What Controls Crystal Diversity and Microphysical Variability in Cirrus Clouds?

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Abstract  Variability of ice microphysical properties like crystal size and density in cirrus clouds is important for climate through its impact on radiative forcing, but challenging to represent in models. For the first time, recent laboratory experiments of particle growth (tied to crystal morphology via deposition density) are combined with a state-of-the-art Lagrangian particle-based microphysics model in large-eddy simulations to examine sources of microphysical variability in cirrus. Simulated particle size distributions compare well against balloon-borne observations. Overall, microphysical variability is dominated by variability in the particles’ thermodynamic histories. However, diversity in crystal morphology notably increases spatial variability of mean particle size and density, especially at mid-levels in the cloud. Little correlation between instantaneous crystal properties and supersaturation occurs even though the modeled particle morphology is directly tied to supersaturation based on laboratory measurements. Thus, the individual thermodynamic paths of each particle, not the instantaneous conditions, control the evolution of particle properties.

Plain Language Summary  Thin, high-altitude ice clouds—cirrus—are critical to climate through their interactions with incoming solar radiation and outgoing longwave radiation. With a zoomed-in view, observations show that cirrus comprise ice crystals of diverse sizes and shapes. These crystal properties determine the bulk properties of the clouds, like their ice water content. What controls this diversity of crystal properties? To address this question, we performed numerical simulations using a state-of-the-art model that tracks the growth of individual particles, informed by laboratory crystal growth experiments, in a realistic turbulent cloud flow. We show that variability in the local environmental conditions (e.g., relative humidity) that particles experience in a turbulent environment is a primary driver of crystal diversity in cirrus. Diversity is also driven by different shapes of newly formed crystals, leading to different growth characteristics. This diversity drives spatial variability of properties like mean crystal density across the cloud layer. Climate models that represent cirrus using simple relationships based on observations that are essentially snapshots of average crystal properties cannot capture this variability. Overall, our analysis indicates that the history of environmental conditions along particle trajectories, not just instantaneous conditions, are required to understand crystal growth and variability in cirrus.

1. Introduction

Cirrus clouds often appear optically thin yet are critical for radiative forcing and climate. The sign of their net radiative forcing (warming or cooling) depends on their altitude, thickness, coverage, and ice particle size and density distributions (A. J. Heymsfield et al., 2017; Krämer et al., 2016). But what determines the macro- and micro-scale properties of cirrus clouds? Aircraft observations taken over many years show substantial diversity in particle habits of larger crystals (Lawson et al., 2019). Recent balloon-borne campaigns combined with electron microscopy (e.g., Magee et al., 2021; Majetic, 2023) have highlighted this substantial diversity even for crystals of the smallest sizes in mid-latitude cirrus (< 40°C). These crystals show a bewildering array of shapes, and a substantial degree of surface features such as the macro-steps that are characteristic of hollowing. This diverse array of shapes and surface complexity can significantly impact the scattering properties of cirrus crystals (Baum et al., 2011; Järvinen, Jourdan, et al., 2018). However, the impact of this diversity on the variability of particle properties like size and density is unclear, especially relative to other sources of microphysical variability such as the local thermodynamic or dynamic conditions. This has contributed to uncertainty in understanding the cirrus response to climate change (Baker, 1997; Järvinen, Jourdan, et al., 2018; Kärcher, 2017).
Most numerical models cannot easily treat crystal morphological diversity, by which we specifically mean variability in crystal shape and surface features such as hollowing. Models typically separate crystals into different categories along size boundaries, using mass-dimensional relationships to characterize the habit. Hence, transformation in crystal properties only occurs when crystals move from one category to another, and crystals are constrained to a small set of properties and therefore lack diversity. Remote sensing retrievals of ice cloud properties also typically utilize power-law mass-size relationships (Brown & Francis, 1995; Mascio et al., 2017). These relationships are based on in situ observations that are essentially snapshots of cloud microphysical properties but do not contain any information about particle histories. Moreover, these relationships are usually representative of properties averaged over an ensemble of crystals and hence they contain limited information on particle diversity. Are such instantaneous, ensemble-averaged relationships sufficient to represent ice microphysical processes in cirrus? Laboratory experiments of single particles (Figure 12 in Pokrška et al., 2023) and particle populations (Schmaier et al., 2016) growing by vapor diffusion both show a strong correlation of crystal size and measures of crystal complexity (effective density, complexity factor) with supersaturation. In contrast, in situ cirrus observations (e.g., Figure 5 in Fridlind et al., 2016; Krämer et al., 2009) show significant scatter of data in density-size relationships and little correlation of crystal complexity (Järvinen, Wernli, & Schnaier, 2018; Ulanowski et al., 2014) with supersaturation. Consequently, it is presently unclear why laboratory experiments indicate a strong supersaturation dependence to crystal diversity and complexity, whereas in situ observations show weak to no correlation. Is crystal dynamic and thermodynamic history the missing ingredient, as Järvinen, Wernli, and Schnaier (2018) suggest?

Most earlier process studies of cirrus used parcel models with bin microphysics schemes (e.g., Fridlind et al., 2016; Kärcher et al., 2006; Kienast-Sjögren et al., 2015; Krämer et al., 2016; Rolf et al., 2012; Spichtinger & Gierens, 2009) or large-eddy simulations with bulk schemes (e.g., Cheng et al., 2001; Dobbie & Jonas, 2001); however, these models are limited in their ability to study variability in particle properties. Parcel models lack realistic coupling of the dynamics and thermodynamics with the microphysics. Bin microphysics schemes also suffer from numerical diffusion which impacts particle size distributions (Morrison et al., 2018). Moreover, they do not track individual particle characteristics and growth history, unlike Lagrangian particle-based microphysics schemes, which is important if one wishes to examine sources of variability in particle properties. A few recent studies used Lagrangian particle-based schemes in one-dimensional (e.g., Jensen et al., 2018) or two-dimensional (e.g., Sölch & Kärcher, 2010) frameworks that included feedback between the microphysics and dynamics, but the crystal properties were constrained to follow empirical mass-size relationships. To our knowledge, the only previous study that explicitly investigated sources of ice particle microphysical variability focused on snowfall at temperatures above 20°C (Nelson, 2008). That study used a simplified model driven by observed temperature and updraft velocity fluctuations and realistic surface kinetics, and concluded that temperature-updraft fluctuations are a dominant source of crystal variability. However, this simplified approach only considered small-scale surface variability and neglected variability in growth properties like deposition density as well as feedbacks between the microphysics and thermodynamic and dynamic fields.

The above studies have advanced understanding of ice microphysics, but no studies of which we are aware examined drivers of variability in cirrus crystal properties and the impacts of these drivers on bulk cloud properties. In this study, for example, we study the growth of individual crystals obtained from recent laboratory experiments and associated theories (J. Y. Harrington et al., 2019; Pokrška et al., 2023) and combined with a large-eddy simulation (LES) model of turbulent cloud flow that tracks the physical properties and locations of individual representative crystals using a Lagrangian microphysics scheme. This study investigates the principle factors driving variability in cirrus ice crystal properties (focusing on crystal size and density). These factors include variability in the history of dynamic and thermodynamic conditions experienced by individual crystals and diversity of crystal shape and morphological complexity, such as branching and hollowing. The latter is represented through a deposition density without explicitly treating crystal surface features. A detailed model evaluation with observations is beyond the scope of the study, but we qualitatively compare the simulation results with cirrus observations to provide additional context for the model experiments. In the future, studies of cirrus cases that permit a more detailed comparison with observations could provide valuable information for further model evaluation and improvement.
2. Methods

The Ice Cryo-Encapsulation by Balloon (ICE-Ball) campaign focused on ice crystal sampling in a small cryogenic chamber using balloons from in situ cirrus clouds (formed in situ from ice nucleation at temperature < 30°C due to synoptic lifting, gravity waves, etc.) over the U.S. Southern Great Plains (J. Y. Harrington & Magee, 2023). These sampled crystals were analyzed later with a cold-stage environmental scanning electron microscope to produce detailed morphological information and particle size distributions (PSDs) for analysis.

2.1. Lagrangian Particle-Based Ice Microphysics Scheme in LES

The Cloud Model 1 (CM1) (G. H. Bryan & Fritsch, 2002) is used in a LES configuration with 50–100 m isotropic grid spacings to simulate a cirrus case from the ICE-Ball campaign forced by ECMWF Reanalysis V5 data and an observed sounding. The particle-based microphysics scheme in the model computes and tracks the properties of individual computational particles (“super-particles”) using the approach of S.-i. Shima et al. (2020). Each super-particle represents a number of physical particles having the same properties (this number is referred to as the “multiplicity” of the super-particle). This scheme evolves crystal properties (e.g., three-dimensional location, size, mass, multiplicity, aspect ratio, density, habit) along Lagrangian particle trajectories and includes feedback with the thermodynamics and dynamics.

To investigate sources of variability in ice particle properties, four main simulations with different microphysical assumptions are analyzed. Two particle habits are modeled: polycrystals (e.g., bullet rosettes) and columns. Morphological diversity is considered for polycrystals, which are represented with a spherical enclosing shape and a reduced (effective) density. Thus, the a- and c-axis lengths are equal and represent the radius of polycrystals (herein we present results for the a-axis length). The effective density changes through the density of ice deposited during growth from vapor (deposition density, \( \rho_d \)). \( \rho_d \) is statistically distributed as a function of supersaturation based on laboratory measurements (Pokriška et al., 2023), providing a simple measure of crystal morphological diversity. Three simulations (CTL, DEP-LOCAL, DEP-FIX) consider only polycrystals as the particle habit but have different assumptions for \( \rho_w \), with all else being the same. In CTL, \( \rho_d \) for each particle is randomly sampled from the laboratory-derived \( \rho_d \) distribution of Pokriška et al. (2023) as a function of the local supersaturation when the particle nucleates, and it is constant over the particle’s lifetime. In effect, \( \rho_d \) is assumed to be associated with a particle morphology that is “locked in” at the time of particle nucleation. In DEP-LOCAL, \( \rho_d \) for each particle is based on continuous random sampling of the \( \rho_d \) distribution as a function of the local supersaturation as the particle evolves over time. Which of these two scenarios is more realistic cannot be determined from the laboratory experiments, which held the supersaturation ratio constant over time (Pokriška et al., 2023). In DEP-FIX, \( \rho_d = 200 \, \text{kg m}^{-3} \) for all particles; thus, variability of \( \rho_d \) associated with different crystal morphologies is neglected. The fourth simulation includes both polycrystals (with \( \rho_d \) randomly sampled as in CTL) and columns (2-HAB). A list of these simulations (Table S1 in Supporting Information S1) and details of the method are presented in Supporting Information S1.

3. Results and Discussions

Figure 1 provides an overview of the cloud structure, vertical velocity field, and crystal sizes from the simulations and observations. The cloud field extends from 8 to 9.8 km in altitude. The simulated cloud field shows a distinct three-layer structure (Figure 1c)—an upper cloud layer where crystals nucleate and grow by vapor diffusion (above 9 km), a middle layer (8.2–9 km) where larger crystals sediment and grow further, and a sublimation layer (7.2–8.2 km). This three-layer structure is similar to the conceptual picture of cirrus uncinus presented in A. Heymsfield (1975), but without wind shear. The vertical velocity field shows overturning motion with maximum velocity magnitude 1.2 m s⁻¹ characterizing generating cells. The radar-derived vertical air motion shows a similar magnitude to the simulations but does not capture small-scale structures (see Figure S4 in Supporting Information S1 for an extended window on the radar data). Although the vertical cloud extent appears smaller (1 km) in the zoomed-in radar curtain in Figure 1, the extended radar data in Figure S4 in Supporting Information S1 show a similar vertical extent (2 km) as the simulations. The active upper cloud layer is also the primary region for turbulent mixing of particles. In this layer the ice crystals are small, and the PSDs are narrow (Figures 1e and 1f). In the middle layer, the PSD mode increases in size with decreasing altitude owing to particle growth, and the distributions are broader. Sublimation of crystals in the lower layer again shifts the PSDs toward smaller sizes. The simulated PSD (a-axis) well matches (within 11.1% for the mean) the observed minor axis.
distribution at the same altitude range (8,000–8,500 m), which builds confidence in the realism of the simulations. The simulated c-axis distribution is somewhat smaller than observed, most likely due to the spherical approximation of polycrystals in the model. This deviation is not explained by the occurrence of columnar or plate-like monocrystals, since they account for only 5% of the observed crystal population (J. Y. Harrington & Magee, 2023) and 13.7% in the 2-HAB simulation. Each simulation is run for 8,100 s. The presented analyses focus on the results at 7,200 s, at which point the cloud layer has evolved into a nearly steady-state structure with a thickness of approximately 2.6 km (see Figures S9 and S10 in Supporting Information S1 for details).

### 3.1. Sources of Variability in Particle Properties

The sources of variability in particle properties investigated here are: (a) variability in the thermodynamic and dynamic histories of particles; and (b) crystal morphological diversity associated with variability in deposition density (representing complexity in crystal shape and surface features like hollowing) and particle habit.

These sources of microphysical variability are investigated by analyzing property evolution along individual particle trajectories. Figure 2 shows sample trajectories in space and particle size (a) and density (ρ) variations as a function of particle age after nucleation. The sample trajectories illustrate generating cells and large falling crystals in straight streaks due to the absence of wind shear. This plot also illustrates significant mixing of...
particles with different origin in the generating cells before falling as streaks. Particles grow to larger sizes and the distribution of particle sizes broadens as the particles' age increases in the CTL, DEP-LOCAL, and DEP-FIX simulations. Broadening of the distribution results from variability in thermodynamic conditions along particle trajectories, a classic example of Brownian diffusion in particle size space. However, the mean particle size is reduced for DEP-LOCAL compared to CTL. This is because particles are denser (by roughly a factor of 2 after particles have aged more than 5 min) when $\rho_d$ is determined based on the local supersaturation in DEP-LOCAL, which limits growth of the a-axis length over time. In CTL, DEP-LOCAL, and DEP-FIX, the mean crystal density becomes smaller over time, up to a particle age of 20–25 min, as less dense mass is deposited over solid ice crystals that have an initial density of 917 kg m$^{-3}$. Sublimation produces denser crystals, which explains the small increase in mean density after 25 min. Much higher median density in DEP-LOCAL than CTL occurs because continuous random sampling (at each time step) of the $\rho_d$ distribution as a function of local supersaturation leads
to crystals with a density approaching that of the mean of the $\rho_d$ distribution for the supersaturation ratio range in the cloud, which is 470 kg m$^{-3}$. However, in CTL, with $\rho_d$ for each crystal fixed in time based on the supersaturation at the time of nucleation, the impact of the sampled $\rho_d$ is preserved over the particle lifetime. Although variability in particle density is reduced in DEP-LOCAL compared to CTL, variability across particle size (quantified by quantile ranges in Figures 2b–2e) is still significant in DEP-LOCAL because of variability in the particles’ thermodynamic histories. DEP-FIX also shows significant variability in particle size and density without any morphological diversity associated with $\rho_d$, confirming thermodynamic variability as a primary driver of variability in particle properties.

Impacts of crystal morphological diversity on spatial variability of microphysical properties are investigated by comparing Contoured Frequency by Altitude Diagrams (CFADs) of mean crystal size $a$ and density $\bar{\rho}$ (mean over a grid cell volume weighted by super-particle multiplicity) for the four main simulations (Figure 3). Averaged values of $a$ are small in the upper cloud layer and nearly uniform with altitude, only slightly increasing with height. In the middle layer, formed by crystals falling from the upper layer, average values of $a$ and variability both increase with decreasing altitude and reach a peak near 8,300 m. This is consistent with the trajectory analysis discussed above that showed an increase in mean and variability of particle size as the particles age. In the bottom layer, average values of $a$ decrease from sublimation, but variability increases. The upper nucleation and lower sublimation layers also have larger mean $\bar{\rho}$ and greater variability than the middle cloud layer.

DEP-LOCAL limits the morphological diversity of crystals from its continuous sampling of $\rho_d$, as noted above. As a result, variability in $a$ is reduced, while variability in $\rho_i$ is substantially reduced (especially toward small densities, leading to a skewed distribution of $\rho_i$). DEP-FIX, with a fixed deposition density of 200 kg m$^{-3}$, completely eliminates morphological diversity associated with variable $\rho_d$ and has greatly reduced variability in $a$ and $\rho_i$ compared to CTL in the middle sedimenting cloud layer. It has a larger mean $\rho_i$ due to lower mean $\rho_i$ than the other cases. Remaining variability in $a$ and $\rho_i$ in DEP-FIX, despite all sources of crystal morphological diversity being removed, is because of variable thermodynamic conditions and hence growth histories for different particle trajectories. An additional sensitivity test similar to DEP-FIX but with deposition density at a much higher value (700 kg m$^{-3}$) also shows less variability in $a$ than CTL and DEP-LOCAL (see Figure S5 in Supporting Information S1). Finally, allowing two habits in the model by nucleating columns in addition to poly-crystals in 2-HAB increases variability in grid-mean properties compared to the CTL case. 2-HAB also develops a second mode in $a$ and $\rho_i$ in the middle cloud layer.

Overall, these results show that significant variability of crystal properties is mainly driven by variability in the particles’ thermodynamic histories, but with important contributions from morphological diversity through variations in deposition density and habit. Greater morphological diversity is associated with more spatial variability of grid-mean microphysical quantities (mean size and density), particularly in the middle cloud layer. Similarly, greater morphological diversity is also associated with greater variability of particle size and density within grid cells, quantified by the mean standard deviation of these particle properties (weighted by super-particle multiplicity) within each grid cell volume (Figure S6 in Supporting Information S1).

### 3.2. Local Versus Integral Perspective: Correlation of Ice Crystal Properties With Supersaturation

We analyze joint PDFs of ice crystal density versus ice saturation ratio and crystal size versus ice saturation ratio for individual particles at 7,200 s in the CTL and DEP-LOCAL simulations (Figures 4a–4h) to investigate the correlation of crystal properties with local thermodynamic conditions (as would be sampled in situ by aircraft observations). Data are segmented by altitude corresponding to the upper cloud layer (9,000–9,500 m) and middle layer (8,500–9,000 m). The correlation of crystal density or size with saturation ratio in the upper cloud layer is very weak (e.g., 0.06 for density and 0.25 for size for CTL) and has significant scatter, more so for the crystal density. In the middle sedimenting layer, the correlation is stronger. Crystal density is slightly more negatively correlated with the saturation ratio for CTL (0.21), that is, density decreases with supersaturation. Similarly, crystal size increases with supersaturation (correlation coefficient 0.51 for CTL). A slightly stronger positive correlation could be due to reduced mixing of particles with different growth histories due to weaker turbulence in this layer. However, at all levels there is a significant scatter of data around the mean, indicating that particle transport and variable thermodynamic histories lead to decorrelation of particle properties with the local thermodynamic quantities.
Figure 3. CFADs of mean crystal sizes at each grid box (a–d) and crystal density (e–h) at time $7,200$ s from the four different sensitivity cases presented here. Squares: horizontal average; bars: 10th and 90th percentiles; and dashed line: a reference to aid visual comparison.
Figure 4. Joint probability distribution of crystal density versus ice saturation ratio (a–d), crystal size versus ice saturation ratio (e–h), and crystal density versus crystal size (i–l) for crystals >10 μm at two vertical layers from two different simulation cases (time 7,200 s).
A key result is the reconciliation of laboratory measurements and in situ observations. Even though the input laboratory data for the deposition density and supersaturation are strongly correlated, the simulation outcome after crystal growth and transport is not. This produces scatter that is consistent with in situ field observations (e.g., Krämer et al., 2009), pointing to the significant role of variability in growth history and particle mixing when analyzing observed correlations. For the DEP-LOCAL simulation with reduced morphological diversity, there is less variability in the ice density and size compared to CTL, consistent with the earlier discussion, but similarly weak correlations of particle properties with the local supersaturation field, especially the particle density.

Figures 4i–4l shows joint PDFs of crystal size versus density for individual particles at the two different altitude ranges from the CTL and DEP-LOCAL simulations. Similar to the size or density versus supersaturation relationships, the CTL simulation has significant data scatter. The spread in density is greater for small crystals. The mean density has a weaker response to changes in the crystal size and more scatter (negligible correlation) in the upper cloud layer. This suggests greater mixing of particles with diverse thermodynamic histories in this layer. In the middle sedimenting layer, which has weaker turbulence, the mean crystal density decreases more clearly with an increase in the crystal size, and correlation between the two is moderately negative (−0.499). For the DEP-LOCAL case, the spread of particle densities is significantly less than in CTL. This is associated with reduced morphological diversity from continuous random correlated sampling of \( \rho_d \) as discussed earlier. The data also show a stronger negative correlation in the upper cloud layer for this case than CTL. This is because the time integration of mass growth from continuous sampling of \( \rho_d \) in DEP-LOCAL leads to a stronger negative correlation between size and density during the initial growth phase before the crystal density saturates at the mean \( \rho_d \) of 470 kg m\(^{-3}\) at a particle age of 2–3 min (see Figure 2e). Because these particles tend to sediment into the middle cloud layer as they age, the density in the middle layer is nearly constant at 470 kg m\(^{-3}\) and the correlation with particle size is much weaker than in the upper layer. In contrast, for the CTL case, in which \( \rho_d \) is sampled based on supersaturation at the time of particle nucleation and then held fixed, local thermodynamic variability is a primary driver of variability in particle microphysical properties in the upper cloud layer. Once particles become large enough, variations in \( \rho_d \) become an important driver of microphysical variability owing to the fixed \( \rho_d \) of each particle. As a result, there is a stronger negative correlation of particle density with size in the middle sedimenting layer than in the upper layer.

These contrasting results for the CTL and DEP-LOCAL cases lead to an obvious question—what is the most realistic representation of crystal growth: fixing \( \rho_d \) of a crystal based on the supersaturation at the time it nucleates as in CTL, or sampling from the \( \rho_d \) distribution over time as a function of the local supersaturation as in DEP-LOCAL? Significant scatter in density-size and mass-size relationships from in situ observations in cirrus clouds (e.g., Fridlind et al., 2016; Mascio et al., 2017) is consistent with large variability in particle properties (size and density) present in the CTL case. This indirectly suggests that fixing \( \rho_d \) at the time of particle nucleation is more realistic than using a time-varying deposition density for each crystal based on local supersaturation. However, it is worth noting that the derivation of particle mass and density from in situ measurements typically involves numerous assumptions that might affect mass and density variability. Nonetheless, qualitative analysis of crystals observed duringICE-Ball showed significant diversity and complexity (branching and hallowing) of crystals within the same cloud (J. Y. Harrington & Magee, 2023). Further investigation, ideally in a laboratory setting with a controlled time-varying supersaturation environment, is required to support this claim directly.

4. Conclusions

Microphysical properties of thin cirrus clouds are highly variable when zoomed in to the particle level. This variability of particle microphysical properties like size and density affects integral properties, like radiative forcing and cloud lifetime, that are critical for climate. We investigated possible sources of this microphysical variability by combining laboratory data on particle growth with a Lagrangian particle-based microphysics scheme in LES to simulate an observed cirrus case. Particle vapor diffusional growth in the model was based directly on laboratory measurements from Pokrifa et al. (2023).

Our analysis showed that variability in the particles’ thermodynamic histories is a key driver of variability in particle sizes, densities, and fall-speeds. This aligns with Nelson (2008), who specified updraft-temperature fluctuations in their model, but here using a model explicitly representing particle-flow interactions. Moreover, there was little correlation between ice crystal properties and supersaturation (e.g., as would be sampled
using an aircraft or a balloon) even though particle growth was directly tied to supersaturation in the model. This behavior is explained by substantial variability in the growth histories of particles with trajectories that end up in close proximity (i.e., the same model grid cell) at a particular time. Variability in the deposition density associated with crystal morphological diversity and thermodynamic conditions at the time and location of nucleation are also important for driving diversity of crystal sizes and densities if the basic crystal morphology (and thus deposition density) is set at the time of nucleation. Crystal morphological diversity also drives spatial variability of grid-averaged crystal properties, particularly in the middle cloud layer. These simulations strongly imply that the cycling of crystals among diverse trajectories is likely why observed crystal complexity is not correlated with in situ thermodynamic properties (Ulanowski et al., 2014) or supersaturation estimated along back trajectories (Järvinen, Wernli, & Schnaiter, 2018). This helps to reconcile the strong correlation of crystal complexity and morphology (and hence deposition density) with supersaturation measured in the lab with the lack of such correlation observed in situ in cirrus clouds.

It remains a significant challenge to account for particle variability in bulk microphysics schemes that typically employ single mass-size, density-size, and fall-speed-size relationships to represent cloud ice. This is likely important since different particle shapes can substantially alter the single scattering properties of crystals (Mitchell et al., 1996) and complex surface features such as hollowing can strongly alter these properties (Baum et al., 2011; Järvinen et al., 2016; van Diedenhoven et al., 2016).

We also analyzed the impact of different representations of crystal morphology via the deposition density and habit on integrated cloud properties (Figure S7 in Supporting Information S1), including mean ice water mixing ratio, sedimentation velocity, and dynamical impacts, the latter quantified by the resolved turbulent kinetic energy (TKE). Different assumptions for deposition density and habit primarily impacted the mean ice water mixing ratio and settling velocity in the sedimentation layer where the crystals were sufficiently large. This significantly affected the cloud dynamics in the upper cloud layer through the dynamical coupling of the cloud layers. Larger TKE occurred for the cases with denser crystals, and assuming two crystal habits (columns and polycrystals) instead of one (polycrystals only) increased the TKE further. Additional analysis will be done in the future to investigate the impact of these microphysics-dynamics interactions on the macro-scale properties of cirrus.

Data Availability Statement

All data from the ICEBall field campaign including crystal images, soundings, radar data are directly available from the DOE-ARM data archive (J. Harrington & Magee, 2024). CM1 code with detailed documentation is available in G. Bryan (2019). SDM code provided by Shin-ichiro Shima is available in S. Shima (2020).

References


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