraft, leading to a relatively small flux (3.5 g m\(^{-2}\) s\(^{-1}\)) of aggregates out of the convective region at 6 h (not shown). Explicit breakup of aggregates is not included in ISHMAEL, which may occur in updrafts, but breakup is implicitly treated by limiting the mean size of aggregates. In AGG, there is no TZ apparent in the reflectivity field (Fig. 14), but it still exists in the precipitation rate (not shown). The increase in aggregation rate rearward of the TZ widens the ESPR (Fig. 14), and the reflectivity values become larger than observed aloft. The increase in reflectivity near \( x = -100, z = 6 \) km compared to the baseline simulation is from aggregates, which become as large as \( D_3 \approx 1 \) cm (Fig. 14, black contours). The vertical structure of reflectivity in the ESPR (from \( x = -50 \) to \(-125 \) km) in AGG is in better agreement with the observations than CTRL. In AGG, reflectivity decreases with increasing height throughout the ESPR, whereas in CTRL above \( z = 4 \) km reflectivity decreases faster with height toward the rear of the ESPR. Perhaps higher aggregation rates occur in the ESPR in the real system than captured in CTRL, especially aloft near the rear of the ESPR where reflectivity is biased low in the simulation.

The loss of the TZ at low levels in the reflectivity field in the AGG simulation is produced from a secondary effect, since little aggregate ice reaches the melting level in the TZ. Above \( z = 6 \) km in the TZ, aggregation leads to an increase in reflectivity. At low levels, increasing aggregation rates reduces ice-2 number concentrations, thereby increasing the mean size of ice-2 where significant aggregates are produced (Fig. 15a, red line near \( z = 7 \) km). The increase in ice-2 size from aggregation means that the smaller ice-2 particles are lost from the distribution (from self- and cross-collection) at a faster rate than the larger ice-2 particles. Using a distribution shape of \( \nu = 4 \), the larger ice-2 particles are too low in number to produce aggregates, hence the mean size increase in ice-2 during aggregation. The increase in the size of ice-2 advected from the convective updraft in

![Fig. 14. Line-averaged reflectivity at 6 h using ISHMAEL with increased aggregation rates (AGG). Reflectivity from aggregates alone is shown as solid black contours, from 5 to 30 dBZ, every 5 dBZ.](image-url)
AGG leads to an increase in ice-2 size and fall speed in the TZ from $z = 4 - 6$ km (Fig. 15b), seen as a tail of larger and faster falling particles. This result is consistent with an analysis of the vertically integrated line-averaged process rates (not shown), revealing that no significant aggregate melting occurs in the TZ. This explanation for the loss of the TZ region in AGG is further supported by an additional test following AGG except that the number concentration loss caused by aggregation from ice-2 was diagnosed such that the mean size of ice-2 remained constant. This simulation produces a similar squall line to that of the baseline case, with a TZ, but with increased reflectivity at the rear of the squall line ($x = -1.50, z = 4 - 8$ km). Setting $f_i = 1$ for the 1SP simulation (1SP-AGG) produces increased reflectivity at the rear of the squall line and in the ESPR, similar to AGG, but the TZ is maintained in 1SP-AGG. In 1SP-AGG, ice in the convective region is smaller than in AGG, and therefore, in 1SP-AGG less aggregation occurs in the convective region, which means that the changes to the properties of precipitating ice that occur in AGG due to aggregation (Fig. 15) do not occur to the same degree in 1SP-AGG.

6. Conclusions

Microphysical parameterization schemes, like ISHMAEL, that explicitly predict ice particle properties are useful and unique tools for exploring how evolving ice properties impact cloud-system features. In quasi-idealized squall-line simulations, ISHMAEL produces both a low-reflectivity and precipitation rate transition zone (TZ) and an enhanced stratiform precipitation region (ESPR) consistent with observations from this case. In the model, predicting the properties of ice, specifically those that impact fall speed such as size and density, generates particles that advect from the convective region with appropriate fall speeds to produce both the TZ and ESPR. Rimed particles advected from the convective region produce the ESPR, and the location of the ESPR depends on the fall speed of this rimed ice. Our simulations suggest that predicting the shape of ice particles in squall lines may be less important than predicting the density and fall speed transitions as ice evolves. Ice is nearly isometric throughout the simulation domain because of riming and ice nucleation (all ice initiation processes including frozen raindrops) being dominant microphysical processes. Predicting both vapor-growth and rime densities without separating ice between unrimed and rimed categories produces the size and falls speed distributions of ice that lead to ESPR formation.

While results suggest that sublimation of ice aloft and dynamical features (a coherent updraft structure in the adjacent convective region) contribute to low-reflectivity TZs, sensitivity tests suggest that their existence depends on hydrometeor sorting. The existence of the TZ in these simulations depends on ice particles advecting into that region aloft with a narrow distribution of mean sizes $0.5 < D_l < 1.5$ mm and fall speeds
$2 < v_f < 3 \text{ m s}^{-1}$, strongly suggesting that size sorting of ice hydrometeors is necessary for the existence of the TZ. Simulation results suggest that squall-line features may depend on the continuous evolution of ice particle properties as ice grows in the convective updraft and advects rearward. The ice advected rearward from a squall-line convective updraft may be a mix of vapor grown and rimed ice, meaning that predicting the evolution of those particles rather than characterizing them as either snow or graupel may be a more natural way to simulate squall lines.

The TZ is sensitive to aggregation, rim splintering, and ice size distribution shape; these processes affect the mean size and fall speed of precipitating ice. The ice size distribution shape partly determines the spatial location where ice advected rearward from the convective region will fall out. Without rim splintering, the mean size and fall speeds of ice advected from the convective region are large enough to allow that ice to fall to the melting level and thus eliminate the TZ. The dependence of the TZ on rim splintering reveals the importance of secondary ice production on squall-line features in this case. The main effect of aggregation in these simulations is to increase reflectivity as a result of the increase in mean ice particle size, with a weak impact on precipitation rate. The evolution of the system in time partially depends on ice density through its impact on particle size and fall speed. Predicting ice particle properties may be quite important for the initiation of certain cloud systems and their early stages of evolution.

ISHMAEL should be able to simulate other cloud systems and regimes where evolution of ice particle properties is important, which will be investigated in future work. More modeling studies are needed to determine the environmental conditions when in situ vapor-growth aggregation dominate the stratiform region versus ice advected from convective updrafts. Better aggregation parameterizations including breakup of aggregates based on observations would improve understanding of squall lines. Future improvements to ISHMAEL will involve adding improved wet growth, hail, and frozen rain parameterizations. Comparing ISHMAEL to dual-polarization radar will be useful in the future to help constrain ice shape evolution occurring through various microphysical processes.

Acknowledgments. This research was supported by an NSF-AGS Postdoctoral Research Fellowship (AGS-1524267), the NCAR ASP visitor program, the U.S. Department of Energy’s Atmospheric Science Program Atmospheric System Research, and an Office of Science, Office of Biological and Environmental Research program, under DE-SC0012827. We would like to acknowledge high-performance computing support from Yellowstone (ark:/85065/d7wd3xhc) provided by NCAR’s Computational and Information Systems Laboratory, which is sponsored by the National Science Foundation.

REFERENCES


