Precipitation Growth Processes in the Comma Head Region of the 7 February 2020 Northeast Snowstorm: results from IMPACTS


1Department of Atmospheric Sciences, University of Illinois Urbana-Champaign, Urbana, Illinois
2Cooperative Institute for Severe and High-Impact Weather Research and Operations, University of Oklahoma, Norman, Oklahoma
3School of Meteorology, University of Oklahoma, Norman, Oklahoma
4Department of Atmospheric Sciences, University of Washington, Seattle, Washington
5NOAA/OAR National Severe Storms Laboratory, Norman, Oklahoma
6Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research, Eggenstein-Leopoldshafen, Germany
7Department of Atmospheric Sciences, University of North Dakota, Grand Forks, North Dakota
8NASA Goddard Space Flight Center, Greenbelt, Maryland

Submitted to the Journal of Atmospheric Sciences

*Corresponding Author: Robert M. Rauber, University of Illinois Urbana-Champaign, r-rauber@illinois.edu

Early Online Release: This preliminary version has been accepted for publication in Journal of the Atmospheric Sciences, may be fully cited, and has been assigned DOI 10.1175/JAS-D-22-0118.1. The final typeset copyedited article will replace the EOR at the above DOI when it is published.

© 2022 American Meteorological Society
Abstract

On 7 February 2020, precipitation within the comma-head region of an extratropical cyclone was sampled remotely and in-situ by two research aircraft, providing a vertical cross-section of microphysical observations and fine-scale radar measurements. The sampled region was stratified vertically by distinct temperature layers and horizontally into a stratiform region on the west side, and a region of elevated convection on the east side. In the stratiform region, precipitation formed near cloud top as side-plane, polycrystalline, and plate-like particles. These habits occurred through cloud depth, implying that the cloud top region was the primary source of particles. Almost no supercooled water was present. The ice water content within the stratiform region showed an overall increase with depth between the aircraft flight levels, while the total number concentration slightly decreased, consistent with growth by vapor deposition and aggregation. In the convective region, new particle habits were observed within each temperature-defined layer along with detectable amounts of supercooled water, implying that ice particle formation occurred in several layers. Total number concentration decreased from cloud top to the -8°C level, consistent with particle aggregation. At temperatures >-8°C, ice particle concentrations in some regions increased to >100 L⁻¹, suggesting secondary ice production occurred at lower altitudes. WSR-88D reflectivity composites during the sampling period showed a weak, loosely organized banded feature. The band, evident on earlier flight legs, was consistent with enhanced vertical motion associated with frontogenesis, and at least partial melting of ice particles near the surface. A conceptual model of precipitation growth processes within the comma head is presented.

Significance Statement

Snowstorms over the Northeast U.S. have major impacts on travel, power availability, and commerce. The processes by which snow forms in winter storms over this region are complex and their snowfall totals are hard to forecast accurately because of a poor understanding of the microphysical processes within the clouds composing the storms. This paper presents a case study from the NASA IMPACTS field campaign that involved two aircraft sampling the storm simultaneously with radars, and probes that measure the microphysical properties within the storms. The paper examines how variations in stability and frontal structure influence the microphysical evolution of ice particles as they fall from cloud top to the surface within the storm.
1 Introduction

The comma-head region of extratropical cyclones over the midwestern and eastern United States have been shown in both observational and modeling studies to often exhibit an elevated layer of potential instability and convection on their equatorward (warm) sides, and stable air, often topped by shallow convective cloud-top generating cells on their poleward (cold) sides (Weismuller and Zubrick 1998; Martin 1998; Nicosia and Grumm 1999; Novak et al. 2008, 2009; Rauber et al. 2014; Rosenow et al. 2014). Studies have also shown that the elevated potential instability is associated with the intrusion of dry air over the cyclones’ warm front, the dry air originating within the cyclones’ dry slot (e.g., Han et al. 2007; Grim et al. 2007; Rauber et al. 2014; Rosenow et al. 2014).

Research on the microphysical structure of the comma-head region, and the relationship of microphysical processes to mesoscale storm dynamics and precipitation bands within the comma head, has focused on storms over the Pacific Northwest associated with the Cyclonic Extratropical Storm Project (CYCLES) and the Improvement of Microphysical Parameterization through Observational Verification Experiment (IMPROVE-1) campaigns (e.g., Houze et al. 1976a,b, 1979, 1981; Matejka et al. 1980; Hobbs et al. 1980; Herzegh and Hobbs 1980, 1981; Evans et al. 2005), and over the central U.S. during the Profiling of Winter Storms (PLOWS) campaign (e.g., Plummer et al. 2014, 2015; Murphy et al. 2017). Outside of these geographic regions, studies of the microphysical structure of cold season continental cyclones, and other winter cloud systems not associated with cyclones, have focused on the low level production of supercooled water (e.g., Guan et al. 2001; Cober et al. 2001), processes leading to formation and depletion of supercooled water (Rasmussen et al. 1992), the prolonged existence of mixed phase clouds (e.g., Cober et al. 2001; Vaillancourt et al. 2003; Korolev and Isaac 2006), and feedbacks on dynamics due to latent cooling at the melting layer (e.g. Szeto and Stewart 1997). There are also limited studies reporting the size distributions of solid hydrometeors in Midwest winter cyclones (Passarelli 1978a,b) and in other winter storms (Gunn and Marshall 1958).

Microphysical investigations in winter storms along the U.S. East Coast are limited, despite these storms’ prevalence and impact. Recent studies have been confined to surface and remote sensing observations. Stark et al. (2013) analyzed surface microphysical observations within two banded winter cyclones and characterized pre-band, mature-band, and post-band microphysics, finding a rapid transition in ice particle habits, riming, and snow densities as snowbands passed...
over the observing location. They also noted the presence of generating cells and referenced their relationship to increased precipitation at the surface. Colle et al. (2014) expanded upon this by presenting surface microphysics observations collected in 12 cyclones over 3 winter seasons. Habit and riming characteristics were analyzed in the context of their spatial location relative to the cyclone low-pressure centers. The influence of generating cells and elevated convection on microphysical processes through different growth layers in East Coast winter storms has yet to be explored, although radar studies examining generating cells have been conducted in this geographic region using vertically-pointing radars since the 1950s (e.g. Marshall, 1953; Wexler and Atlas, 1959). More recently, Rauber et al. (2017) used an airborne W-band radar to investigate a Northeast cyclone finding several distinct substructures such as generating cells and elevated convection. Kumjian and Lombardo (2017) investigated the radar polarization characteristics of six Northeast winter storms using Quasi-Vertical Profiles (e.g. Ryzhkov et al. 2016), showing distinct changes in reflectivity, differential reflectivity, and differential phase across the dendritic growth layer, and rapid changes in melting layer height over short timescales.

Increasing interest in the physics and dynamics of banded precipitation, the dynamics and thermodynamics of cloud top and elevated convective substructures, the lack of in-situ microphysical observations to characterize these features, and societal impacts of recent winter storms along the East Coast of the U.S. motivated the National Aeronautics and Space Administration (NASA) Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS; McMurdie et al. 2022) field campaign. IMPACTS employed a modern suite of instruments aboard the NASA P-3 Orion (P-3) and the NASA Earth Resources 2 (ER-2) aircraft to collect in-situ microphysics and airborne radar data within the comma-head region of Atlantic Coast cyclones. The 7 February 2020 event had the best coordination between the P-3 and ER-2 aircraft during the 2020 deployment. The comma head was characterized by both stratiform and convective regions and provided an opportunity to investigate the microphysical processes within these regions through the depth of the storm. In this paper, microphysical processes are analyzed in the context of the storm’s thermodynamic, frontal, and radar structures in order to differentiate the microphysical evolution that occurs with depth between the aircraft flight levels within the stratiform and convective regions of the storms’ comma head, and within the banded features evident in the low-level reflectivity field.
The paper is organized as follows: Sec. 2 provides an overview of the extratropical cyclone’s frontal and airmass structure, Sec. 3 provides a discussion of IMPACTS aircraft operations on 7 February 2020, Sec. 4 describes the stability and moisture characteristics across the sample region, and Sec. 5 describes how the microphysical characteristics varied with depth between the aircraft flight levels in temperature defined particle growth layers. Sec. 6 discusses the nature of precipitation bands evident on radar. Key findings are summarized in Sec. 7.

2 Storm Overview

The 7 February 2020 cyclone developed during the early morning hours as a result of rapid cyclogenesis on the leeward side of the Appalachian Mountains. Rapid cyclogenesis was enhanced by the phasing of two mid-level shortwaves into a negatively-tilted trough, resulting in the development of a low over southeast Pennsylvania (Fig. 1a). Coupled jet streak dynamics and subsequent phasing of the subtropical and polar jet streams into a single jet streak with wind speeds $>100 \text{ m s}^{-1}$ at 300 hPa across eastern New York were responsible for the rapid intensification of the surface low (Fig. 1b). Within the 12 hours between 1200 UTC 7 February and 0000 UTC 8 February the surface low pressure center deepened from a mean sea-level pressure of 980 hPa to 966 hPa. As the surface low strengthened, well-defined surface frontal boundaries were evident. A surface cold front extended south along the Atlantic Coast, while a surface warm front extended east from the center of the low. A preexisting stationary front extended northward from the low-pressure center across central New York (Fig. 1a). The IMPACTS flights sampled the storm across the stationary front between 1400 and 1800 UTC during this period of deepening (see flight track plotted in Fig. 2). Twenty-four-hour snow accumulations of nearly 20-30 cm (7.8-11.8 inches) were recorded over west and central New York state by 0000 UTC 8 February (Fig. 2).
Fig. 1: RAP analysis valid at 1500 UTC on 7 February 2020. a: 2 m temperature shaded (°C), mean sea level pressure (1 hPa contours), and 10 m winds (m s\(^{-1}\)). b: 300 hPa heights (60 m contours), and wind speed (m s\(^{-1}\), shaded). Wind barb convention: half barb 5 m s\(^{-1}\), full barb 10 m s\(^{-1}\), and flag 50 m s\(^{-1}\). Frontal boundaries are based on subjective analysis of the 2 m temperature, sea-level pressure, and 10-m winds. Fronts use standard depictions for cold, warm, and stationary fronts.

Fig. 2: 24-hour snowfall ending 00 UTC on 8 February 2020 (NOHRSC, 2022). The dashed black line represents the cross sections in Figs. 4 and 5. The red line represents the flight track location of the ER-2 and P-3 through central New York and the cross sections in Figs. 6, 9, and 10.

Weather Surveillance Radar 1988 Doppler (WSR-88D) equivalent reflectivity factor, \(Z_e\), hereafter reflectivity, composites at 2.5 km altitude overlaid with the 700 mb kinematic frontogenesis field from the Rapid Refresh (RAP; Benjamin et al. 2016) analysis show the hourly
The evolution of the comma head from 1400-1700 UTC as the two aircraft sampled the storm (Fig. 3a,c,d,e). The comma head exhibited a broad mesoscale region of higher $Z_e$ that was oriented linearly from southwest to northeast. The region of higher $Z_e$ did not fit the Novak et al. (2008) or Ganetis et al. (2018) definitions of mesoscale snowbands. For simplicity, we will refer to this linear region of higher $Z_e$ as a band. The band axis was collocated with the axis of maximum frontogenesis at 700 hPa during all periods (white dashed line; Fig. 3). An abrupt gradient in the value of the WSR-88D correlation coefficient, determined by visual inspection, marked the location of the rain-snow line at 2.5 km along the warm side of the comma head (black dashed line; Fig. 3b,f). A second region of higher $Z_e$ appeared along the warm side of the correlation coefficient gradient and coincided with the location of the radar bright band associated with melting ice particles at 2.5 km (Fig. 3a,c, and d).

Fig. 4a-f show vertical cross sections of thermodynamic and kinematic variables from the Rapid Refresh Model analysis valid 7 February 2020 at 1500 UTC from Central Michigan to a point south of Maine over the Atlantic Ocean (dashed black line on Fig. 2) along the flight paths of the ER-2 and P-3 over New York State (red line on Fig. 2). The warm frontal zone is denoted by the transparent red shading, and the stationary frontal zone by the transparent blue shading on Fig. 4a-c. On Fig. 4d-f the frontal zones are outlined by dark solid lines. The thick vertical black lines bound the region sampled by the ER-2 and P-3.

The warm front extended from the surface just south of Nova Scotia upward to a weak dynamic tropopause fold (Fig. 4a) at the 7 km level over southwestern Ontario. The warm front was identified by an enhanced horizontal and vertical gradient of potential temperature and equivalent potential temperature, as well as an axis of kinematic frontogenesis with values ranging from 0.2 to 1.2 K 100 km$^{-1}$ 3 hr$^{-1}$ (Fig. 4a-c). The surface position of the stationary front was located 50 km west of Albany, NY (Fig. 1a). The front sloped upward and westward reaching a level of ~2 km over Central Michigan at 1500 UTC. This front was the boundary between air circulating anticyклонically about a 1022 hPa high-pressure center located south of Hudson Bay and air circulating cyclonically off the North Atlantic north of the warm front. The front was marked by a shift of the wind from a northerly to southerly component with increasing altitude, and an enhanced horizontal and vertical gradient of potential temperature and equivalent potential temperature (Fig. 4a,b,e).
The jet axis at 1500 UTC was located at 11 km elevation on the east end of the cross section and coincided with the eastern end of the ER-2 flight legs (Fig. 4e). The jet had a maximum wind speed of 97 m s\(^{-1}\) over Eastern New York state. A dry air intrusion associated with the jet extended slantwise downward toward the east from -75.25° to -68.5° longitude from the dynamic tropopause (10 km, 2 PVU) to 3.5 km (Fig. 4f).

Fig. 3: WSR-88D 2.5 km composites of \(Z_e\) and 700 hPa kinematic frontogenesis (K\(^{-1}\) 100 km\(^{-1}\) 3 hr\(^{-1}\); contoured) from RAP analysis for a: 1400, c: 1500, d: 1600, and e: 1700 UTC 7 February 2020. WSR-88D correlation coefficient for b: 1400 and f: 1700 UTC 7 February 2020. The white dashed lines in a, c, d, and e represent the axis of the mesoscale snowband discussed in the text. The black dashed lines in a, c, d, and e represent the location of the melting level at 2.5 km subjectively determined using the correlation coefficient. The black line in a, b, c, and d is the flight track of the ER-2 and blue line in d, e, and f is the flight track of the P-3. Flight legs (FL) are labeled.
To better understand the airmass structure across the comma head associated with the cross sections in Fig. 4, North American Model (NAM) 12-km, 48-hour HYSPLIT back trajectories were plotted every 500 m for every degree of longitude between -85° and -70° along the cross section (Fig. 5). The atmospheric kinematic and thermodynamic structure in Fig. 4 is related to the trajectories starting within the stratosphere and continuing downward to the ground.

Air parcels within and above the jet maxima were part of the subtropical jet stream and originated 48 hours earlier over the subtropical North Pacific Ocean (Fig. 5f). Air beneath the jet maxima originated within the polar front jet stream 48 hours earlier over the Pacific Ocean west of Washington state and British Columbia. This air traveled through the ridge present west of the Rockies and then through the trough over the Central U.S. before arriving at the cross section (Fig. 5a,e). Air within the polar jet stream had low relative humidity compared to the moist subtropical air above it (Fig. 4f). The airmass associated with the polar jet stream formed the dry air intrusion evident in GOES-16 satellite imagery (not shown) and influenced the stability structure on the eastern side of the cross section (see Sec. 4).

Moist air above the warm front and below the polar jet airmass originated 48 hours earlier over the Baja region and the Gulf of Mexico (Fig. 5a,d). Air parcels arriving at lower altitudes on the eastern end of the cross section had limited vertical ascent and sourced over the Gulf of Mexico while parcels with the greatest ascent, and consequently the highest relative humidity, were sourced over the Northeast Pacific at low elevations near the Baja Peninsula (Fig. 5a,d,h). Synoptic scale ascent above the warm front was of the order of 0.3 to 0.5 m s\(^{-1}\) based on model-derived vertical motion (Fig. 4d). The airmass directly above the warm front was saturated with respect to ice and contained cloud (Fig. 4f).

Air originating beneath the stationary front was sourced 48 hours earlier from air near the Canadian Border north of the cross section. Air beneath the stationary front remained at low levels with most trajectories traversing eastward toward the developing low without appreciable vertical motions (Fig. 5a,b,h). Air between the two frontal zones was also saturated with respect to ice, and originated 48 hours earlier over the U.S. Great Plains and the Rocky Mountains, again without appreciable ascent over the previous 48 hours (Fig. 5a,c,h).
Fig. 4: RAP analysis cross sections along flight tracks at 42.9° latitude between -85 and -65° longitude valid at 1500 UTC on 7 February 2020. On panels a, b, and c the stationary frontal zone is shaded in blue and the warm frontal zone is shaded in red. These regions are outlined by black solid lines on d, e, and f. The vertical black lines represent the study area sampled by the ER-2 and P-3. The dashed black line is the dynamic tropopause (2 PVU). a: $\theta$ (K). b: $\theta_e$ (K). c: kinematic frontogenesis in K$^{-1}$ 100 km$^{-1}$ 3 hr$^{-1}$. d: model updraft strength ($w$) (m s$^{-1}$). e: $u$ component of the wind is shaded and the $v$ component of the wind is contoured (m s$^{-1}$) (white contours for wind speeds greater than 55 m s$^{-1}$ for clarity). The dashed contours represent winds coming out of the page and solid contours represent winds into the page. f: relative humidity with respect to ice ($RH_{ice}$). Hatched regions denote $RH_{ice} > 100\%$. 

Accepted for publication in *Journal of the Atmospheric Sciences*. DOI 10.1175/JAS-D-22-0118.1.
Fig. 4 continued.
Fig. 5: Cross section showing ending points (in time) of 48-hour HYSPLIT back trajectories calculated using 12-km NAM data valid at 1500 UTC 7 February 2020. a: Colors correspond to trajectories coming from various source regions in b-f below. \( \theta \) (K) from RAP analysis valid at 1500 is overlaid over the different airmasses. b: blue trajectories represent air beneath the stationary front. c: teal trajectories represent air between the stationary and warm front. d: green trajectories represent air above the warm front. e: yellow trajectories represent air associated with the polar jet stream. f: orange trajectories represent air associated with the subtropical jet stream. g: change in relative humidity with respect to water (\( RH_{\text{Water}} \)) between the start and end points of the trajectories. h: change in height (km) between the start and end points of the trajectories associated with different air masses. Letters and box plot colors correspond to the panels above. Boxes represent the 25th, 50th, and 75th percentiles. Whiskers represent the maximum and minimum data points.
3 IMPACTS Aircraft Data

The ER-2 aircraft sampled the storm between 1355 and 1613 UTC and completed six total flight legs at an altitude of approximately 20 km. The ER-2 carried three radars, the ER-2 X-band Doppler Radar (EXRAD, 9.6 GHz; McLinden et al. 2021a) with a conical/cross-track scanning beam and a fixed nadir beam, the High-Altitude Imaging nadir pointing Wind and Rain Airborne Profiler (HIWRAP, Ku-13.9 GHz, Ka-35.6 GHz; Li et al. 2008), and the nadir pointing W-band Cloud Radar System (CRS, 94 GHz; McLinden et al. 2021b). This analysis examines the horizontal variability of cloud substructures and circulations using the EXRAD fixed nadir beam equivalent reflectivity factor, $Z_e$, in order to take advantage of reduced attenuation, and the CRS vertical radial velocity, $V_r$, due to its smaller beamwidth and higher sensitivity (McLinden et al. 2021a). The EXRAD beamwidth is 3.3° with a footprint of 1.2 km at the surface when the aircraft is flying at 20 km. The CRS beamwidth is 0.46° with a footprint of 0.16 km at the surface from the same altitude.

The P-3 aircraft sampled the storm between 1507 and 1718 UTC, completing seven total flight legs. On flight legs 6 and 7, the reflectivity in the upper part of the cloud had weakened substantially. Elevated convection, and its impact on precipitation, had ceased by the time the fifth leg was completed and the P-3 was only sampling the rapidly weakening stratiform region of the comma head at higher altitudes. Therefore, flight legs 6 and 7 were not included in the analysis in this paper. This analysis considers the first five P-3 flight legs (referred to as Flight Legs 1-5 or FL1-5 in Table 1). The P-3 flight legs were completed at altitudes between 2 and 6 km, and at temperatures between 0°C and -27°C and are shown in subsequent figures from highest to lowest altitude. Both aircraft flew a fixed flight track over central New York from longitudes of approximately -73.50° to -76.50°, with latitudes varying between 42.9° and 43.1°. Three flight legs between the ER-2 and P-3 were coordinated, followed by additional P-3 flight legs when the ER-2 returned to base.
Table 1: Sampling Characteristics of each P-3 flight leg. Coordinated flight legs with the ER-2 are in bold. Temperature layers sampled include the dendritic growth layer (DGL), plate growth layer (PGL), needle growth layer (NGL), and enhanced aggregation layer (EAL).

<table>
<thead>
<tr>
<th>Flight Leg</th>
<th>Time (UTC)</th>
<th>Direction</th>
<th>Altitude (km)</th>
<th>Temperature (°C)</th>
<th>Temperature Layer Sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Stratiform Region</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>15:03:50-15:12:02</td>
<td>West-East</td>
<td>5.2</td>
<td>-15.9 to -15.0</td>
<td>DGL</td>
</tr>
<tr>
<td>2</td>
<td>15:37:18-15:49:20</td>
<td>East-West</td>
<td>3.6</td>
<td>-12.2 to -8.3</td>
<td>PGL</td>
</tr>
<tr>
<td>3</td>
<td>15:52:00-16:06:25</td>
<td>West-East</td>
<td>3.3</td>
<td>-12.8 to -7.3</td>
<td>PGL, NGL</td>
</tr>
<tr>
<td>4</td>
<td>16:28:18-16:43:20</td>
<td>East-West</td>
<td>2.4</td>
<td>-5.0 to -2.8</td>
<td>NGL</td>
</tr>
<tr>
<td><strong>Convective Region</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>15:12:02-15:22:50</td>
<td>West-East</td>
<td>5.2</td>
<td>-15.6 to -13.9</td>
<td>DGL</td>
</tr>
<tr>
<td>2</td>
<td>15:26:40-15:37:18</td>
<td>East-West</td>
<td>3.6</td>
<td>-8.6 to -5.4</td>
<td>PGL, NGL</td>
</tr>
<tr>
<td>3</td>
<td>16:06:25-16:13:40</td>
<td>West-East</td>
<td>3.3</td>
<td>-7.7 to -2.2</td>
<td>NGL, EAL</td>
</tr>
<tr>
<td>4</td>
<td>17:03:16-17:18:20</td>
<td>West-East</td>
<td>2.7</td>
<td>-5.0 to -0.7</td>
<td>NGL, EAL</td>
</tr>
<tr>
<td>4</td>
<td>16:17:20-16:28:18</td>
<td>East-West</td>
<td>2.4</td>
<td>-3.7 to -0.2</td>
<td>NGL, EAL</td>
</tr>
</tbody>
</table>

Fig. 6a-h shows vertical Multi-Radar Multi Sensor (MRMS; Smith et al. 2016) cross sections of WSR-88D Z_e during all ER-2 and P-3 flight legs together with EXRAD Z_e (Figs. 6i-n) along the same cross section when available. The P-3 arrived onsite after the ER-2 had completed three flight legs (Figs. 6i-n). The height, location, and temperatures at which the P-3 was sampling are noted along each MRMS and EXRAD cross section. The ER-2 departed at 1613 UTC, and the P-3 continued to sample through 1820 UTC. The vertical cross sections show the storm weakening from the west with time especially along later P-3 flight legs. The mesoscale snowband was visible in EXRAD Z_e cross sections (at 2.5 km where Z_e was >32.5 dBZ) but was too fine scale and/or low to be retrieved by the MRMS resampling algorithm. The vertically stacked flight legs of the P-3 allowed for the sampling of different particle growth layers and a vertical profile of particle growth in the comma head of the 7 February 2020 snowstorm.

The P-3 aircraft was equipped with a full suite of microphysics instrumentation, including a Cloud Droplet Probe (CDP; Lance et al. 2010, 2012), a Two-Dimensional Stereo probe (2DS; Lawson et al. 2006), and High-Volume Precipitation Spectrometers (HVPS-3A and HVPS-3B; Lawson 1993; 1998) for particle size information. The HVPS-3A (hereafter referred to as HVPS) was mounted to the P-3 vertically (its orientation consistent with the channel used herein with the 2DS). A Particle Habit Imaging and Polar Scattering Probe (PHIPS; Abdelmonem et al. 2016; Schnaiter et al. 2018) was used for particle imagery; and the Rosemount Icing Detector (RICE; Baumgardner and Rodi 1989) for supercooled water detection. Data from the CDP were used for
particles between 2 and 50 µm; the 2DS for particles between 100 and 1400 µm (1.4 mm); and the HVPS for particles >1400 µm (1.4 mm). The size ranges used for the 2DS and HVPS probes were determined as follows: (1) A lower threshold (100 µm) for the 2DS was chosen in accordance with previous studies to minimize uncertainty in the depth of field (e.g., Lawson et al., 2006) and to remove potentially shattered artifacts (e.g., Korolev et al. 2011; Jackson et al. 2014). (2) An upper threshold (1400 µm, or 1.4 mm) was selected as the 2DS-HVPS cutoff point. The 1.4 mm threshold was selected because the concentrations from the 2DS and HVPS most consistently overlapped at this size (Fig. 7), even though this size is larger than the approximately 1 mm threshold that has been used in several prior studies (e.g., Hu et al. 2021).

Fig. 6: a-h: Cross sections of MRMS $Z_e$ (left) valid at times shown. i-n: EXRAD $Z_e$ cross sections (right). P-3 flight level heights, temperatures, and times are overlaid over both sets of cross sections. See Table 1 for P-3 flight leg times, temperature ranges, and ice particle growth regimes being sampled. The solid vertical black lines indicate the SR-CR boundary.
2DS and HVPS probe data were processed using the University of Illinois/Oklahoma Optical Array Probe Processing Software (UIOOPS; McFarquhar et al. 2018). Using UIOOPS, several steps were taken to ensure the quality of the data. A time-dependent threshold, calculated for every 25,000 particles, was used to remove shattered artifacts from the 2DS data following the approaches of Field et al. (2006) and Stechman et al. (2020). Following the removal of shattered artifacts, an additional processing technique was applied to estimate particle size for particles that were not entirely within the 2-D sensing area, as outlined in Heymsfield and Parrish (1978). Finally, the size of each particle was determined as the diameter of the minimum enclosing circle, and bulk microphysical characteristics were calculated at 1-Hz intervals. The 2DS experienced overloads (McFarquhar et al. 2017) where particle images were lost. When this occurred, there was a dead period when no data were recorded. Although the 2DS tracks dead time so that the sample volume can be corrected during overload periods, it is uncertain how reliable size distributions and the calculation of total number concentration are for time periods with large dead time. In this study, all 1 s periods with a dead time greater than 0.7 s were removed from subsequent analysis. Further, periods with dead times greater than 0.2 s were flagged and are denoted in the 2DS time series appearing later in the paper as calculated concentrations are more uncertain in these regions. Large deadtimes primarily occurred during the first P-3 flight leg. If a more stringent dead time than 0.7 s was chosen for inclusion, there would be a bias away from times with higher concentrations (see Appendix).
In addition to the quantitative information provided by the 2DS and HVPS probes, PHIPS stereo-imagery was manually classified according to particle habit types identified in Bailey and Hallett (2009). Information about particle characteristics, particle growth, riming, dendritic growth, and particle habit were manually recorded and quantified for FL 1-3 using the same approach as in Waitz et al. (2022). The manual classification was performed by three people independently from each other. In total, 9134 stereo-image pairs were visually inspected, from which 3414 were assigned a habit classification. Images that were not given a habit assignment were shattering events where no identification of the original particle was possible. The absolute uncertainty in the given particle fraction is around ±5%.

Five microphysical quantities were analyzed: (1) total number concentration, \( N_t \), (2) ice water content, \( IWC \), (3) supercooled liquid water (SLW) content, (4) composite ice particle size distributions, and (5) PHIPS stereo-images to determine particle habit and characteristics. \( N_t \) was calculated by summing the number concentration within each bin of the 2DS probe, \( N_{2DS} \), particle sizes with maximum diameters \( 100 \, \mu m < D < 1.4 \, mm \) and the number concentration within each bin of the HVPS probe \( N_{HVPS} \), particles sizes \( D > 1.4 \, mm \). Composite particle size distributions in the stratiform and convective regions of the storm were developed from the 2DS and HVPS measurements. Total ice water content was calculated using mass-area relationships following Baker and Lawson (2006). Mass may be underestimated for particles that touch the edge of the photodiode array since the particle area could not be reconstructed. This mass underestimation is more likely for particles approaching 1.4 mm as the 2DS field of view is only 1.28 mm. The CDP and RICE probes were used together to detect SLW when temperatures were lower than -7°C. The CDP can be triggered by both cloud droplets and ice particles. Periods with CDP concentrations >10 cm\(^{-3}\) or voltage changes of at least 2 Hz were identified as periods with SLW present (e.g., Hobbs and Rangno 1998; Cober et al. 2001; Lance et al. 2010; Um et al. 2018; Finlon et al. 2019; Wang et al. 2020). At temperatures greater than -7°C, the RICE probe data becomes unreliable and only the CDP concentration criteria were used to identify SLW regions. Cloud liquid water measurements were made at a rate of 1 Hz.

Several distinct temperature layers were observed by the P-3, which correspond to the ice particle growth regimes identified by Bailey and Hallett (2009) as a function of temperature and supersaturation. Using the Bailey and Hallett criteria, temperature \( T \) layers were defined as follows: (1) the polycrystalline growth layer \((PCGL; T < -18^\circ C)\); (2) the dendritic growth layer

17
(DGL; \(-18^\circ C \leq T < -12^\circ C\)); (3) the plate growth layer (PGL; \(-12^\circ C \leq T < -8^\circ C\)); and (4) the needle growth layer (NGL; \(-8^\circ C \leq T < -3^\circ C\)). An additional layer, the enhanced aggregation layer (EAL), was defined between -3°C and 0°C. Note that although particle habits are established in these layers, particles with these habits can be observed at warmer temperatures as particles fall through the cloud.

The variability and magnitude of \(N_t\), IWC, and SLW are quantitatively analyzed using box-and-whisker plots that show the minimum and maximum values \((N_{min} \text{ and } N_{max})\), 25th and 75th percentile values \((N_{25} \text{ and } N_{75})\), and median values \((N_{median})\), where each data point represents a 1 Hz sample, or for the CDP, 1 Hz SLW content integrated from the droplet size distributions. Particle size distributions were developed for the stratiform and convective regions on each flight leg as discussed below. \(N_{2DS}\) and \(N_{HVPS}\) were also calculated within those regions. PHIPS stereo-images shown are the most representative particle habits within these regions.

Vapor deposition was inferred by examining the existence of faceted crystals in the PHIPS stereo-images and whether they were consistent with temperature regimes defined in Bailey and Hallett (2009), or consistent with temperatures above the altitude they were observed (implying that the particles fell from aloft). Increases in IWC between layers provided quantitative evidence for vapor depositional growth. Particle growth consistent with aggregation was inferred by decreases in \(N_t\) and \(N_{2DS}\) that were accompanied by increases in \(N_{HVPS}\) between layers. PHIPS stereo-images were used to qualitatively confirm aggregation. Particle growth by riming was inferred by the presence of frozen cloud droplets attached to ice particles in PHIPS stereo-images. Some Bailey and Hallett (2009) defined particle growth layers were sampled on two or more flight legs; when this occurred, microphysical quantities from each flight leg will be presented.

To identify particle growth mechanisms consistent with observations through the depth of the cloud requires the assumption that a steady state exists during the 3-hour sampling time of the flight legs. Although trends in the microphysical data were generally consistent with particle growth mechanisms expected in various layers, the observations were not obtained in a Lagrangian framework or in a steady state cloud system, especially given that the component of the wind normal to the cross section was large (Fig. 4e). Winds beneath the stationary front were northerly at 10-13 m s\(^{-1}\), while winds above the warm front were southerly at 20-50 m s\(^{-1}\). The entire weather system moved northward during the sampling period, with MRMS radar echoes in both the eastern (convective) region and western (stratiform) region weakening with time, particularly after FL5 of
the P-3. For this reason, analyses herein are limited to the first 5 P-3 flight legs. The results shown in Sec. 5 should be interpreted with these caveats in mind.

4 Stability and Moisture Characteristics

For the purpose of microphysical analysis, airborne measurements of $Z_e$ and $V_r$ collected by the ER-2 aircraft, together with thermodynamic data from the RAP analysis, were used to divide the sampling cross section within the comma head into two distinct regions. Fig. 8 shows shorter $Z_e$ and $V_r$ cross sections of ER-2 FL1 that were representative of these two regions. To the west, the comma head was characterized by a deep stratiform region (SR) with $Z_e$ increasing eastward and with depth beneath cloud top (Fig. 8a). Except near radar echo top, the CRS $V_r$ showed little variation with depth beneath cloud top, with a median value ranging from -1.2 to -0.9 m s\(^{-1}\) between 2 km and 7.5 km, typical terminal velocity values for unrimed ice particles falling from high altitudes to the ground (Figs. 8b,c) (e.g. Rosenow et al. 2014, Grasmick and Geerts, 2020). Below the cloud top region, none of the values exceeded 0 m s\(^{-1}\). The cloud top in the SR was capped by generating cells which had a depth of 1 km with a median $V_r$ of 0.75 m s\(^{-1}\) and extreme values of $V_r$ approaching +1 m s\(^{-1}\) (Fig. 8c). To the east, an elevated convective region (CR) was present within the comma head, with $Z_e$ in the layer between 3 km and echo top characterized by reflectivity towers east of -75.2° longitude (Fig. 8d). The layer between 5 and 7 km within the CR was weakly potentially unstable, and $V_r$ within this region had median values ranging from -0.75 to -0.4 m s\(^{-1}\) and extreme values approaching +2 m s\(^{-1}\) (Fig. 8e,f). Updrafts extending to cloud top had median $V_r$ of 0.25 m s\(^{-1}\) with extreme values again approaching +2 m s\(^{-1}\). In the CR, the median $V_r$ decreased with depth beneath cloud top to values near -2 to -1.5 m s\(^{-1}\) just above the melting layer, which was located at the 3 km level on the east side of the CR. The melting layer sloped downward to the surface west of -74.6° longitude.

The position of the SR-CR boundary was determined qualitatively from the EXRAD radar data and by a distinct change in particle habits determined using PHIPS stereo-imagery. This boundary was evident on all five P-3 flight legs. Times and locations used to separate the SR from the CR can be found below in Table 2. In Sec. 5 the microphysical boundary is used to delineate processes within the two regions.
Fig. 8: Expanded segments of FL1 from the SR (a-b) and CR (d-e). a: EXRAD $Z_e$ valid between 141847 and 142556 7 February 2020 in the SR. b: CRS $V_r$ (m s$^{-1}$) from flight leg 1 overlain with $\theta_e$ (K) in the SR. c: Contoured frequency by altitude diagram (CFAD) of CRS $V_r$ binned every 100 m in altitude and 0.1 m s$^{-1}$ for the data in b. d: EXRAD $Z_e$ valid between 135704 and 140426 7 February 2020 in the CR. e: CRS $V_r$ (m s$^{-1}$) overlain with $\theta_e$ (K) in the CR. f: CFAD of CRS $V_r$ binned every 100 m in altitude and 0.1 m s$^{-1}$ for the data in e.
Table 2: Location and time of the stratiform-convective boundary based on PHIPS stereo-images. Periods of the westernmost rain-snow transition observed during P-3 flight legs are also noted.

<table>
<thead>
<tr>
<th>Flight Leg</th>
<th>SR-CR Boundary Microphysics Lon</th>
<th>SR-CR Boundary Microphysics Time</th>
<th>Westernmost Rain-Snow Boundary Lon</th>
<th>Westernmost Rain-Snow Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-75.06</td>
<td>15:12:02 UTC</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>-74.97</td>
<td>15:37:18 UTC</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>-74.64</td>
<td>16:06:25 UTC</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>-74.67</td>
<td>17:03:16 UTC</td>
<td>-73.58</td>
<td>17:13:48 UTC</td>
</tr>
<tr>
<td>4</td>
<td>-74.86</td>
<td>16:28:18 UTC</td>
<td>-73.92</td>
<td>16:18:26 UTC</td>
</tr>
</tbody>
</table>

The SR was characterized by a stable vertical profile (Fig. 9b) with synoptic scale vertical motion above the warm frontal zone of 0.1 to 0.3 m s$^{-1}$ (Fig. 10), lower temperatures (Fig. 9c), intrusion of unsaturated air in the mid-levels on the western side of the cross section (Fig. 9d,e), and an overall weakening trend in precipitation during the sampling period with WSR-88D reflectivity decreasing from ~20 dBZ at 1500 UTC to ~10 dBZ by 1800 UTC (Fig. 6i, j). Within the SR, relative humidity with respect to ice ($RH_{Ice}$) exceeded 100% above the warm front and below the stationary front but decreased beneath 100% between 2-4 km (Fig. 9e). No air was saturated with respect to water within the SR based on the RAP analysis (Fig. 9d). With only weak, non-convective vertical motions below cloud top observed with the CRS radar $V_r$, air within the SR would have rarely reached water saturation in the natural cloud (Fig. 9b). Precipitation reached the ground as snow within the SR, except possibly within the mesoscale snowband (Fig. 9c). There, between the surface and 1 km altitude, $V_r$ decreased from ~1 m s$^{-1}$ to ~4 m s$^{-1}$, characteristic of ice particles melting into raindrops (Fig. 9b). No direct observations were available at the surface beneath the band to determine whether precipitation at the ground consisted of wet snowflakes or rain, but the higher reflectivities associated with the band were clearly influenced by melting (Fig. 9a).

The CR was characterized by higher temperatures, higher ice supersaturations relative to the SR (Fig. 9c, e), and synoptic scale vertical motions above the warm frontal zone of 0.2 to 0.5 m s$^{-1}$ (Fig. 10). The primary features of the CR were 2-2.5 km deep sloped reflectivity plumes descending beneath elevated convection (Fig. 9a,c). The location of these convective vertical motions coincided with a layer of weak potential instability along the interface of the moist airmass over the warm front and drier air associated with the polar front jet (Figs. 4f, 5a, 9e). Based on the presence of SLW within convection sampled by the P-3 (see next section), the convective vertical motions were sufficient for the rising air to exceed water saturation.
Fig. 9: a: ER-2 EXRAD $Z_e$ cross section from 1355 to 1429 UTC on 7 February 2020. b: ER-2 CRS vertical $V_r$ (m s$^{-1}$) overlaid with $\theta_e$ (K) from RAP analysis valid at 1500 UTC. c: particle growth layers overlaid with temperature from RAP analysis at 1500 UTC (°C) (Bailey and Hallett 2009). Particle growth layers include the polycrystalline growth layer (PCGL) in blue, the dendritic growth layer (DGL) in green, the plate growth layer (PGL) in lime green, the needle growth layer (NGL) in yellow, the enhanced aggregation layer (EAL) in orange, and the above freezing layer (ABF) in red. d: relative humidity with respect to water ($RH_{\text{water}}$). e: relative humidity with respect to ice ($RH_{\text{ice}}$). Hatched regions denote $RH_{\text{ice}} > 100\%$. On all cross sections the stationary and warm frontal zones are outlined by black lines. Solid vertical lines on all panels indicate the boundary between the SR and CR estimated from $Z_e$ and $V_r$. The P-3 had not yet arrived, and microphysical data were not available on this flight leg.
Fig. 10: Model $w$ from RAP analysis valid at a: 1400 UTC, b: 1500 UTC, c: 1600 UTC, d: 1700 UTC on 7 February 2020. Solid vertical lines delineate the boundary between the stratiform region (left) and convective region (right) determined using microphysics data. The horizontal line indicates the flight height along a given research flight.
5 Microphysical Characteristics

5.1 Stratiform Region

As evident in Fig. 6, the radar reflectivity within the SR weakened with time, particularly on the west side of the cross section. Flight legs 1-4 (FL1-4) sampled the DGL, PGL, and NGL progressively downward earlier in the storm, with FL5 higher in altitude than FL4, but also in the NGL.

FL1 sampled the DGL at an altitude of 5.2 km (-15.9 to -15.0°C) in the SR. \( N \) ranged from 10.3-99.6 L\(^{-1} \) with \( N_{\text{median}} = 20.6 \) L\(^{-1} \) (Fig. 11, Table 3) for periods with dead time \( \leq 0.7 \) s and from 10.3-27.5 L\(^{-1} \) with \( N_{\text{median}} = 17.6 \) L\(^{-1} \) for periods with dead time \( \leq 0.2 \) s (Table 3). \( N_{\text{2DS}} \) and \( N_{\text{HVPS}} \) varied little relative to the CR across the SR at this altitude (Figs. 12, 13). The particle size distribution (PSD) had mean \( N_{\text{2DS}} = 21.5 \) L\(^{-1} \) (15.0 L\(^{-1} \) for dead time \( \leq 0.2 \) s) and had mean \( N_{\text{HVPS}} = 3.0 \) L\(^{-1} \) (Fig. 14, Table 4). Limited SLW was present across the SR in the DGL, consistent with the air being unsaturated with respect to water and dendritic particle formation and growth not occurring (Figs. 15, 16, 17). Particle habit analysis using PHIPS stereo-imagery showed primarily side planes (83.5% of particles), other polycrystalline habits (9.7% of particles) and single plate-like particles (3% of particles) (Figs. 18, 19, Table 5) consistent with the fall of particles from above the flight altitude into the DGL from the PCGL, rather than formation in the DGL. Of the PHIPS analyzed particles, 96.1% were unrimed in the SR on FL1. The IWC of the particles in the DGL ranged from 0.5-1.7 g m\(^{-3} \), with \( IWC_{\text{median}} = 0.8 \) g m\(^{-3} \) (Fig. 20, Table 6).

FL2 sampled the PGL (-12.2 to -8.3°C) at an altitude of 3.6 km and FL3 sampled the PGL and colder temperatures of the NGL (-12.8 to -7.3°C) at an altitude of 3.3 km. \( N \) ranged from 4.5-38.9 L\(^{-1} \) with \( N_{\text{median}} = 12.4 \) L\(^{-1} \) on FL2 (from 4.5-18.8 L\(^{-1} \) with \( N_{\text{median}} = 10.4 \) L\(^{-1} \) for dead time \( \leq 0.2 \) s) and from 5.0-42.0 L\(^{-1} \) with \( N_{\text{median}} = 13.8 \) L\(^{-1} \) on FL3 (from 5.0-21.2 L\(^{-1} \) with \( N_{\text{median}} = 13.2 \) L\(^{-1} \) for dead time \( \leq 0.2 \) s) (Fig. 11, Table 3), concentrations comparable to those sampled in the DGL. Again, \( N_{\text{2DS}} \) and \( N_{\text{HVPS}} \) varied little relative to the CR across the SR at these altitudes (Figs. 12, 13). Averages of \( N_{\text{2DS}} = 9.9 \) L\(^{-1} \) (7.9 L\(^{-1} \) for dead time \( \leq 0.2 \) s) and \( N_{\text{HVPS}} = 3.2 \) L\(^{-1} \) for FL2 and \( N_{\text{2DS}} = 10.8 \) L\(^{-1} \) (10.0 L\(^{-1} \) for dead time \( \leq 0.2 \) s) and \( N_{\text{HVPS}} = 3.2 \) L\(^{-1} \) for FL3 (Fig. 14, Table 4) were observed. Again, there was no SLW observed on both flight legs (Figs. 15, 16, 17), and PHIPS stereo-imagery analysis showed side planes (76.8%-82.2% of particles), polycrystalline habits (6.3-7.2% of particles) and single plate like particles (2.4-2.9% of particles) (Figs. 18, 19, Table 5).
5). On FL2-3 over 90% of PHIPS analyzed particles were unrimed and any riming was very light. Capped columns and plate-column mixes were also observed (4.6-6.2% of particles). The $IWC$ of the particles in the $PGL$ on FL2 ranged from 0.4-2.9 g m$^{-3}$, with $IWC_{median} = 1.1$ g m$^{-3}$, and on FL3 ranged from 0.6-1.7 g m$^{-3}$, with $IWC_{median} = 1.1$ g m$^{-3}$ (Fig. 20, Table 6). These data together imply that most particles fell from aloft and continued to grow by vapor deposition as they fell through the $PGL$ and upper $NGL$, with few new particles, such as plate-column mixes, forming in situ.

FL4 and FL5 sampled the $NGL$ at altitudes of 2.4 (-5.0 to -2.8°C) and 2.7 km (-6.6 to -4.5°C). Again, there was little variation along the track in $N_{2DS}$ or $N_{HVPS}$ at these altitudes (Figs. 12, 13). For example, $N$, ranged from 5.0-21.6 L$^{-1}$ with $N_{median} = 10.4$ L$^{-1}$ on FL4 and from 5.0-18.8 L$^{-1}$ with $N_{median} = 11.8$ L$^{-1}$ on FL5 (Fig. 11, Table 3), concentrations similar to that within the $PGL$. Since dead times were minimal on FL4 and FL5, there were few potential periods with high concentrations that would be excluded using a more conservative dead time threshold. The PSDs had $N_{2DS} = 8.3$ L$^{-1}$ and $N_{HVPS} = 2.5$ L$^{-1}$ for FL4 and $N_{2DS} = 9.4$ L$^{-1}$ and $N_{HVPS} = 2.6$ L$^{-1}$ for FL5 (Fig. 14, Table 4). There was limited SLW on either flight leg (Figs. 15, 16, 17), and PHIPS stereo-imagery again showed that the dominant particle habits were side planes and plate-like particles with a few plates and capped columns. The $IWC$ of the particles in the $NGL$ on FL4 ranged from 0.2-2.1 g m$^{-3}$, with $IWC_{median} = 1.0$ g m$^{-3}$ and on FL5 from 0.3-1.8 g m$^{-3}$, with $IWC_{median} = 0.9$ g m$^{-3}$ (Fig. 20, Table 6).

A comparison of backscatter coefficient and depolarization ratio from the cloud physics lidar revealed that cloud top within the SR was dominated by ice. Based on the lidar returns at cloud top, no supercooled water was present. The cloud top was colder than -40°C across most of the SR meaning side planes likely formed as a result of heterogeneous freezing on aerosol at temperatures colder than -40°C. Based on aircraft in situ measurements, and habit analysis, there was very limited supercooled liquid water if any present within the SR beneath cloud top and growth by accretion was relatively rare. There was no systematic increase in $N_{HVPS}$ with depth between the aircraft flight levels (Fig. 13) implying that growth by aggregation was also limited. In situ measurements in the SR are consistent with the formation of side planes and plate-like particles forming in the upper part of the cloud above the highest flight level and growing by vapor deposition through the depth of the cloud.
Table 3: Measurements of total number concentration (number per L\(^{-1}\)) for the minimum \((N_{\text{min}})\), 25\(^{\text{th}}\) \((N_{25})\), 50\(^{\text{th}}\) \((N_{50})\), 75\(^{\text{th}}\) \((N_{75})\), and maximum \((N_{\text{max}})\) values in the stratiform and convective regions corresponding to Fig. 11. For flight levels where more than 20% of the 1 s time periods have dead times (dt) > 0.2 s, separate statistics on \(N_t\) are provided using a more conservative dead time threshold (≤ 0.2 s).

<table>
<thead>
<tr>
<th>Flight Leg</th>
<th>Particle Growth Layer</th>
<th>(N_{\text{min}})</th>
<th>(N_{25})</th>
<th>(N_{50})</th>
<th>(N_{75})</th>
<th>(N_{\text{max}})</th>
<th>Particle Growth Layer</th>
<th>(N_{\text{min}})</th>
<th>(N_{25})</th>
<th>(N_{50})</th>
<th>(N_{75})</th>
<th>(N_{\text{max}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (dt ≤ 0.2 s)</td>
<td>DGL</td>
<td>10.3</td>
<td>15.9</td>
<td>17.6</td>
<td>19.4</td>
<td>27.5</td>
<td>DGL</td>
<td>1.9</td>
<td>5.3</td>
<td>7.6</td>
<td>10.2</td>
<td>33.4</td>
</tr>
<tr>
<td>1 (dt ≤ 0.7 s)</td>
<td>DGL</td>
<td>10.3</td>
<td>17.3</td>
<td>20.6</td>
<td>29.6</td>
<td>99.6</td>
<td>DGL</td>
<td>1.9</td>
<td>6.2</td>
<td>8.6</td>
<td>13.8</td>
<td>55.0</td>
</tr>
<tr>
<td>2 (dt ≤ 0.2 s)</td>
<td>PGL</td>
<td>4.5</td>
<td>8.8</td>
<td>10.4</td>
<td>12.4</td>
<td>18.8</td>
<td>PGL, NGL</td>
<td>0.1</td>
<td>2.0</td>
<td>7.5</td>
<td>10.1</td>
<td>57.5</td>
</tr>
<tr>
<td>2 (dt ≤ 0.7 s)</td>
<td>PGL</td>
<td>4.5</td>
<td>9.6</td>
<td>12.4</td>
<td>15.8</td>
<td>38.9</td>
<td>PGL, NGL</td>
<td>0.1</td>
<td>2.1</td>
<td>7.5</td>
<td>10.2</td>
<td>69.4</td>
</tr>
<tr>
<td>3 (dt ≤ 0.2 s)</td>
<td>PGL</td>
<td>5.0</td>
<td>11.2</td>
<td>13.2</td>
<td>15.2</td>
<td>21.2</td>
<td>PGL, NGL</td>
<td>2.8</td>
<td>8.9</td>
<td>10.9</td>
<td>15.4</td>
<td>172.3</td>
</tr>
<tr>
<td>3 (dt ≤ 0.7 s)</td>
<td>PGL</td>
<td>5.0</td>
<td>11.5</td>
<td>13.8</td>
<td>15.9</td>
<td>42.0</td>
<td>PGL, NGL</td>
<td>2.8</td>
<td>9.3</td>
<td>11.9</td>
<td>17.8</td>
<td>174.1</td>
</tr>
<tr>
<td>5</td>
<td>NGL</td>
<td>5.0</td>
<td>10.5</td>
<td>11.8</td>
<td>13.5</td>
<td>18.8</td>
<td>NGL, EAL</td>
<td>0.1</td>
<td>7.8</td>
<td>11.5</td>
<td>17.8</td>
<td>121.7</td>
</tr>
<tr>
<td>4</td>
<td>NGL</td>
<td>5.0</td>
<td>9.0</td>
<td>10.4</td>
<td>12.1</td>
<td>21.6</td>
<td>NGL, EAL</td>
<td>3.0</td>
<td>11.2</td>
<td>16.7</td>
<td>26.2</td>
<td>140.5</td>
</tr>
</tbody>
</table>

Fig. 11: Box and whiskers plot of \(N_t\) (number per L\(^{-1}\)) for the stratiform region (left) and the convective region (right) for all 1 Hz samples with dead time ≤ 0.7 s. Box plots have temperatures organized from lowest temperature (top) to highest temperature (bottom), specifically: \(DGL\), \(PGL\), \(NGL\), and \(EAL\). Boxes represent the 25\(^{\text{th}}\), 50\(^{\text{th}}\), and 75\(^{\text{th}}\) percentiles. Whiskers represent the mean ±1.5 times the interquartile range. Times of each flight leg can be found in Table 1 and percentiles in Table 3.
Fig. 12: $N_{2DS}$ (number per L$^{-1}$) for each flight leg as a function of longitude for all 1 Hz samples with dead time $\leq 0.7$ s. The red solid line along each flight leg indicates the microphysics boundary between the stratiform and convective region. Red arrows are subsets of microphysical data that will be shown in Fig. 21. Green shaded areas are regions where raindrops were observed. Pink shaded regions are periods of 2DS dead time $> 0.2$ s.
Fig. 13: Same as Fig. 12 except $N_{HVPS}$ (number per L$^{-1}$) is shown.
Table 4: Mean particle concentration measurements of $N_{2DS}$ and $N_{HVPS}$ corresponding to size distributions in Fig. 14 (number per L$^{-1}$). For flight levels where more than 20% of the 1 s time periods have dead times (dt) $> 0.2$ s, separate statistics on $N_t$ are provided using a more conservative dead time threshold ($\leq 0.2$ s).

<table>
<thead>
<tr>
<th>Flight Leg</th>
<th>Particle Growth Layer</th>
<th>$N_{2DS}$ (number/L$^{-1}$)</th>
<th>$N_{HVPS}$ (number/L$^{-1}$)</th>
<th>Particle Growth Layer</th>
<th>$N_{2DS}$ (number/L$^{-1}$)</th>
<th>$N_{HVPS}$ (number/L$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ($dt \leq 0.2$ s)</td>
<td>DGL</td>
<td>15.0</td>
<td>3.0</td>
<td>DGL</td>
<td>6.6</td>
<td>2.8</td>
</tr>
<tr>
<td>1 ($dt \leq 0.7$ s)</td>
<td>DGL</td>
<td>21.5</td>
<td>3.0</td>
<td>DGL</td>
<td>8.1</td>
<td>2.8</td>
</tr>
<tr>
<td>2 ($dt \leq 0.2$ s)</td>
<td>DGL</td>
<td>7.9</td>
<td>3.2</td>
<td>DGL</td>
<td>7.1</td>
<td>0.8</td>
</tr>
<tr>
<td>2 ($dt \leq 0.7$ s)</td>
<td>DGL</td>
<td>9.9</td>
<td>3.2</td>
<td>DGL</td>
<td>7.3</td>
<td>0.8</td>
</tr>
<tr>
<td>3 ($dt \leq 0.2$ s)</td>
<td>DGL</td>
<td>10.0</td>
<td>3.2</td>
<td>DGL</td>
<td>16.7</td>
<td>2.1</td>
</tr>
<tr>
<td>3 ($dt \leq 0.7$ s)</td>
<td>DGL</td>
<td>10.8</td>
<td>3.2</td>
<td>DGL</td>
<td>19.8</td>
<td>2.1</td>
</tr>
<tr>
<td>5 NGL</td>
<td></td>
<td>9.4</td>
<td>2.6</td>
<td>NGL, EAL</td>
<td>15.3</td>
<td>1.4</td>
</tr>
<tr>
<td>4 NGL</td>
<td></td>
<td>8.3</td>
<td>2.5</td>
<td>NGL, EAL</td>
<td>20.9</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Fig. 14: Representative particle size distributions averaged separately over the SR (a) and CR (b) for each flight leg for the 2DS and HVPS with 2DS dead time $\leq 0.7$ s. Flight leg times can be found in Table 1 and the boundaries between the CR and SR can be found in Table 2. Mean 2DS and HVPS $N_t$ for each flight leg can be found in Table 4. At smaller sizes FL2-5 have similar concentrations and overlap in panel a.
Fig. 15: Same as Fig. 11 except for supercooled liquid water content (g m\(^{-3}\)). Whiskers represent the maximum data points.

Fig. 16: Supercooled liquid water content (g m\(^{-3}\)) across the P3 flight track measured by the CDP for all five flight legs. The red solid line along each flight leg separates the stratiform region and convective region and was determined using microphysics data. Red arrows are subsets of microphysical data that will be shown in Fig. 21. Green shaded areas are regions where raindrops were observed.
Fig. 17: Same as Fig. 16 except CDP $N_{CDP}$ (number per cm$^3$) is shown.
Fig. 18: PHIPS stereo-image statistics in the SR and CR for FL 1-3 (See Table 5), based on the number of particles sampled, particle growth characteristics, particle riming, particle dendritic growth, and particle habits.
Fig. 19: Representative particle images from the PHIPS probe in the stratiform region of each particle growth layer (left) and the convective region (right).

Table 5: PHIPS stereo-image statistics corresponding to columns on Fig. 18 for Flight Legs 1-3. Statistics are based on the number of particles sampled, particle growth characteristics, particle riming, particle dendritic growth, and particle habits.

<table>
<thead>
<tr>
<th>Particles Sampled and Characteristics</th>
<th>SR FL1</th>
<th>CR FL1</th>
<th>SR FL2</th>
<th>CR FL2</th>
<th>SR FL3</th>
<th>CR FL3</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Particles Sampled</td>
<td>1293</td>
<td>1576</td>
<td>1934</td>
<td>1022</td>
<td>2286</td>
<td>1023</td>
</tr>
<tr>
<td># of Particles Analyzed</td>
<td>665</td>
<td>575</td>
<td>655</td>
<td>385</td>
<td>783</td>
<td>351</td>
</tr>
<tr>
<td>Single Crystal %</td>
<td>5.1%</td>
<td>25.2%</td>
<td>3.2%</td>
<td>23.4%</td>
<td>3.7%</td>
<td>24.8%</td>
</tr>
<tr>
<td>Polycrystal %</td>
<td>94.9%</td>
<td>75.8%</td>
<td>96.8%</td>
<td>76.6%</td>
<td>96.3%</td>
<td>75.2%</td>
</tr>
<tr>
<td>Growth Characteristics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate Like</td>
<td>96.5%</td>
<td>91.5%</td>
<td>87.2%</td>
<td>62.1%</td>
<td>92.1%</td>
<td>76.3%</td>
</tr>
<tr>
<td>Columnar</td>
<td>1.7%</td>
<td>0.0%</td>
<td>15.6%</td>
<td>0.0%</td>
<td>17.9%</td>
<td></td>
</tr>
<tr>
<td>Column – Plate Mix</td>
<td>1.2%</td>
<td>3.0%</td>
<td>6.3%</td>
<td>12.7%</td>
<td>4.6%</td>
<td>4.8%</td>
</tr>
<tr>
<td>Other</td>
<td>0.0%</td>
<td>5.5%</td>
<td>6.5%</td>
<td>9.6%</td>
<td>3.3%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Dendritic Growth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dendritic Growth</td>
<td>3.0%</td>
<td>42.4%</td>
<td>12.2%</td>
<td>36.6%</td>
<td>8.6%</td>
<td>21.1%</td>
</tr>
<tr>
<td>No Dendritic Growth</td>
<td>97.0%</td>
<td>57.6%</td>
<td>87.8%</td>
<td>63.4%</td>
<td>91.4%</td>
<td>78.9%</td>
</tr>
<tr>
<td>Riming Characteristics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rimed</td>
<td>3.9%</td>
<td>68.7%</td>
<td>9.3%</td>
<td>67.5%</td>
<td>9.1%</td>
<td>67.8%</td>
</tr>
<tr>
<td>Unrimed</td>
<td>96.1%</td>
<td>31.3%</td>
<td>90.7%</td>
<td>32.5%</td>
<td>90.9%</td>
<td>32.2%</td>
</tr>
<tr>
<td>Individual Habit Percentages</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate</td>
<td>1.4%</td>
<td>0.4%</td>
<td>0.5%</td>
<td>1.3%</td>
<td>0.1%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Skeleton Plate</td>
<td>0.2%</td>
<td>0.4%</td>
<td>0.3%</td>
<td>0.0%</td>
<td>0.3%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Seccored Plate</td>
<td>1.4%</td>
<td>6.1%</td>
<td>2.1%</td>
<td>0.8%</td>
<td>1.9%</td>
<td>6.6%</td>
</tr>
<tr>
<td>Dendrite</td>
<td>14.8%</td>
<td>14.8%</td>
<td>0.3%</td>
<td>5.7%</td>
<td>1.4%</td>
<td>5.1%</td>
</tr>
<tr>
<td>Column</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>14.3%</td>
<td>0.0%</td>
<td>4.6%</td>
</tr>
<tr>
<td>Other – Polycrystalline Plate</td>
<td>8.9%</td>
<td>16.9%</td>
<td>7.2%</td>
<td>26.8%</td>
<td>6.3%</td>
<td>37.0%</td>
</tr>
<tr>
<td>Other – Polycrystalline Column</td>
<td>0.8%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>5.4%</td>
</tr>
<tr>
<td>Capped Column</td>
<td>1.2%</td>
<td>2.8%</td>
<td>4.4%</td>
<td>6.5%</td>
<td>1.7%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Other – Plate-Column Mix</td>
<td>0.0%</td>
<td>0.2%</td>
<td>1.8%</td>
<td>6.2%</td>
<td>2.9%</td>
<td>4.3%</td>
</tr>
<tr>
<td>Needle</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>1.3%</td>
<td>0.0%</td>
<td>8.0%</td>
</tr>
<tr>
<td>Graupel</td>
<td>0.0%</td>
<td>3.7%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Other</td>
<td>0.6%</td>
<td>1.9%</td>
<td>6.6%</td>
<td>9.6%</td>
<td>3.3%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

Accepted for publication in *Journal of the Atmospheric Sciences*. DOI: 10.1175/JAS-D-22-0118.1.
Table 6: Measurements of $IWC$ (g m$^{-3}$) for the minimum ($IWC_{\text{min}}$), 25th ($IWC_{25}$), 50th ($IWC_{50}$), 75th ($IWC_{75}$), and maximum ($IWC_{\text{max}}$) values in the stratiform and convective regions corresponding to Fig. 20.

<table>
<thead>
<tr>
<th>Flight Leg</th>
<th>Particle Growth Layer</th>
<th>$IWC_{\text{min}}$</th>
<th>$IWC_{25}$</th>
<th>$IWC_{50}$</th>
<th>$IWC_{75}$</th>
<th>$IWC_{\text{max}}$</th>
<th>Particle Growth Layer</th>
<th>$IWC_{\text{min}}$</th>
<th>$IWC_{25}$</th>
<th>$IWC_{50}$</th>
<th>$IWC_{75}$</th>
<th>$IWC_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DGL</td>
<td>0.5</td>
<td>0.6</td>
<td>0.8</td>
<td>0.9</td>
<td>1.7</td>
<td>DGL</td>
<td>0.1</td>
<td>0.4</td>
<td>0.6</td>
<td>1.1</td>
<td>2.4</td>
</tr>
<tr>
<td>2</td>
<td>PGL</td>
<td>0.4</td>
<td>0.8</td>
<td>1.1</td>
<td>1.4</td>
<td>2.9</td>
<td>PGL, NGL</td>
<td>0.0</td>
<td>0.1</td>
<td>0.3</td>
<td>0.8</td>
<td>2.7</td>
</tr>
<tr>
<td>3</td>
<td>PGL</td>
<td>0.6</td>
<td>0.9</td>
<td>1.1</td>
<td>1.2</td>
<td>1.7</td>
<td>PGL, NGL</td>
<td>0.1</td>
<td>0.4</td>
<td>0.8</td>
<td>1.2</td>
<td>2.0</td>
</tr>
<tr>
<td>4</td>
<td>NGL</td>
<td>0.3</td>
<td>0.5</td>
<td>0.9</td>
<td>1.0</td>
<td>1.8</td>
<td>NGL, EAL</td>
<td>0.0</td>
<td>0.6</td>
<td>0.8</td>
<td>1.0</td>
<td>1.8</td>
</tr>
<tr>
<td>5</td>
<td>NGL</td>
<td>0.2</td>
<td>0.6</td>
<td>1.0</td>
<td>1.2</td>
<td>2.1</td>
<td>NGL, EAL</td>
<td>0.0</td>
<td>0.5</td>
<td>0.7</td>
<td>0.9</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Fig. 20: Same as Fig. 11 except for total ice water content (g m$^{-3}$). Percentiles can be found in Table 5. Whiskers represent the mean ±1.5 times the interquartile range.
5.2 Convective Region

FL1-4 sampled the convective region descending on each subsequent flight leg through the DGL, PGL, NGL, and EAL, with FL2-4 sampling more than one growth layer because the isotherms sloped upward toward the east. FL5 sampled the NGL and EAL.

FL1 sampled the DGL at an altitude of 5.2 km (-15.6 to -13.9°C) in the CR. \( N_t \) ranged from 1.9-55.0 L\(^{-1} \) with \( N_{\text{median}} = 8.6 \) L\(^{-1} \) (Fig. 11, Table 3) for periods with dead time \( \leq 0.7 \) s and from 1.9-33.4 L\(^{-1} \) with \( N_{\text{median}} = 7.6 \) L\(^{-1} \) for periods with dead time \( \leq 0.2 \) s (Table 3). There were isolated peaks in \( N_{2DS} \) up to 30-60 L\(^{-1} \) along the flight leg (Fig. 12). The mean PSD across the CR had \( N_{2DS} = 8.1 \) L\(^{-1} \) (6.6 L\(^{-1} \) for dead time \( \leq 0.2 \) s) and \( N_{HVPS} = 2.8 \) L\(^{-1} \) (Fig. 14, Table 4). The CDP detected SLW in the DGL between -75.25° to -74.5° longitude with typical SLW values ranging from 0.01-0.05 g m\(^{-3} \) with maximum values up to 0.15 g m\(^{-3} \) (Figs. 15, 16). Droplet concentrations in SLW regions ranged from 20-30 cm\(^{-3} \) (Fig. 17). PHIPS stereo-imagery analysis revealed a mix of particle habits including side planes (53.0% of particles), polycrystalline (16.9% of particles) and other plates (6.9% of particles), dendrites (14.8% of particles), capped columns (2.8% of particles), and graupel (3.7% of particles) (Fig. 18, 19, Table 5). Side planes and other polycrystalline particles likely descended into the DGL from the PCGL aloft, while dendrites formed in situ. PHIPS analyzed imagery also contained side plane crystals that had started to grow dendritic structures. Of the PHIPS particles analyzed, 68.7% were rimed in the CR along FL1. The IWC of the particles in the DGL on FL1 ranged from 0.1-2.4 g m\(^{-3} \), with \( IWC_{\text{median}} = 0.6 \) g m\(^{-3} \) (Fig. 20, Table 6).

FL2 sampled the lower PGL and upper NGL (-8.6 to -5.4°C) at an altitude of 3.6 km. On this leg, \( N_t \) ranged from 0.1-59.4 L\(^{-1} \) with \( N_{\text{median}} = 7.5 \) L\(^{-1} \) (from 0.1-57.5 L\(^{-1} \) with \( N_{\text{median}} = 7.5 \) L\(^{-1} \) for dead time \( \leq 0.2 \) s) (Figs. 11, 12, 13, Table 3). The mean PSD across the CR on this leg had \( N_{2DS} = 7.3 \) L\(^{-1} \) (7.1 L\(^{-1} \) for dead time \( \leq 0.2 \) s) and \( N_{HVPS} = 0.8 \) L\(^{-1} \) (Fig. 14). Droplet concentrations ranged from 10-80 cm\(^{-3} \) across the CR with SLW ranging from 0.01 to 0.25 g m\(^{-3} \). Again, a mix of particle habits were observed including side planes (27.5% of particles), polycrystalline and plate-like particles (28.9% of particles), columns (14.3% of columns), capped columns (6.5% of particles), and plate-column mixes (6.2% of particles), dendrites (5.7% of particles), and needles (1.3% of particles) (Figs. 18, 19, Table 5), implying that particle formation occurred within the PGL and upper NGL. Of the PHIPS particles analyzed, 67.5% were rimed. IWC ranged from 0.1-2.0 g m\(^{-3} \), with \( IWC_{\text{median}} = 0.3 \) g m\(^{-3} \) (Fig. 20, Table 6).
FL3 sampled the NGL and upper EAL (-7.7 to -2.2°C) at an altitude of 3.3 km. \( N_t \) ranged from 2.8-174.1 L\(^{-1}\) with \( N_{\text{median}} = 11.9 \) L\(^{-1}\) (from 2.8-172.3 L\(^{-1}\) with \( N_{\text{median}} = 10.9 \) L\(^{-1}\) for dead time \( \leq 0.2 \) s) (Figs. 11, 12, 13, Table 3). The mean PSD was \( N_{2DS} = 19.8 \) L\(^{-1}\) (16.7 L\(^{-1}\) for dead time \( \leq 0.2 \) s) and \( N_{\text{HVPS}} = 2.1 \) L\(^{-1}\). The maximum value of \( N_{2DS} \) increased substantially from FL2 to FL3, which sampled more of the NGL along the cross section (Fig. 11, Table 4). \( N_{2DS} \) had several peaks in region A1 of FL3 with particle concentrations > 100 L\(^{-1}\) (Figs. 12, 21). The CDP probe detected SLW > 0.20 g m\(^{-3}\), mainly east of -74.75° longitude (Figs. 15, 16, 17) with droplet concentrations ranging from 10-60 cm\(^{-3}\) on FL3 (Fig. 17). PHIPS stereo-imagery analysis revealed that habits were primarily side planes (27.4% of particles), other polycrystalline plates (37.0% of particles) and single plates (6.8% of particles), needles (8.0% of particles), columns (4.6% of particles), capped columns (1.7% of particles), and other plate-column mixes (9.5% of particles), and dendrites (5.1% of particles) (Fig. 18, 19, Table 5). Secondary ice production, either by the Hallett-Mossop (Hallett and Mossop 1974), droplet shattering (e.g. Mason and Maybank 1960; Brownscombe and Thorndike 1968), or the crystal-crystal collision (e.g. Phillips et al. 2017a,b) process likely contributed to enhanced values of \( N_t \). This was qualitatively supported by the presence of needles, columns, and rimed particles. Of the PHIPS particles analyzed, 67.8% were rimed. \( IWC \) ranged from 0.0-2.0 g m\(^{-3}\), with \( IWC_{\text{median}} = 0.8 \) g m\(^{-3}\) (Fig. 20, Table 6).

FL4 and FL5 sampled the NGL and EAL at altitudes of 2.4 km (-3.7 to -0.2°C) and 2.7 km (-5.0 to -0.7°C). In the NGL and EAL, \( N_t \) ranged from 3.0-140.5 L\(^{-1}\) with \( N_{\text{median}} = 16.7 \) L\(^{-1}\) on FL4 and from 0.1-121.7 L\(^{-1}\) with \( N_{\text{median}} = 11.5 \) L\(^{-1}\) on FL5 (Figs. 11, 12, 13, Table 3). The PSDs had \( N_{2DS} = 20.9 \) L\(^{-1}\) and \( N_{\text{HVPS}} = 1.7 \) L\(^{-1}\) for FL4 and \( N_{2DS} = 15.3 \) L\(^{-1}\) and \( N_{\text{HVPS}} = 1.4 \) L\(^{-1}\) for FL5 (Fig. 14, Table 4). Only localized values of SLW (0.01 – 0.15 g m\(^{-3}\)) were observed at lower altitudes in the CR (Figs. 15, 16, 17). Particle habits sampled during FL4 and FL5 in the CR were consistent with previous altitudes with an increase in particle aggregation (Fig. 14). Regions A2 and A4 had enhanced particle concentrations consistent with the process of secondary ice formation with \( N_t \) ranging from 40-120 L\(^{-1}\) (Fig. 12, 21). \( IWC \) ranged from 0.0-2.2 g m\(^{-3}\), with \( IWC_{\text{median}} = 0.7 \) g m\(^{-3}\) on FL4 and from 0.0-1.8 g m\(^{-3}\), with \( IWC_{\text{median}} = 0.8 \) g m\(^{-3}\) on FL5 (Fig. 20, Table 6). Region A3 on FL5 and A5 on FL4 (Figs 12, 13, 16, 17, Table 2) were periods when droplets were observed within the PHIPS stereo-imagery. During these periods small drizzle drops were apparently being lofted through the 0°C isotherm.
The measurements in the CR show that water saturation was achieved in convective turrets allowing for the formation and growth of new particles at all altitudes (Figs. 15, 16, 17). Supercooled liquid water was present at cloud top based on an analysis of lidar returns at cloud top. At the same time, side planes and polycrystalline particles formed in the upper part of the cloud above the highest flight level and fell through the DGL, PGL, NGL, and EAL. The presence of supercooled liquid water allowed a large percentage of these particles to become rimed. These observations are also consistent with the action of secondary ice production at temperatures between -8 and -3°C leading to higher particle concentrations and the growth of needles and columns which subsequently aggregated.

Fig. 21: Total number concentration (# per L⁻¹) (blue) and total ice water content (g m⁻³) (red) during periods of enhanced concentrations due to needle growth. Whiskers represent the mean ±1.5 times the interquartile range. The regions A1, A2, and A4 refer to Figs. 12, 13, 16, and 17.
6 Nature of the Precipitation Band

Fig. 3 shows a band of higher reflectivity at 2.5 km altitude within the comma head. The band appeared on the cross section near -75° longitude at 1500 UTC (Fig. 9) and was within the 2.5 km region of high correlation coefficient (>0.96, Fig. 3), indicating ice at that level. The band aligned with the axis of maximum 700 mb kinematic frontogenesis suggesting that vertical circulations associated with frontogenesis might be important. Examining Fig. 10, the maximum synoptic scale vertical motion indeed occurred above the region of maximum frontogenesis (Fig. 4c). The band was in the SR near the boundary between the SR and CR, and the $Z_e$ values were the highest anywhere within the SR. The cross section in Fig. 9 shows that even higher $Z_e$ associated with the band was present at altitudes below the region of maximum frontogenesis. A key to understanding the nature of this region appears in Fig. 9, where the highest $Z_e$ values were collocated with negative radial velocities of $\sim$4 m s$^{-1}$, values consistent with those in the melting layer further to the east.

These observations together indicate that the band was the result of enhanced growth of ice particles within the SR within the region of increased synoptic scale vertical motion associated with frontogenesis. Although not observed, it is likely that these particles aggregated as they approached a warm zone of air near the surface and then melted or partially melted, creating large wet snowflakes and the high $Z_e$ near the ground. Unfortunately, the P-3 was unable to fly low enough to sample this region and confirm this hypothetical chain of events.

7 Summary

This paper examined the microphysical evolution of precipitation in the context of storm frontal structure and kinematics across the comma head region of a northeast US snowstorm. Although past studies have shown that many of these storms have convective and stratiform regions, the evolution of precipitation within these regions within northeast snowstorms, to our knowledge, has never been investigated in situ and interpreted in the context of airborne radar observations and frontal structure.

The 7 February 2020 winter storm was a rapidly deepening extratropical cyclone that exhibited different precipitation growth processes within the comma-head region. The storm was observed using two aircraft as part of the NASA Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) field campaign. From a synoptic scale perspective, a convective region developed as unsaturated air within the cyclone's dry slot moved
over the cloud layer ascending over the cyclone’s warm front. A stratiform region occurred west of the impinging dry slot airstream. This resulted in two distinct microphysical regions across the comma head. The distinction between these regions was evident in the high-resolution reflectivity and radial velocity characteristics observed in the ER-2 radar profiles. Reflectivity towers with updrafts of 1-2 m s\(^{-1}\) were observed in the upper cloud layer within the convective region with corresponding plumes of reflectivity descending into the lower cloud; while the stratiform region was characterized by a more uniform reflectivity gradient both horizontally and vertically, and weaker vertical circulations near cloud top.

The microphysical evolution of particles within the CR differed from the SR. Differences between the SR and CR are summarized in an idealized conceptual model in Fig. 22. In the SR, observations support the formation of ice crystals in the polycrystalline growth layer near cloud top. As ice crystals fell through subsequent particle growth layers, the observations were consistent with particle growth by vapor deposition, quantitatively supported by an overall slight increase in IWC with depth between the aircraft flight levels (Fig 20). Very few new particle habits were observed in the PHIPS stereo-images implying that new particle formation was rare at lower altitudes within the SR. This was quantitatively confirmed by the lack of variation in the statistical distribution of \(N\) with depth between the aircraft flight levels within the cloud (Figs. 11, 12, 13).

![Fig. 22: Conceptual model of precipitation processes in the stratiform region and convective region. Particle habits are represented by black shapes and are denoted above the figure. SLW is represented by blue dots. SLW was present in developing convective cells but converted to ice as the cells matured. The region denoted partially melted particles is the location of the band on the WSR-88D radar composite.](image-url)
In the CR, new particle habits (e.g., dendrites, columns, needles) were observed within each temperature-defined growth layer along with detectable amounts of supercooled liquid water, consistent with ice particle formation in several particle growth layers. Updrafts within the CR penetrated through the polycrystalline growth layer and dendritic growth layer and were a source of SLW throughout the upper cloud layer. SLW was present in developing convective cells and was sampled at different heights on numerous flight legs. As the cells evolved and matured, SLW was converted to ice. At higher temperatures (-8 to -3°C) sampled during the flight, pockets with ice particle concentrations exceeding 100 L⁻¹ were present, consistent with secondary ice production at these altitudes. Expected particle habits associated with secondary ice production, specifically heavily rimed particles together with columns and needles and supercooled drizzle drops (e.g., Luke et al. 2021), provided supportive evidence.

Fig. 23 shows the total surface precipitation across New York State for the period of 1400 to 1800 UTC. Total precipitation (rain + snow) was generally larger near the transition zone between the SR and CR during the time period of the flight. WSR-88D reflectivity composites during the flight sampling period showed a weak, banded feature. The band, evident most prominently on earlier flight legs, was shown to be associated with enhanced vertical motion associated with frontogenesis, followed by particle aggregation and subsequent melting (likely partial melting) of ice particles near the surface. This band coincided with the maximum in total precipitation during the period.

![Fig. 23](image)

Fig. 23: Total precipitation between 1400 UTC and 1800 UTC on 7 February 2020 from the New York State Mesonet (Brotzge et al. 2020). The dark horizontal line with the arrows represents the flight track and the black vertical lines are the westernmost and easternmost positions of the SR-CR boundary as determined from the microphysical analysis.
As noted in the introduction, the comma heads of extratropical cyclones over the eastern United States have previously been shown to often exhibit an elevated layer of potential instability and convection on their warm sides, and stable air, often topped by shallow convective cloud-top generating cells on their cold sides. This study provides the first in-situ quantitative microphysical analysis of the stratiform and elevated convective regions of the comma head of a northeast U.S. winter cyclone. The IMPACTS project is a 3-year effort to further document and understand the range of microphysical scenarios that occur in cyclones with a range of intensities and banded organization over the northeast U.S. Future work using a similar framework will allow exploration of particle growth mechanisms within a variety of synoptic environments.
Appendix

Fig. A1 shows the differences in the amount of data for $N_{2DS}$ available for 1 s periods when different dead time thresholds are applied on FL1. Note that as the dead time threshold increases, $N_{2DS}$ has a progressively greater spread (standard deviation of 11 L$^{-1}$ for dead time $\leq 0.7$ s and a standard deviation of 6 L$^{-1}$ for dead time $\leq 0.2$ s). It is uncertain how reliable the calculation of $N_{2DS}$ is for time periods with large dead time. In this paper periods with dead time $\leq 0.7$ s are included in plots and the calculated concentrations. However, all points with dead time $> 0.2$ s are flagged because more uncertainty in the calculated concentrations exist. For flight levels where more than 20% of the 1 s time periods have dead times $> 0.2$ s, separate statistics on $N_{2DS}$ are provided using a more conservative dead time threshold ($\leq 0.2$ s). Another approach to reduce the uncertainty caused by dead time is to average over longer time periods and choose a less restrictive dead time. For example, Dunnavan et al. (2022) used this approach when comparing radar data from the WSR-88D network to microphysical observations made during the 7 February 2020 case. Finlon et al. (2022) also used this approach in their comparison of enhanced regions of Dual-Frequency Ratios to microphysical properties during the 7 February 2020 case. In these cases, averaging was appropriate because they were comparing to the large sample volumes associated with ground based and airborne radars.

Fig. A1: $N_{2DS}$ (number per L$^{-1}$) measured for each 1 HZ sample for different dead time thresholds for FL1. Each dot represents one measurement. a: Most restrictive threshold (dead time $= 0.0$ s), b) dead time $\leq 0.2$ s, c: dead time $\leq 0.7$ s, and d: the least restrictive threshold (dead time $\leq 1.0$ s). The threshold with dead time $\leq 0.7$ s was used in this paper.
Acknowledgments

Field campaigns of this size depend on the dedication and support of many individuals and institutions. We thank everyone involved in the planning, execution, and support of the IMPACTS field campaign. We also thank the NASA Earth Science Division (ESD) and Earth Venture Suborbital Program under the NASA Airborne Science Program for their support of this program. We especially thank the crews from the NASA P-3 Orion and the NASA Earth Resources 2 aircrafts. This work was funded by the NASA Earth Venture Suborbital-3 (EVS-3) program under grants 80NSSC19K0355 (UIUC), 80NSSC19K0338 (UW), 80NSSC19K0399 (OU), and 80NSSC19K0328 (UND). This work has also received funding from the Helmholtz Research Program Atmosphere and Climate and by the German Research Foundation (DFG grant JA 2818/1-1). The PHIPS deployment during IMPACTS was based on a collaboration agreement between NASA and KIT. We thank three anonymous reviewers for comments and suggestions that helped substantially improve the quality of the paper.

Data Availability Statement

All IMPACTS quick-look images and mission scientist reports from the 2020 deployment are highlighted in the IMPACTS field catalog at http://catalog.eol.ucar.edu/impacts_2020 and the data can be obtained from the Global Hydrology Resource Center Distributed Active Archive Center at https://ghrc.nsstc.nasa.gov/uso/ds_details/collections/impactsC.html and McMurdie et al. (2019).
References


Accepted for publication in *Journal of the Atmospheric Sciences*. DOI:10.1175/JAS-D-22-0118.1.


Lance, S., 2012: Coincidence errors in a Cloud Droplet Probe (CDP) and a Cloud and Aerosol Spectrometer (CAS), and the improved performance of a modified CDP. *J. Atmos. and Ocean. Technol.*, 29(10), 1532–1541. https://doi.org/10.1175/JTECH- D- 11- 00208.1


High-Resolution Particle Imaging Probe, *J. Atmos. and Ocean. Technol.*, 23(11), 1462-1477. https://doi.org/10.1175/JTECH1927.1


Accepted for publication in *Journal of the Atmospheric Sciences*. DOI 10.1175/JAS-D-22-0118.1.


Novak, D. R., B. A. Colle, and S. E. Yuter, 2008: High-resolution observations and model simulations of the life cycle of an intense mesoscale snowband over the northeastern


