

Retrievals of cloud droplet size from the research scanning polarimeter data: Validation using in situ measurements

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Abstract

We present comparisons of cloud droplet size distributions (DSDs) retrieved from the Research Scanning Polarimeter (RSP) data with correlative *in situ* measurements made during the North Atlantic Aerosols and Marine Ecosystems Study (NAAMES). The airborne portion of this field experiment was based out of St. John's airport, Newfoundland, Canada with the focus of this paper being on the deployment in May - June 2016. RSP was onboard the NASA C-130 aircraft together with an array of *in situ* and other remote sensing instrumentation. The RSP is an along-track scanner measuring the polarized and total reflectance in 9 spectral channels. Its uniquely high an-

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gular resolution allows for characterization of liquid water droplet sizes using the rainbow structure observed in the polarized reflectance over the scattering angle range from 135 to 165 degrees. The rainbow is dominated by single scattering of light by cloud droplets, so its structure is characteristic specifically of the droplet sizes at cloud top (within unit optical depth into the cloud, equivalent to approximately 50 m). A parametric fitting algorithm applied to the polarized reflectance provides retrievals of the droplet effective radius and variance assuming a prescribed size distribution shape (gamma distribution). In addition to this, we use a non-parametric method, the Rainbow Fourier Transform (RFT), which allows us to retrieve the droplet size distribution itself. The latter is important in the case of clouds with complex microphysical structure, or multiple layers of cloud, which result in multi-modal DSDs. During NAAMES the aircraft performed a number of flight patterns specifically designed for comparisons between remote sensing retrievals and *in situ* measurements. These patterns consisted of two flight segments above the same straight ground track. One of these segments was flown above clouds allowing for remote sensing measurements, while the other was near the cloud top where cloud droplets were sampled. We compare the DSDs retrieved from the RSP data with *in situ* measurements made by the Cloud Droplet Probe (CDP). The comparisons generally show good agreement (better than 1 μm for effective radius and in most cases better than 0.02 for effective variance) with deviations explainable by the position of the aircraft within the cloud, or by the presence of additional cloud layers between the cloud being sampled by the *in situ* instrumentation and the altitude of the remote sensing segment. In the latter case, the multi-modal

DSDs retrieved from the RSP data were consistent with the multi-layer cloud structures observed in the correlative High Spectral Resolution Lidar (HSRL) profiles. The results of these comparisons provide a rare validation of polarimetric droplet size retrieval techniques, demonstrating their accuracy and robustness and the potential of satellite data of this kind on a global scale.

Keywords: Clouds, Electromagnetic scattering, Polarization, Rainbow, Remote sensing, *In situ* measurements

1. Introduction

Cloud feedbacks remain the most uncertain radiative feedbacks in climate models and there continue to be large uncertainties in the estimates of the forcings associated with aerosol-cloud interactions (e.g., Boucher et al., 2013; Flato et al., 2013). The optical properties of liquid water clouds depend on the droplet size distribution (DSD) while their radiative properties are controlled by their temperature (vertical location), water path and optical properties. In addition to providing data for understanding of cloud processes themselves, accurate and robust remote sensing estimates of droplet sizes for different cloud types (especially for broken clouds) are also crucial for studies of the interactions between clouds and aerosols.

In this study we focus on polarimetric techniques for cloud droplet size retrievals and estimate their accuracy by comparison with *in situ* measurements. Cloud droplet size retrievals from polarized observations of the reflected light in the rainbow region (at scattering angles between 135° and 165°) utilize the strong dependence of the polarized rainbow (cloud bow) on cloud DSD. The polarized rainbow structure is dominated by single scatter-

18 ing, thus, deriving the DSD or the parameters that define it from observations
19 of the rainbow reduce, or eliminate, many of the uncertainties associated
20 with 3D effects and unknown aerosol loadings. For the same reason, polar-
21 ized rainbow observations carry information specific to the droplets at cloud
22 top (within unit optical depth into the cloud) rather than weighted charac-
23 teristics of the full cloud profile (as is the case for total reflectances, see e.g.,
24 Platnick (2000)). This is the same information that can be obtained from
25 direct *in situ* measurements at cloud top which, can therefore be used for
26 validation of remote sensing retrievals. The polarized rainbow technique has
27 previously been used to retrieve cloud droplet effective radii from the Polar-
28 ization and Directionality of the Earths Reflectances (POLDER, (Deschamps
29 et al., 1994)) measurements (Bréon & Goloub, 1998; Bréon & Doutriaux-
30 Boucher, 2005). A similar technique was adopted in the data analysis of the
31 airborne Research Scanning Polarimeter (RSP) (Alexandrov et al., 2012b,a,
32 2015, 2016a) and was planned to be applied to satellite measurements from
33 the Aerosol Polarimetry Sensor (APS) built as part of the NASA Glory
34 Project (Mishchenko, 2006; Mishchenko et al., 2007). Unfortunately, despite
35 extensive deployment of the RSP in numerous field experiments, until now,
36 no direct validation of the polarized rainbow technique against *in situ* mea-
37 surements has been possible. The purpose of this study is to fill this gap.

38 The North Atlantic Aerosols and Marine Ecosystems Study (NAAMES,
39 <https://naames.larc.nasa.gov/>) is a five-year project focused on the lifecycle
40 of the largest plankton bloom on Earth, which is in the North Atlantic, as
41 well as on atmospheric aerosols and clouds. There are four combined ship
42 and aircraft field deployments planned within the duration of the project.

43 Three of these deployments have already been completed. During these de-
44 ployments the RSP, together with an array of *in situ* and other remote sens-
45 ing instrumentation, was onboard the NASA Wallops Flight Facility C-130
46 research aircraft based at St. John's airport, Newfoundland, Canada. In
47 this study we use the data from the second deployment (May 11 – June 5,
48 2016) when a series of patterns were flown that were specifically designed
49 for comparison between remote sensing cloud retrievals and *in situ* mea-
50 surements. Each of these patterns consisted of two flight segments with
51 the same straight ground track. One of these segments was flown above
52 clouds allowing for remote sensing measurements, while the other was in-
53 side the cloud where cloud droplets were sampled. The NASA Langley
54 Research Center High Spectral Resolution Lidar (HSRL-1) deployed on-
55 board the C-130 aircraft provided the cloud backscatter and depolariza-
56 tion profiles, which serve as the cloud vertical structure context for the
57 RSP and *in situ* measurements. The airborne measurements made dur-
58 ing NAAMES were complemented by satellite imagery and retrievals from
59 NASA Geostationary Operational Environmental Satellite GOES-13 (op-
60 erating as GOES-East) available at [https://cloudsgate2.larc.nasa.gov/cgi-](https://cloudsgate2.larc.nasa.gov/cgi-bin/site/showdoc?docid=22&lkdomain=Y&domain=NAAMES-SATGIF)
61 [bin/site/showdoc?docid=22&lkdomain=Y&domain=NAAMES-SATGIF](https://cloudsgate2.larc.nasa.gov/cgi-bin/site/showdoc?docid=22&lkdomain=Y&domain=NAAMES-SATGIF). These
62 images provide synoptic-scale cloud system context for our intercomparison
63 datasets.

64 **2. The Research Scanning Polarimeter**

65 *2.1. Instrument design and measurements*

66 The RSP (Cairns et al., 1999) is a scanning polarimeter, which scans its
67 14 mrad field of view in a meridional plane taking Earth viewing samples
68 at 0.8° intervals within $\pm 60^\circ$ from the normal to the instrument base-plate,
69 with additional observations of a polarimetric calibrator and a dark reference
70 being obtained on the back side of each scan. The RSP has nine spectral
71 bands centered at 410, 470, 550, 670, 865, 960, 1590, 1880, and 2260 nm. The
72 wide angular and spectral ranges of the RSP measurements complemented by
73 very high polarimetric accuracy ($< 0.2\%$ for the degree of polarization) and
74 exceptional radiometric performance (stability of $\sim 1\%/year$) were among
75 the reasons it was used as an airborne prototype for the satellite Aerosol Po-
76 larimetry Sensor (APS), which was built as part of the NASA Glory Project
77 (Mishchenko, 2006; Mishchenko et al., 2007).

78 The RSP's design features three pairs of telescopes with one in each pair
79 making simultaneous measurements of the linear polarization components
80 of the intensity in orthogonal planes at 0° and 90° and the other making
81 simultaneous measurements of linear polarization in orthogonal planes at
82 45° and 135° . The data obtained in each scan consists of 195 measurements
83 of which ~ 150 are of the Earth scene, 10 are of the dark reference and 10
84 are of the in flight polarimetric calibrator. The intensity, and the degree and
85 azimuth of linear polarization determined simultaneously from each of these
86 measurements are then converted into the I , Q , and U components of the
87 Stokes vector (Hansen & Travis, 1974; Mishchenko et al., 2006) and further

88 into the total and polarized reflectances

$$R = \frac{\pi I}{\mu_s F_0} \quad \text{and} \quad R_p = -\frac{\pi Q}{\mu_s F_0}. \quad (1)$$

89 Here F_0 is the extraterrestrial solar irradiance and μ_s is the cosine of the
90 solar zenith angle (SZA). The Stokes vector components, initially defined
91 with respect to the scan plane of the instrument, are rotated (see Hansen &
92 Travis, 1974) into the scattering plane (the plane containing both solar and
93 view directions). There the contribution of first order scattering by spherical
94 particles to Stokes parameter U is identically zero and higher order scattering
95 contributions are negligibly small (Hansen & Travis, 1974; Mishchenko et al.,
96 2006). This allows the polarized reflectance, R_p , to be related to a particular
97 element of the phase matrix (Bréon & Doutriaux-Boucher, 2005). Note the
98 difference between the sign convention used here (and also by Waquet et al.
99 (2009); Alexandrov et al. (2012b,a, 2015, 2016a)) and that adopted by Bréon
100 & Goloub (1998) and Bréon & Doutriaux-Boucher (2005).

101 The RSP makes measurements along the direction of travel of the aircraft
102 and for the data analysis its actual scans are aggregated into “virtual” scans
103 consisting of the reflectances at the full range of viewing angles at a single
104 point on the ground or at cloud top (see, e.g., Alexandrov et al., 2012a).

105 *2.2. Polarimetric retrievals of cloud properties*

106 The polarimetric techniques for cloud droplet size characterization using
107 the RSP data are based on analysis of the rainbow structure that is sharply
108 defined in the polarized reflectance within the scattering angle range between
109 137° and 165° (Bréon & Goloub, 1998; Bréon & Doutriaux-Boucher, 2005;

110 Alexandrov et al., 2012b,a, 2015, 2016a). The structure of variations in the
 111 polarized reflectance in the angular range of the rainbow is dominated by
 112 single scattering of light by cloud particles, even though its amplitude can
 113 be affected by aerosols and the geometric structure of clouds. This fact
 114 allows us to avoid the retrieval uncertainties associated with 3D effects as
 115 well as unknown surface albedo, aerosol loadings, and amounts of ice over
 116 or mixed with liquid water layers. For the same reason the retrievals are
 117 accurate even for low cloud optical thicknesses (COTs), down to unity. The
 118 single-scattering nature of the rainbow structure makes the RSP retrievals
 119 representative of a unit effective optical depth into the cloud (Alexandrov
 120 et al., 2012a).

121 Two different methods for rainbow structure analysis were developed in
 122 our previous studies. Both of these methods are applied to RSP data in five
 123 visible and near infrared (NIR) bands: 410, 470, 550, 670, and 865 nm. The
 124 first method is a parametric technique (Alexandrov et al., 2012a), which fits
 125 the angular shape of the polarized rainbow from Eq. (1) using the functions
 126 of the form

$$R_p(\theta) = A \cdot P_{12}^{(Mie)}(\theta; r_{\text{eff}}, v_{\text{eff}}) + B \cdot \cos^2 \theta + C, \quad (2)$$

127 where θ is the scattering angle, r_{eff} and v_{eff} are respectively the effective ra-
 128 dius and variance of the cloud droplet size distribution (see Appendix A for
 129 definitions of DSD parameters). Phase matrix elements $P_{12}^{(Mie)}(\theta)$ forming
 130 a look-up table (LUT) are pre-computed according to Mie theory with 0.2°
 131 resolution in scattering angle. These computations assume that the droplet
 132 size distribution has a gamma distribution shape, thus, the parametric re-

133 retrieval technique returns the effective radius and variance of such a DSD.
 134 The grid values of r_{eff} in this LUT range from 5 to 30 μm with 0.5 μm in-
 135 crements. The grid for v_{eff} runs from 0.002 to 0.35, with spacing depending
 136 on the value range (0.002 for $v_{\text{eff}} < 0.008$; 0.01 for $v_{\text{eff}} \in [0.008, 0.14]$; and
 137 0.025 for $v_{\text{eff}} > 0.14$). The spacing of the tabulated values of effective vari-
 138 ance is designed so that it is not a limiting factor in retrieval accuracy, but
 139 does reflect the increasing uncertainty in the retrieval of v_{eff} as a function
 140 of its value. The ranges for r_{eff} and v_{eff} have been sufficiently wide for all
 141 types of clouds that we have observed to this day. The coefficients A , B ,
 142 and C in Eq. (2) are empirical fitting parameters accounting for contribu-
 143 tions to the polarized reflectance from everything beyond single scattering by
 144 cloud droplets. These include multiple scattering, Rayleigh scattering by the
 145 atmosphere, aerosol and overlaying cirrus cloud extinction, ground surface
 146 reflectance for thin clouds, etc. Note that contributions of these factors to the
 147 polarized reflectance are slow functions of scattering angle easily separated
 148 by a regression from sharp rainbow structure.

149 The second method, the Rainbow Fourier Transform (RFT, (Alexandrov
 150 et al., 2012b)) retrieves the whole DSD without *a priori* assumptions of its
 151 functional shape. It is based on the observation that Mie-theory-derived po-
 152 larized reflectance as a function of both the scattering angle (in the rainbow
 153 angular range) and the (mono-disperse) particle radius is akin to a kernel
 154 of an integral transform (similar to the sine Fourier transform on the posi-
 155 tive semi-axis). The direct transform (with integration over radius) is simply
 156 the computation of the polarized reflectance for a given DSD, while the in-
 157 verse transform (with integration over scattering angle) allows the DSD to

158 be estimated from this polarized reflectance. The contributions of multiple
159 scattering and other factors, beyond single scattering by cloud drops, de-
160 scribed above are assumed to have the same effect on R_p as in Eq. (2) and
161 are removed using a regression as a part of the RFT algorithm (see Section 7
162 in Alexandrov et al. (2012b) for details). The RFT is computationally faster
163 than the parametric method, since it does not involve fitting of LUT.

164 The RSP's high angular resolution provides detailed characterization of
165 the polarized rainbow, which translates into accurate determination of the
166 DSD shape using the RFT. In the case of narrow monomodal DSDs, such as
167 those observed at the top of shallow cumulus and stratocumulus clouds, both
168 methods demonstrated an excellent agreement (Alexandrov et al., 2015).
169 The situation is different in cases involving multilayer cloud systems such
170 as fogs (Alexandrov et al., 2015) and high-altitude supercooled liquid water
171 or mixed-phase clouds (Alexandrov et al., 2016a). In such cases the RFT
172 allows us to retrieve multimodal DSDs with different size modes (each hav-
173 ing gamma-distribution shape) that corresponding to the DSDs of different
174 cloud layers. These modes can then be extracted and characterized sepa-
175 rately (Alexandrov et al., 2015, 2016a). In contrast, such multimodality is
176 only indicated in the parametric retrievals by a large v_{eff} of 0.1 or greater,
177 which does not represent a local microphysical DSD (e.g., observable *in situ*).
178 The advantage of the parametric fitting technique is in its better stability
179 due to lower sensitivity to noise and artifacts in the measurements. It also
180 can work on data with a more limited scattering angle range. The two re-
181 trieval methods usually complement and cross-validate one another, thus, in
182 this study we present the results from both of them.

183 3. Comparison between remote sensing and in situ measurements

184 For comparison between remote sensing cloud retrievals and *in situ* mea-
185 surements we use the data from specifically arranged pairs of flight segments
186 sharing the same straight ground/cloud track: one above clouds allowing
187 for remote sensing measurements, the other – inside the cloud where cloud
188 droplets were sampled. The polarized cloud bow is generated over a unit opti-
189 cal depth from the cloud top (Alexandrov et al., 2012a), thus, we selected the
190 parts of the *in situ* segments when the aircraft was either entering, or exiting
191 the cloud or grazing its top. The dataset that we use for *in situ* validation
192 of RSP droplet size retrievals was derived from Cloud Droplet Probe (CDP)
193 measurements. This instrument was deployed on the same NASA C-130 air-
194 craft as the RSP and was operated by the NASA Langley Aerosol Research
195 Group Experiment (LARGE) group (<https://science.larc.nasa.gov/large/>).

196 The CDP ([http://www.dropletmeasurement.com/products/airborne/CDP-](http://www.dropletmeasurement.com/products/airborne/CDP-2)
197 2) is a low-power cloud particle spectrometer measuring droplets in the
198 diameter range between 2 and 50 μm for concentrations as high as 2000
199 particles/ cm^3 (Lance et al., 2010). The manufacturer-stated qualified sam-
200 ple cross section for the CDP is 0.24 mm^2 . The swept volume is dependent
201 on true airspeed, which during NAAMES in-cloud segments varied between
202 100 and 120 m/s. Generally, the CDP’s counting rate can be affected by the
203 “coincidence” artifact (Lance, 2012), when more than one droplet is detected
204 at the same time, thus, resulting in the underestimation of the droplet num-
205 ber concentration and a high bias in the cloud particle size. However, this is
206 unlikely to be an issue for the relatively large droplet sizes and low number
207 concentrations encountered during NAAMES. It should be mentioned that

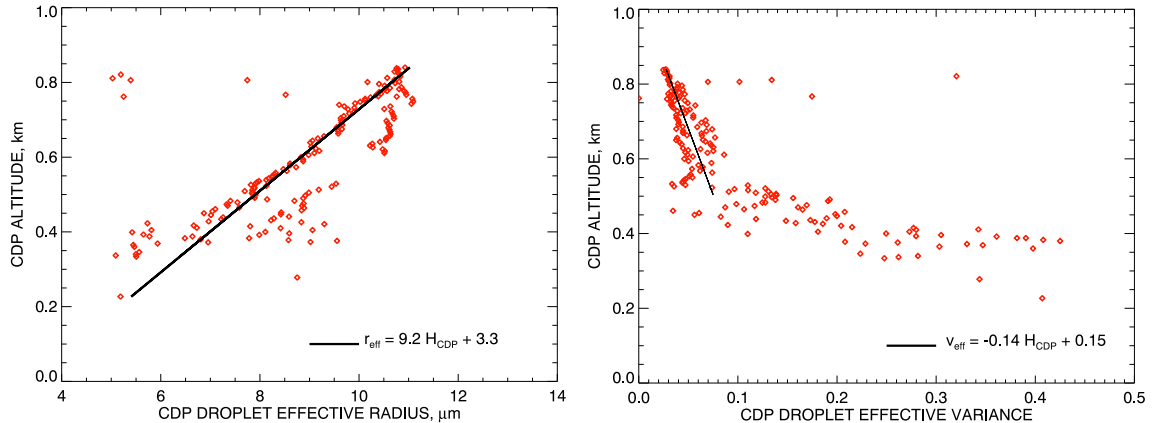


Figure 1: CDP-derived vertical profiles of droplet effective radius (left) and variance (right) for May 18, 2016 (see Fig. 3 for the location and CDP altitude). Linear fits are provided to show how fast these parameters change with altitude near cloud top.

208 the CDP has very small dead time losses and also uses fast electronics (40
 209 MHz clock) which leads to major performance improvements of this instru-
 210 ment compared to its predecessors (Lance et al., 2010). The CDP sampling
 211 histograms are reported at 1 Hz rate, that makes each of them representative
 212 of a linear segment 100–120 m long (or volume of about 26 cm³).

213 The RSP continuously scans 14 mrad field of view taking 0.8 sec for each
 214 scan. This field of view $\Delta\theta$ translates into horizontal footprint of the length

$$\Delta x = h (1 + \tan^2 \theta) \Delta\theta, \quad (3)$$

215 where θ is the viewing angle and h is the aircraft altitude above cloud (cf.
 216 Alexandrov et al., 2016b). During NAAMES' remote sensing segments the
 217 C-130 aircraft typically flew at about 5000 m above cloud top with the speed
 218 ~ 160 m/s. This corresponds to the length of a single-pixel footprint being 70

219 m (nadir view) at cloud top and the distance between centers of successive
220 nadir footprints being 128 m. A unit optical depth from the cloud top,
221 which contributes to RSP measurements, is achieved after 15 m, for droplets
222 of 10 μm radius with a concentration of 100 drops per cm^3 . However, strong
223 forward scattering by cloud drops such as these means that the total depth
224 that contributes to the cloud bow is about 50 m for this droplet size and
225 concentration. The sampling volume for RSP is therefore very different to
226 CDP ($\sim 10^{12} \text{ cm}^3$), but the horizontal scale for a single sample for both RSP
227 and CDP is similar at $\sim 100 \text{ m}$.

228 Most of the clouds observed during the NAAMES deployments over the
229 North Atlantic had DSD profiles where the effective radius increases and the
230 effective variance decreases significantly with height as a result of condensa-
231 tional growth of droplets as cloudy air parcels are lifted (Rogers & Yau, 1989).
232 An example of this behavior provided by CDP observations as a function of
233 the aircraft altitude inside cloud is shown in Figure 1. This reveals rapid
234 changes in both r_{eff} and v_{eff} with the depth into cloud and these changes are
235 quantified in Fig. 1 using linear fits to observations of the upper part of the
236 cloud. We see from Fig. 1 (left) that $\Delta r_{\text{eff}}/\Delta H_{\text{CDP}} \approx 10 \mu\text{m}/\text{km}$, meaning
237 that the effective radius decreases by 1 μm for each 100 m of depth into the
238 cloud. Similarly, Fig. 1 (right) shows that v_{eff} increases by more than 0.01
239 at a 100 m depth into cloud top. Thus, direct comparisons between RSP
240 retrievals of DSDs and *in situ* measurements from CDP are only appropriate
241 when the latter are made at cloud top.

242 We note that there are few data points at cloud top in Fig. 1 which
243 sharply deviate from general profile, showing smaller r_{eff} (down to 5 μm) and

244 larger v_{eff} (up to 0.3). These data are consistent with droplet evaporation
245 due to cloud-top entrainment, and due to their small contribution to the RSP
246 sampling volume do not show up in RSP retrievals. To avoid the influence of
247 such data (as well as any noise in CDP measurements) in comparisons with
248 RSP, we impose a certain smoothness condition on CDP data by removing
249 data points deviating by more than $1 \mu\text{m}$ in r_{eff} from one of its immediate
250 neighbors. Together with the requirement of $r_{\text{eff}} > 4.5 \mu\text{m}$ these are the only
251 screening conditions uniformly used for selection of CDP data suitable for
252 the comparisons.

253 We define cloud-top height in an ascending (descending) flight segment as
254 the altitude of the point where the aircraft exits (enters) the cloud, i.e., that
255 of the highest point with the CDP data satisfying the above-listed screening
256 conditions. Then, a CDP data segment is selected from the immediate vicin-
257 ity of the exit (entry) point with the measurement altitudes ranging within
258 50 m below the cloud top. To select an appropriate data interval for a flight
259 pattern when the aircraft grazes the cloud top without exiting or entering
260 the cloud, we rely on HSRL profiles. After the CDP data interval is selected,
261 we take the RSP data record from the same ground/cloud track and for each
262 RSP data point locate the nearest point in the CDP interval within the RSP
263 measurement spacing (if such a point does exist). The results of compar-
264 isons (means and standard deviations of r_{eff} and v_{eff}) between the RSP and
265 CDP datasets selected using the above-described procedure are presented in
266 the next section and in Table 1. In addition to comparisons of CDP data
267 with RSP retrievals made using the parametric algorithm, we also compare
268 them with parameters of one of the modes of RFT-derived DSDs. The latter

269 comparisons may have advantages in the cases of two-layer cloud systems,
 270 when DSDs sampled by CDP in one layer correspond to only one mode of
 271 the bimodal DSDs retrieved from RSP data. Parametric RSP retrievals in
 272 such cases show values of v_{eff} (large) and r_{eff} which are not representative of
 273 either of the size modes.

274 In addition to comparison of DSD statistics (r_{eff} and v_{eff}), we will show
 275 examples of remotely sensed and *in situ* DSDs themselves. The metric Δ
 276 (Alexandrov et al., 2010, 2012b) will be used for quantitative comparison of
 277 the shapes of the normalized droplet size distributions $n_{\text{RSP}}(r)$ and $n_{\text{CDP}}(r)$:

$$\Delta = \frac{1}{2} \int_0^{\infty} |n_{\text{RSP}}(r) - n_{\text{CDP}}(r)| \, dr. \quad (4)$$

278 The value of Δ varies between zero (for identical DSDs) and one (for distri-
 279 butions without common support). This metric responds to both systematic
 280 and random discrepancies between two distributions. Given the uncertainties
 281 in both RSP and *in situ* data we consider comparisons for which $\Delta \lesssim 20\%$ as
 282 showing good agreement between the two size distributions and comparisons
 283 with $\Delta \lesssim 30\%$ as showing acceptable agreement. Note that the single-point
 284 plots comparing DSD shapes serve only as illustrations and subjects for dis-
 285 cussion, while quantitative results presented in Table 1 are based on entire
 286 sets of all *in situ* samples made within 50 m from cloud top.

287 While the RSP and CDP sampling volumes are different, the horizontal
 288 linear sizes of their samples are similar (70 vs. 110 m), so the effects of
 289 horizontal inhomogeneity on comparisons are not expected to be significant.
 290 The sharp vertical profiles of droplet size parameters appears to present the

291 greatest challenge for comparisons, requiring careful selection of *in situ* data
292 from cloud tops. Other uncertainties can be caused by differences in mea-
293 surement times and locations. Remote sensing and *in situ* measurements
294 were made on co-located ground tracks, while at different times (up to 1 h
295 apart). This can raise questions as to whether the cloud field shifted from
296 its initial location or otherwise changed during the time between the mea-
297 surements. Fortunately, on three out of four days reported in this study the
298 validation segments were flown over vast stratocumulus cloud decks known
299 for their steadiness and spatial homogeneity. Also, NASA GOES satellite
300 images made with one-hour interval between them show no visible changes
301 in cloud fields in the vicinities and at times of the measurements. We should
302 also note that the good intercomparison results obtained in this study can
303 be themselves considered as an evidence of successful co-location of RSP and
304 CDP data.

305 **4. Case studies**

306 Several good opportunities for direct inter-comparisons between remote
307 sensing retrievals and cloud-top *in situ* measurements of cloud DSDs occurred
308 during the second NAAMES deployment: on May 18, 20, 27, and 30 of 2016.
309 These cases are described below and summarized in Table 1. Plots of the RSP
310 and CDP datasets being compared in each case are presented in Supplemental
311 material accompanying this paper.

312 *4.1. May 18, 2016*

313 The first opportunity for intercomparison of RSP and *in situ* retrievals
314 of cloud droplet size distributions was on May 18. The C-130 flew two

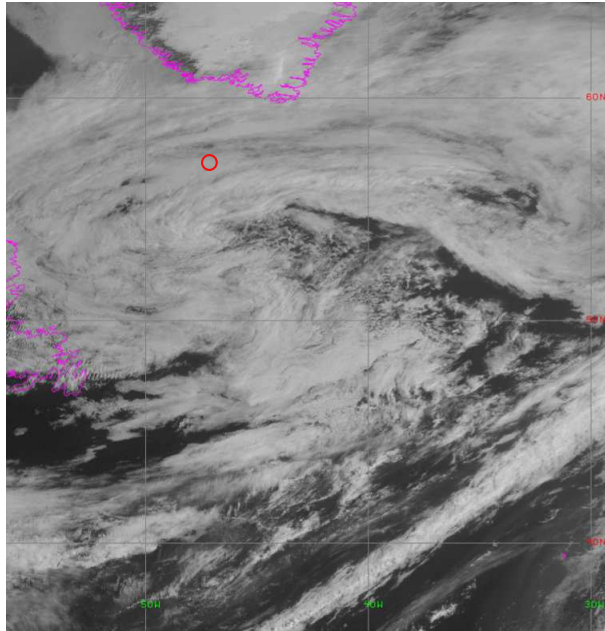


Figure 2: GOES satellite image of North Atlantic ocean for 11:15 UTC on May 18, 2016. The coastline of Newfoundland is shown in the West, while that of Greenland – in the North. The vicinity of the validation flight segments is depicted by red circle.

315 co-located legs between the points with coordinates (56.7°N, 45.2°W) and
316 (57.0°N 47.2°W). The high-altitude leg during which RSP and HSRL mea-
317 surements were made was flown between 10:58:17 and 11:11:56 UTC, while
318 the low-altitude leg that provides characterization of the marine boundary
319 layer and clouds by CDP and other *in situ* measurements was flown about
320 one hour later, between 11:48:00 and 12:04:12 UTC. Figure 2 presents GOES
321 satellite image of the cloud systems in the vicinity of the described flight legs.
322 The site of interest is located within a large low-pressure system spreading
323 between Newfoundland and Greenland. The center of this system at the
324 time of the measurements was just south of the site, with the occluded front
325 wrapped around to the north. The region of interest is dominated by stra-

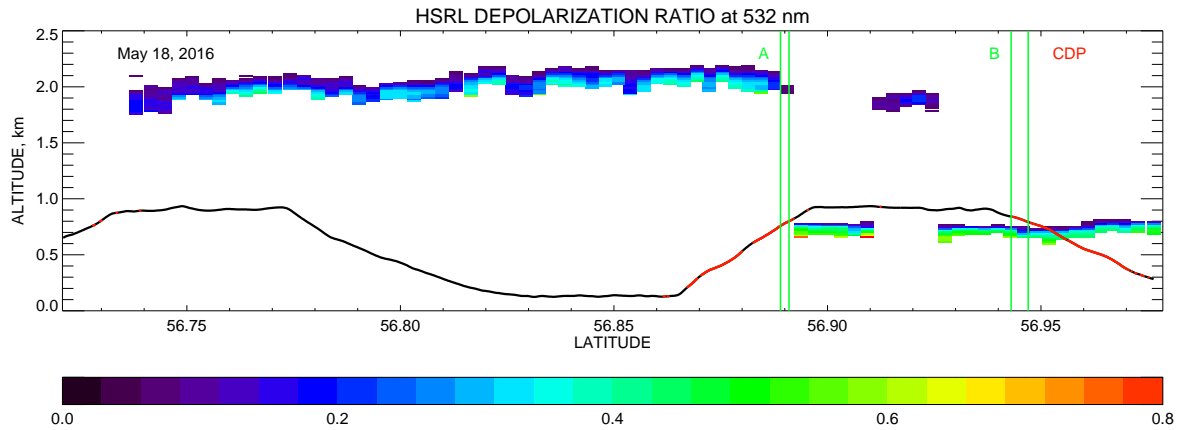


Figure 3: HSRL depolarization ratio profile for the May 18 case. Black curve depicts the altitude of the aircraft during the *in situ* segment. Red points on this curve indicate availability of CDP measurements with $r_{\text{eff}} > 4.5 \mu\text{m}$. The pairs of vertical green lines labeled A and B indicate the intervals used for RSP-CDP intercomparisons presented in Table 1. The DSDs from the top points of these intervals are shown in Fig. 5.

326 tocumulus (Sc) clouds.

327 The aircraft altitude during the *in situ* segment is plotted in Fig. 3
 328 (black curve) as function of latitude. The points where CDP measurements
 329 are available with $r_{\text{eff}} > 4.5 \mu\text{m}$ (indicating in-cloud data) are highlighted
 330 in red. Figure 3 also shows volume depolarization ratios (VDRs) for the
 331 same geographical locations derived from HSRL measurements at 532-nm
 332 wavelength that were made during the remote-sensing leg. They indicate the
 333 cloud tops in the observed scene. Two layers of clouds are clearly seen in this
 334 plot with cloud tops at approximately 0.8 km and 2 km, respectively. Only
 335 the lower-layer cloud was sampled by CDP, while RSP was able to observe
 336 both layers when the top one was optically thin.

337 The results of parametric RSP retrievals of the droplet effective radii and

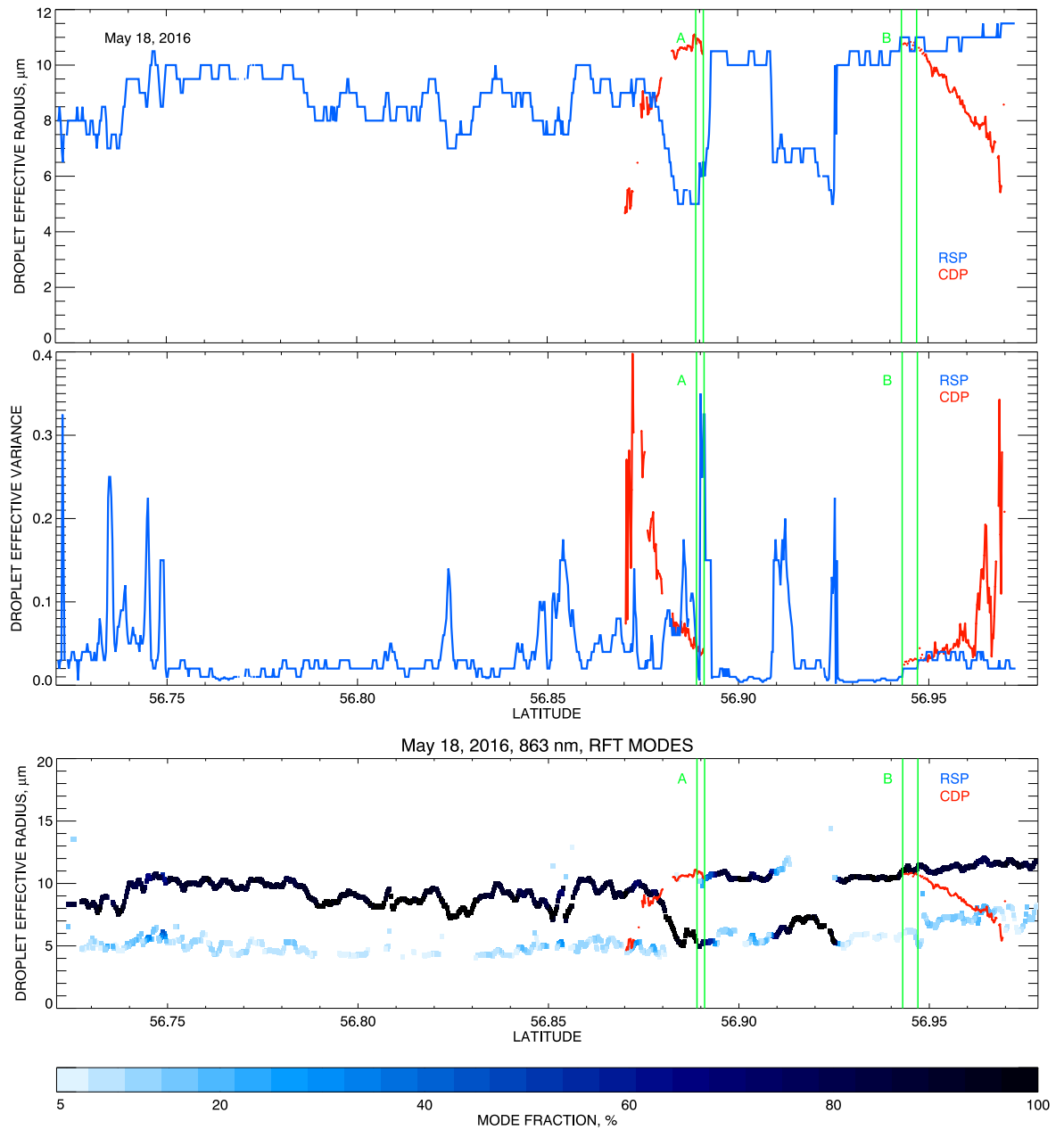


Figure 4: Top and middle: effective radius and variance, respectively, retrieved from the RSP data using the parametric fitting technique (blue curves). The discretization seen in these plots is that of the LUTs used. Bottom: the results of mode decomposition applied to distributions derived from RSP data using RFT. The curves depicting the modes' effective radii are colored according to the modes' respective weights in DSD. The red curves in all panels depict the screened co-located CDP retrievals. The pairs of vertical green lines labeled A and B indicate the intervals used for RSP-CDP intercomparisons presented in Table 1.

338 variances are presented in Fig. 4 (top and middle), while the RFT retrievals
 339 from the RSP data (effective radius and fraction of each mode in total DSD)
 340 are shown in the bottom panel. The correlative screened CDP data is plotted
 341 in all three panels (red curves). These plots show unmistakable similarity
 342 in the positions of sharp changes in droplet size with those of gaps in the
 343 upper cloud layer identified in the HSRL profile (Fig. 3). For example,
 344 the short isolated segment of the upper layer between latitudes 56.91°N and
 345 56.93°N coincides with the sharp drop in RSP-derived r_{eff} from 10 to $7\ \mu\text{m}$
 346 in parametric retrievals and with strengthening of the 5-6- μm size mode in
 347 RFT results (while the 10- μm -mode disappears). This allows us to associate
 348 the smaller mode in DSD with the upper layer and the larger one – with
 349 the lower layer. Unfortunately, the upper layer had not been sampled by the
 350 CDP, so only the RSP retrievals for the lower layer can be validated.

351 Figures 3 and 4 suggest that our choice for quantitative intercomparison
 352 of RSP and CDP retrievals near cloud top in this case is limited to two
 353 locations (indicated in the plots by two pairs of vertical green lines): (A) the
 354 exit from the cloud (11:59 UTC, Lat: 56.89°N) and (B) the entrance back
 355 into cloud at (12:02 UTC, Lat: $56.94\text{-}56.95^\circ\text{N}$). The results of the RSP-CDP
 356 comparisons for the intervals when CDP was less than 50 m below cloud top
 357 are presented in Table 1, while the examples of the RSP- and CDP-derived
 358 DSDs for the highest points of locations A and B are shown in Fig. 5 (top
 359 and bottom panels, respectively). The left panels of Fig. 5 show the droplet
 360 number distribution (from parametric fit for RSP) and right panels - the
 361 droplet area distributions (from RFT for RSP).

362 Figure 5 (top right) indicates that the RSP-derived DSD in case A is

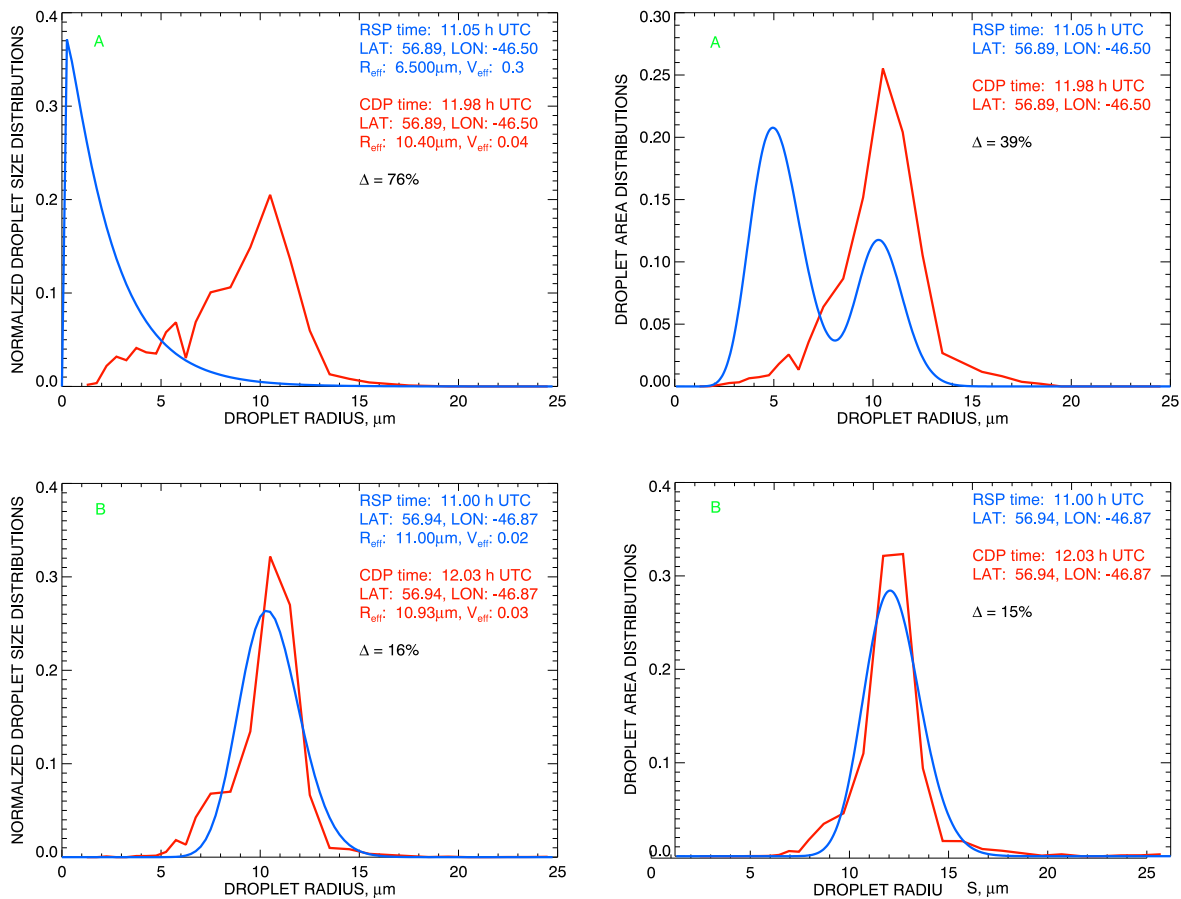


Figure 5: RSP- (blue) and CDP-derived (red) droplet number (left) and area (right) distributions corresponding to cloud exit (A: 11.98 h UTC, top) and entrance (B: 12:03 h UTC, bottom) in the May 18 case (see Fig. 3). The presented RSP retrievals are parametric in left plots and RFT-derived in right plots.

363 essentially bimodal with dominant $5\text{-}\mu\text{m}$ mode attributed to the upper cloud
 364 layer (which was not sampled *in situ*). In parametric retrievals (Fig. 5 (top
 365 left)) this corresponds to small $r_{\text{eff}} = 6.5 \mu\text{m}$ and very large $v_{\text{eff}} = 0.3$ (which
 366 also skews the gamma distribution shape to the left) (cf. Alexandrov et al.,
 367 2015, 2016a). The reason for this bimodality is in the overlap between the

368 upper and lower cloud layers seen in the HSRL profile (Fig. 3), which results
 369 in both layers simultaneously contributing to the RSP measurements. Table
 370 1 indicates that this problem affects parametric RSP retrievals in the whole
 371 9-point interval at cloud top yielding r_{eff} of $5.56 \mu\text{m}$ on average (vs. 10.80
 372 μm for CDP) and v_{eff} of 0.10 (vs. 0.04 for CDP). This means that validation
 373 of parametric RSP retrievals fails in this case, however, the parameters of
 374 the larger size mode in the RFT-derived DSD can still be compared with
 375 *in situ* measurements since they both correspond to the same lower layer
 376 of clouds. Figure 5 (top right) indicates that the larger RFT mode has a
 377 similar shape to the whole CDP-derived distribution (they differ only by a
 378 constant normalization factor). Quantitative comparison for the the whole
 379 interval in Table 1 also shows much better results (presented in parentheses):
 380 RSP's average r_{eff} of $10.75 \mu\text{m}$ and v_{eff} of 0.01 , which corresponds to average
 381 RSP-CDP bias in r_{eff} of $-0.02 \mu\text{m}$ ($0.85 \mu\text{m}$ standard deviation); and in v_{eff}
 382 of -0.02 (0.006 standard deviation).

383 In case B the lower cloud layer was scarcely obscured by the top one,
 384 so CDP and RSP observed droplets in the same cloud layer. This resulted
 385 in good agreement between RSP (both parametric and RFT) and CDP re-
 386 trievals for the 15-point interval at cloud top. Table 1 shows the RSP's
 387 parametric r_{eff} of $10.80 \mu\text{m}$ on average vs. $10.77 \mu\text{m}$ for CDP ($0.035 \mu\text{m}$
 388 mean difference, $0.26 \mu\text{m}$ standard deviation); and RSP v_{eff} of 0.02 on av-
 389 erage vs. 0.03 for CDP (-0.01 mean difference, 0.002 standard deviation).
 390 Fig. 5 (bottom) shows that the DSD shapes for the two instruments also
 391 agree well ($\Delta = 16\%$) at the highest point of the interval B. Note that in
 392 this particular DSD example the RFT yielded no smaller size mode, while

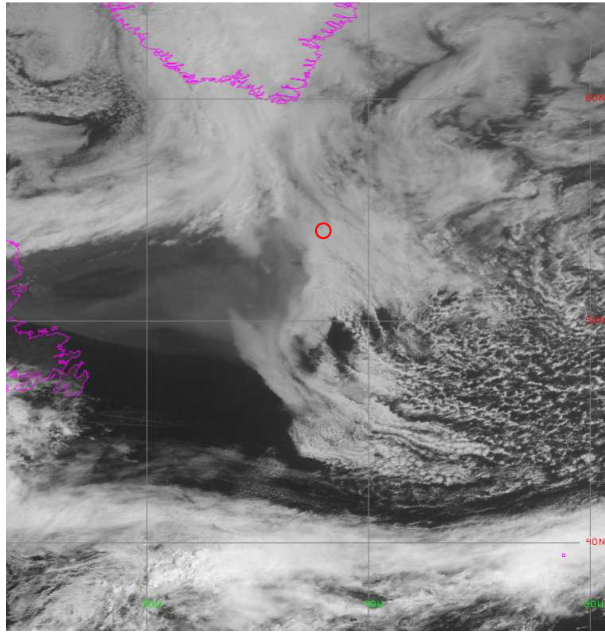


Figure 6: Same as Fig. 2 but for 12:45 UTC on May 20, 2016.

393 for the rest of the interval it constituted 8–12% of the DSDs, as can be seen
 394 in Fig. 4 (bottom).

395 *4.2. May 20, 2016*

396 The validation segments flown on May 20 have similar structures to
 397 those from May 18 with the aircraft porpoising though the full depth of the
 398 cloud. The flight legs were located between points with coordinates (53.2°N,
 399 41.1°W) and (54.3°N, 42.3°W). The high- and low-altitude legs were flown
 400 during the 12:43:55–12:52:58 UTC and 13:17:24–13:37:12 UTC time inter-
 401 vals respectively. The GOES satellite image in Fig. 6 shows cloud fields
 402 at and around the measurement site. The site is located in between frontal
 403 systems, with a region of high pressure to the south-southeast and a series of

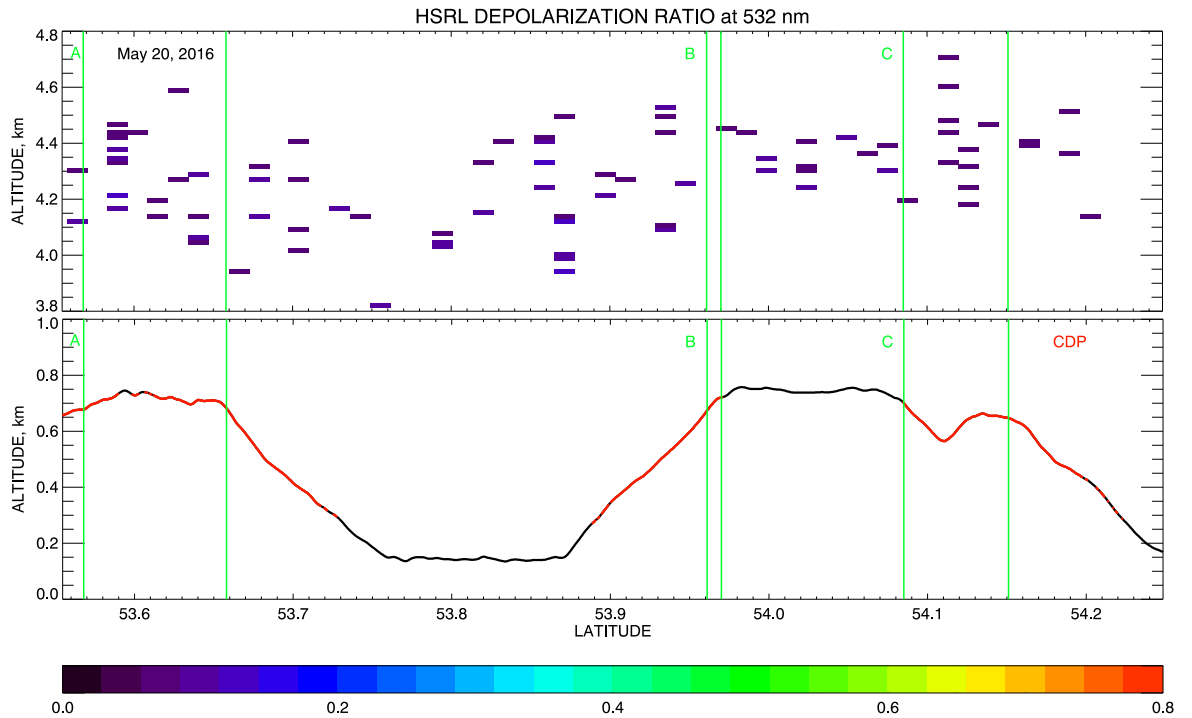


Figure 7: Same as in Fig. 3 but for May 20, 2016 case. The pairs of vertical green lines labeled A, B, and C indicate the intervals used for RSP-CDP intercomparisons presented in Table 1. The DSDs from the top points of these intervals are shown in Fig. 9.

404 weak low-pressure systems to the east. The site is dominated by Sc clouds
 405 which are either induced by these low-pressure systems, or are moving into
 406 the region ahead of a cold front over the Labrador Sea.

407 Figure 7, similar to Fig. 3, shows the altitude of the lower leg and the
 408 availability of *in situ* cloud data (red points). While the presence of cloud
 409 data clearly indicates that the aircraft was porpoising through clouds with
 410 tops of about 750 m and bottoms of 300 m, these clouds are not visible in
 411 HSRL profiles in Fig. 7. However, the low cloud layer can be clearly seen

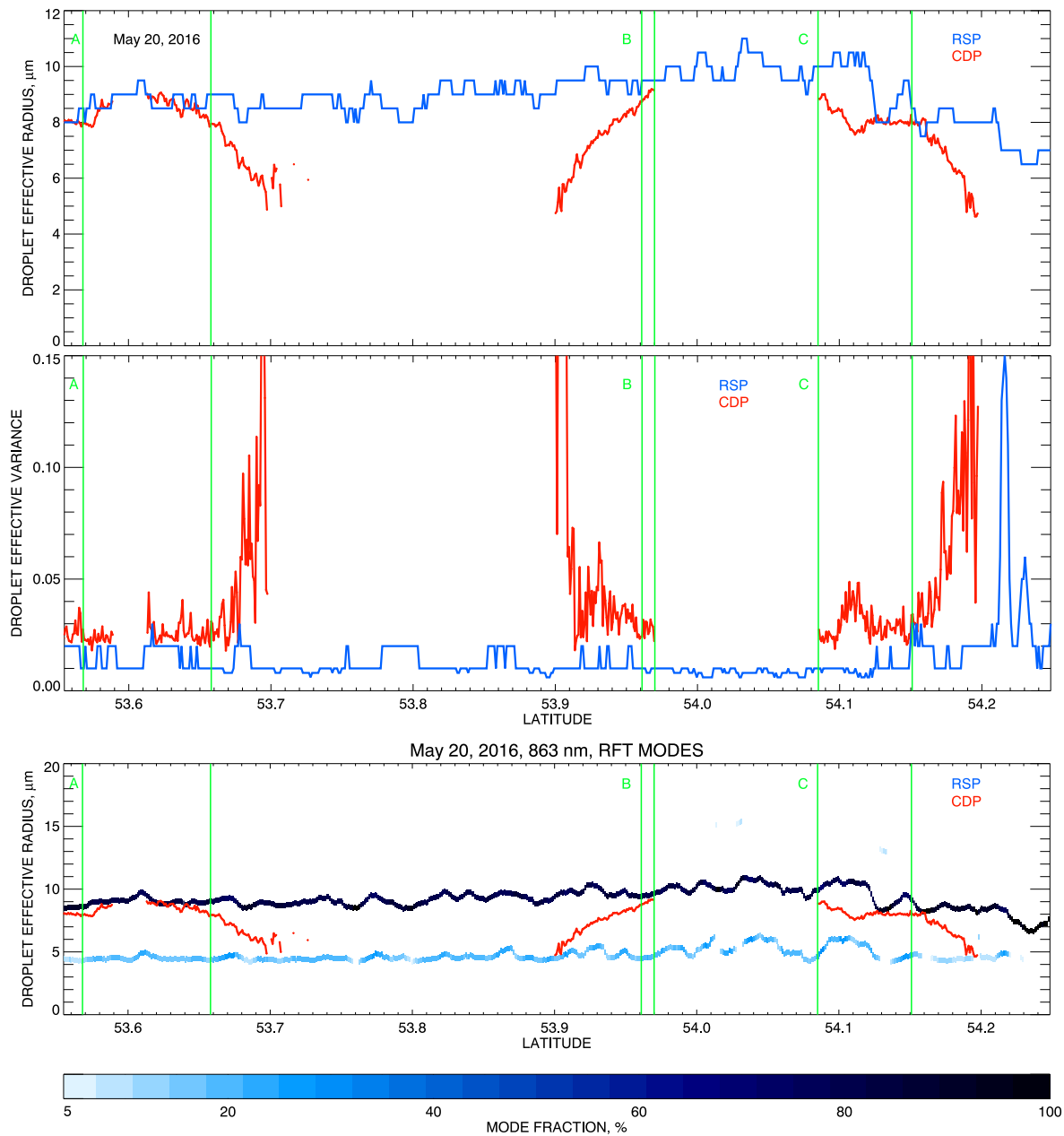


Figure 8: Same as in Fig. 4 but for May 20, 2016 case. The pairs of vertical green lines labeled A, B, and C indicate the intervals used for RSP-CDP intercomparisons presented in Table 1.

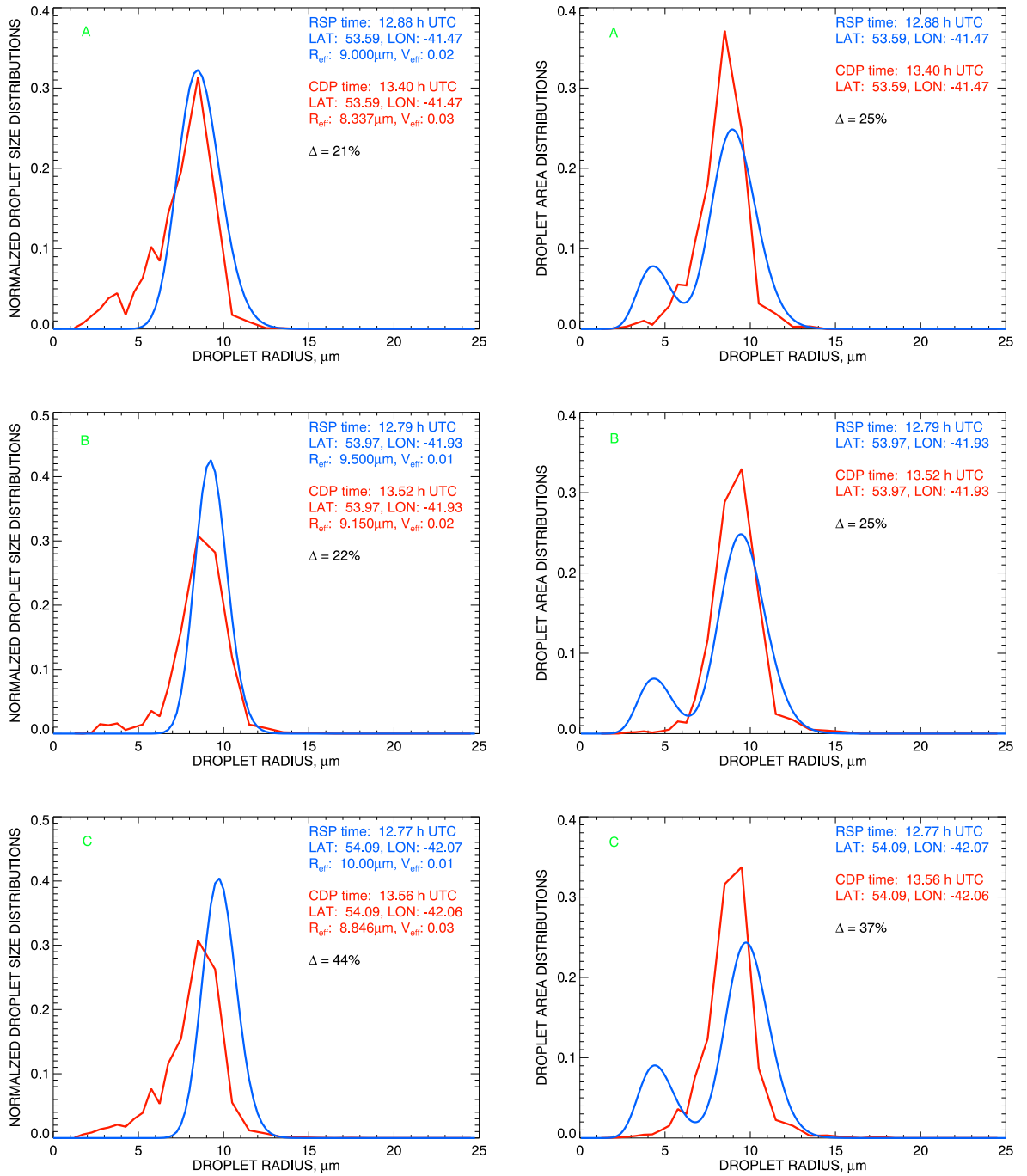


Figure 9: RSP- (blue) and CDP-derived (red) droplet radius (left) and area (right) distributions corresponding to cloud top (A: 13.40 h UTC, top); exit (B: 13.52 h UTC, middle); and entrance (C: 13.56 h UTC, bottom) in the May 20 case (see Fig. 7). The presented RSP retrievals are parametric in left plots and RFT-derived in right plots.

412 if HSRL’s low-signal mask is not applied (see Supplemental material) de-
413 spite the presence of noise in the picture. The most likely reason for such
414 weak signature of the low clouds in HSRL profile is attenuation of the lidar
415 signal by a cloud layer at 4.5 km height, which is apparent in the HSRL
416 532 nm VDR shown in Fig. 7 (top). The low (less than 0.04) VDR values
417 normally correspond to liquid cloud phase. While on this particular flight
418 HSRL measurements may be affected by accidental contamination of the
419 window with oil from the aircraft, the air temperature of about -20°C at
420 4.5 km is consistent with supercooled liquid water or mixed-phase cloud (cf.
421 Alexandrov et al., 2016a). Thus, the upper layer is expected to contribute a
422 secondary size mode to the RSP-derived DSD making it bimodal. Alexan-
423 drov et al. (2016a) reported a similar case when a mixed-phase cloud was
424 observed above a water cloud. In that case a $5\text{-}\mu\text{m}$ mode in bimodal DSD
425 was attributed to the upper layer, while a larger $10\text{-}\mu\text{m}$ mode – to the lower
426 layer.

427 As in the May 18 case, the RSP retrievals of DSD parameters are in
428 good agreement with CDP measurements when the *in situ* measurements
429 are being made within 50 m from cloud top. Figure 8, where the results of
430 the parametric fit and RFT methods applied to RSP data are compared with
431 CDP retrievals, indicates three such intervals within the segment (depicted
432 by labeled pairs of vertical green lines in Figs. 7 and 8): (A) C-130 ascending
433 to the cloud top and remaining there for a while before descending back into
434 cloud (13:23-25 UTC, Lat: $53.57\text{-}53.66^{\circ}\text{N}$); (B) exit from the cloud (13:31
435 UTC, Lat: $53.96\text{-}53.97^{\circ}\text{N}$); and (C) entrance into the cloud (13:33-35 UTC,
436 Lat: $54.09\text{-}54.15^{\circ}\text{N}$; note that the part of the interval where CDP was below

437 50 m was not used in comparisons, see Supplemental file for details). The
438 results of the comparisons between the RSP and CDP retrievals of the droplet
439 effective radius and variance for these three intervals are presented in Table 1
440 (the values corresponding to the larger size mode in RFT-derived DSDs are
441 placed in parentheses). In all three cases RSP retrievals show slightly larger
442 droplet sizes than *in situ* measurements with the largest bias in effective
443 radius of $0.77 \mu\text{m}$ ($1.00 \mu\text{m}$ for RFT) in case C. The RSP-derived values of
444 v_{eff} are biased lower by 0.01-0.02 on average compared to those from CDP.

445 Figure 9 presents examples of DSD shapes derived for the top points
446 of the three intervals. The RFT analysis results shown in the right panels
447 of Fig. 9, as well as Fig. 8 (bottom), strongly indicate the presence of a
448 second smaller ($4.5\text{-}\mu\text{m}$) mode in the cloud DSDs, while the larger ($9\text{--}9.5\text{-}$
449 μm) mode is consistent with *in situ* data (cf. Alexandrov et al., 2016a). This
450 smaller mode may be attributed to the 4.5-km cloud layer seen in Fig. 7
451 (top), implying that this layer is optically thin. Unfortunately, the size of
452 this mode cannot be validated *in situ*, since the upper cloud layer was not
453 sampled. We should note that the parametric algorithm has a tendency to
454 ignore the second mode when it is weak, thus, retrieving the parameters of
455 the dominant mode alone (see Alexandrov et al. (2012a) for more details and
456 simulation results). This is why the parametric RSP results for May 20 agree
457 with those from RFT analysis (both presented in Table 1) on average within
458 $0.3 \mu\text{m}$ in r_{eff} and within 0.01 in v_{eff} .

459 4.3. May 27, 2016

460 The measurements made during the legs flown on May 27 at 15:06:05–
461 15:12:20 UTC (RSP) and 14:39:00–14:46:48 UTC (CDP) resulted in the most

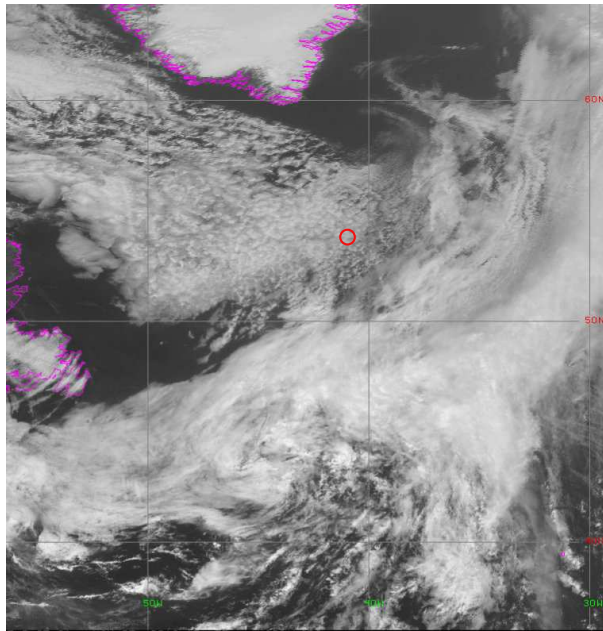


Figure 10: Same as Fig. 2 but for 15:15 UTC on May 27, 2016.

462 extensive (166 RSP scans) dataset from NAAMES campaign suitable for
 463 comparison between remote sensing and *in situ* retrievals, as the aircraft was
 464 grazing cloud tops during the *in situ* leg. The RSP and CDP ground tracks
 465 were between the points with coordinates (53.7°N, 41.3°W) and (54.3°N,
 466 41.3°W). The GOES image of the observed cloud field and its vicinity is
 467 presented in Fig. 10. The measurement site is located in a region just
 468 behind a cold front that passed through the region. The general wind flow
 469 is coming down the Labrador Sea, bringing closed-cell Sc clouds behind the
 470 front. The distance between the tracks of high-altitude and low-altitude legs
 471 in this case was larger than in the other three cases (up to 1 km vs. 200
 472 m). However, the homogeneity of the Sc cloud field means that discrepancies
 473 between *in situ* and remotely sensed DSDs caused by spatial mismatches in

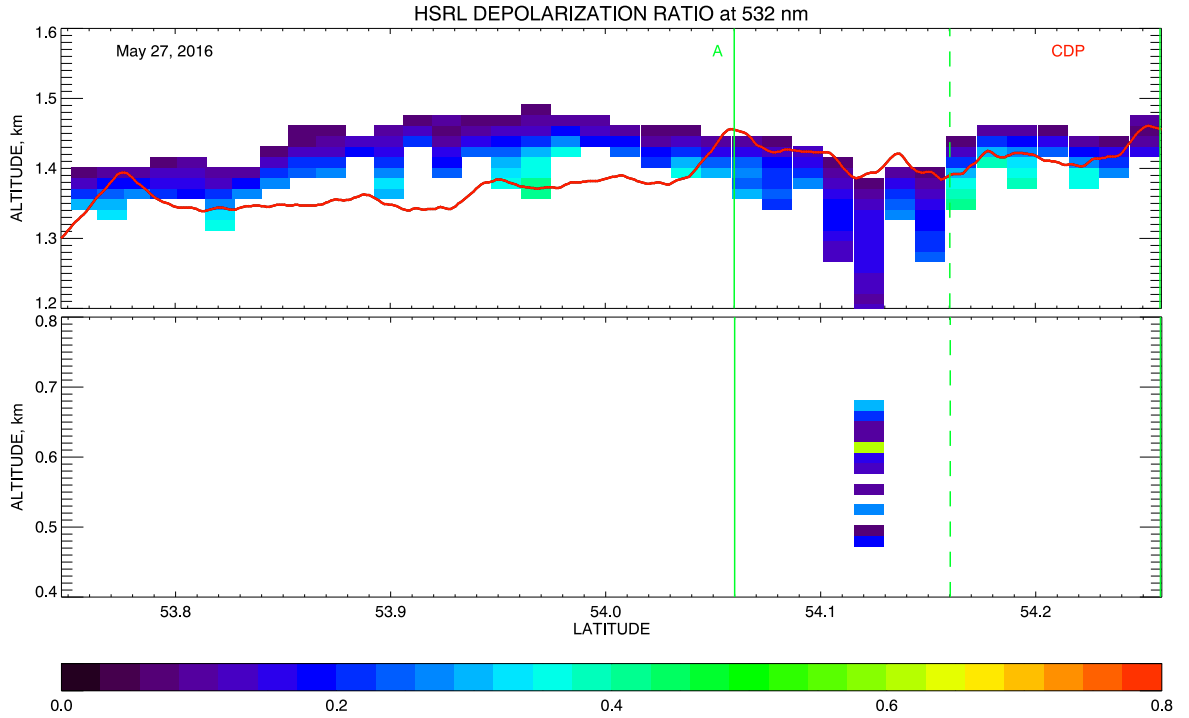


Figure 11: Same as in Fig. 3 but for May 27, 2016 case. Two solid vertical green lines bound the single interval (A) used for comparisons. This two lines together with dashed line between them represent points used in DSD shape comparisons shown in Fig. 13.

474 the horizontal are expected to be minimal.

475 For quantitative comparisons of DSDs effective radius and variance (Fig.
 476 12) we selected the parts of the legs north of 54.06°N where the aircraft was
 477 close to cloud top during the *in situ* leg, as is seen in Fig. 11. Note that unlike
 478 other cases considered in this study, the C-130 had not exited or entered the
 479 cloud during the *in situ* segment, so we cannot determine the exact cloud
 480 top based on CDP data themselves. Thus, in this case our selection of the
 481 CDP data to compare with the RSP retrievals is based on HSRL profiles.

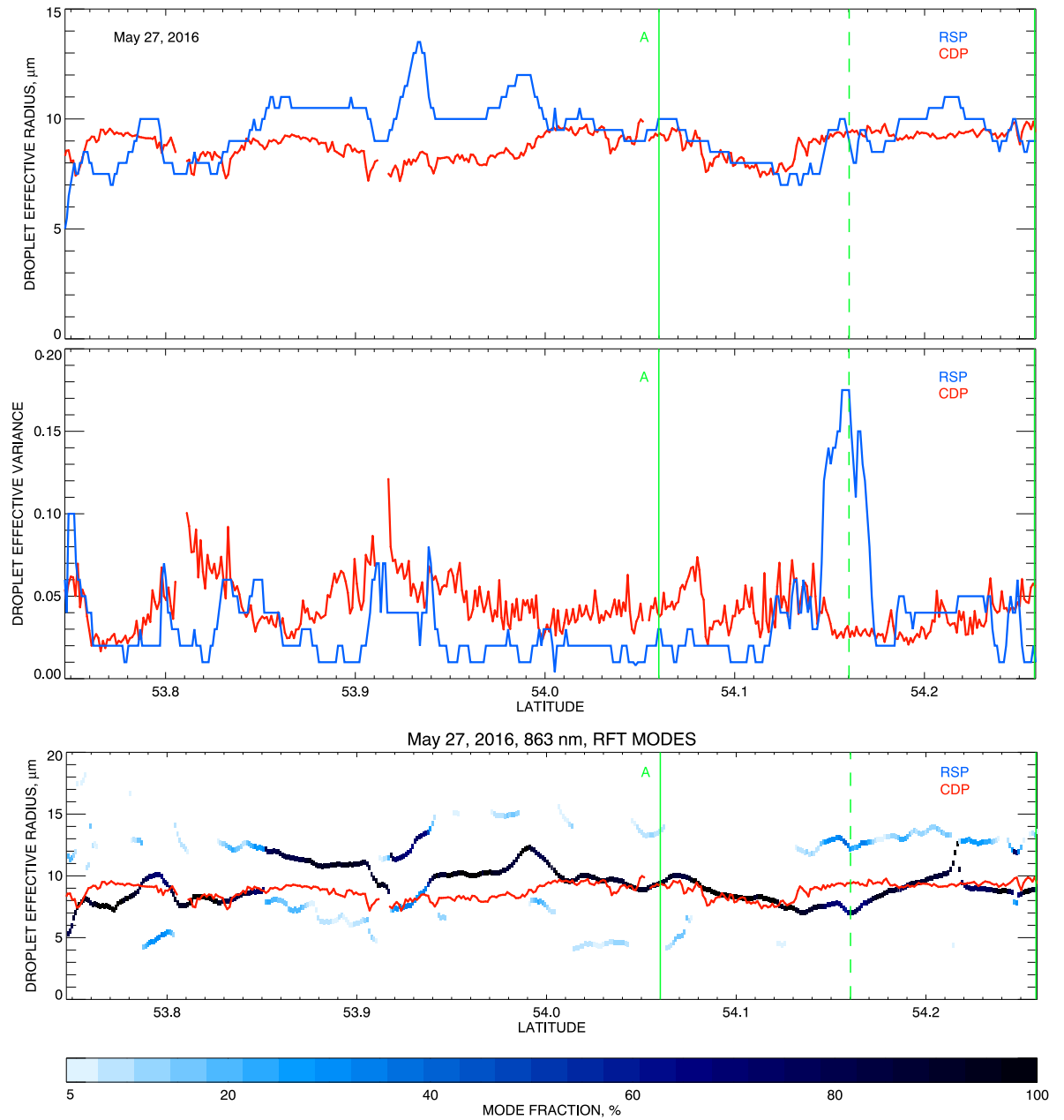


Figure 12: Same as in Fig. 4 but for May 27, 2016 case. Two solid green lines bounding the comparison interval and dashed line between them represent points used in DSD shape comparisons shown in Fig. 13.

482 In the absence of clearly identifiable data points (such as cloud entry or
483 exit) we rather arbitrarily chose the examples for comparison of DSD shapes
484 (Fig. 13) from the first (top panels) and the last (bottom panels) points
485 of the selected interval. In addition to this, Fig. 13 (middle) presents the
486 DSDs from the point in the middle of the interval depicted by a dashed
487 vertical green line in Figs. 11 and 12. This point was chosen because of
488 strong bimodality of the RFT-derived distribution shape (which is discussed
489 below).

490 The results presented in Table 1 show that in the selected interval the
491 RSP's r_{eff} is practically unbiased relative to the CDP retrievals, while the
492 standard deviation of the difference between RSP and CDP values was rel-
493 atively large compared to other cases ($0.82 \mu\text{m}$ for parametric, $1.00 \mu\text{m}$ for
494 dominant RFT mode). The difference in effective variance between *in situ*
495 and remote sensing retrievals is very small on average (less than 0.01), how-
496 ever the standard deviation of the differences is quite large (0.04) when para-
497 metric RSP retrievals are used. This is mostly due to the peak in RSP's
498 v_{eff} around 54.16°N in latitude (Fig. 12 (middle)) reaching values as high
499 as 0.18. As in the May 18 case A, such high variances are associated with
500 a distinctively bimodal structure of the RFT-derived DSDs (Figs. 12 (bot-
501 tom), 13 (middle)), when the parametric fit reflects the width of the whole
502 size distribution rather than the dominant mode (which has smaller v_{eff} close
503 to the CDP value).

504 We usually associate bimodal DSDs with two-layer cloud systems, and in
505 this case there is a feature in HSRL data that can be interpreted as signature
506 of a second cloud layer. Figure 11 (bottom) shows a single lidar profile of a

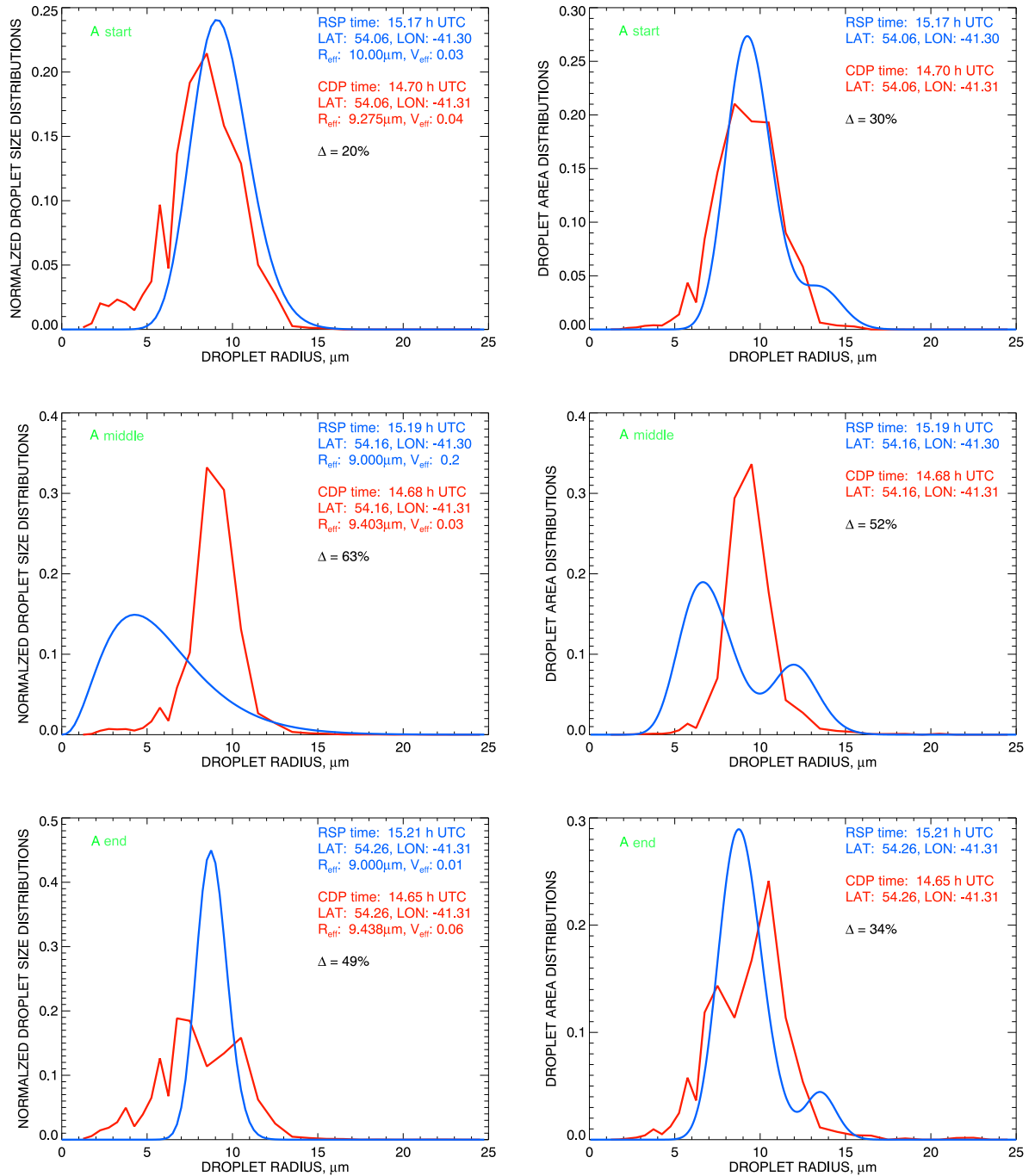


Figure 13: RSP- (blue) and CDP-derived (red) droplet radius (left) and area (right) distributions selected from May 27 data. The CDP time stamps for these examples are 14.70 h UTC (top), 14.68 h UTC (middle), and 14.65 h UTC (bottom). The presented RSP retrievals are parametric in left plots and RFT-derived in right plots. The top and bottom plots correspond to the ends of the comparison interval (solid green lines in Figs. 11 and 12), while the middle plots show distinctly bimodal DSD from the middle of the interval (depicted by dashed line in Figs. 11 and 12).

507 layer with top at about 700 m located below the cloud which was sampled
508 (this signature is wider when HSRL’s low-signal mask is off: see Supplemental
509 material). Note that the reported profile of the top layer (Fig. 11 (top)) at
510 this point goes deeper into the cloud (to 200 m below cloud top) than in
511 the rest of the segment. This indicates that the cloud top is optically more
512 diffuse here allowing the laser signal reflected from deeper into the cloud and
513 possibly the bottom layer to be detected. The DSD modes can be attributed
514 to the two layers based on Fig. 12 (bottom)). There the dominant 9- μm size
515 mode continuously extends to the part of the interval where it becomes the
516 sole mode detected by the RSP. This happens only where the bottom layer is
517 not detectable by the instrument (see also Fig. 13 (top)). Thus, we attribute
518 the smaller droplet size mode to the top cloud layer and the larger 12- μm
519 mode to the bottom layer. This attribution is also consistent with Fig. 12
520 (bottom) where the *in situ* droplet sizes sampled in the top layer are much
521 closer to these of smaller mode in RFT-derived DSD than to those of the
522 larger mode. The top heights of the two cloud layers and the droplet sizes
523 in them are similar to those in May 18 case.

524 4.4. May 30, 2016

525 The validation segments flown on May 30, 2016 between points with
526 coordinates (43.6°N, 44.7°W) and (44.8°N, 44.0°W) were 25 minutes apart:
527 14:32:07–14:46:28 UTC (high altitude remote sensing) and 15:09:00–15:32:24
528 UTC (low altitude *in situ* sampling). The cloud system surrounding the
529 measurement site on this day (Fig. 14) is quite different from the uniform
530 stratocumulus fields observed on the other three days. The site is located
531 in the north-east quadrant of a strong low-pressure system, with a high-

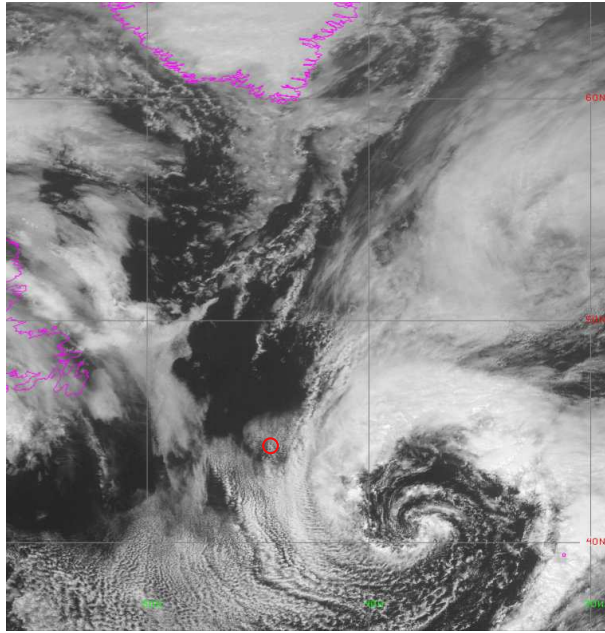


Figure 14: Same as Fig. 2 but for 14:45 UTC on May 30, 2016.

532 pressure system moving in from the west. On the back end of the system,
 533 the northerly flow is mixing in dry air bringing both open-cell and closed-cell
 534 Sc clouds.

535 During the *in situ* leg the aircraft followed the porpoising pattern (Fig.
 536 15) similar to that of May 18 and 20. As in May 20 case, here the CDP
 537 droplet size measurements made within 50 m from cloud top are present in
 538 three short intervals (indicated by pairs of vertical green lines labeled A, B,
 539 and C in Figs. 15 and 16): (A) exiting the cloud (15:18-19 UTC, Lat: 44.09-
 540 44.11°N); (B) entering it from above (15:22 UTC, Lat: 44.21-44.22°N); and
 541 (C) crossing a thin part of the cloud (15:29 UTC, Lat: 44.65-44.66°N).

542 The complexity of cloud morphology in the May 30 case seen in Fig. 14
 543 also shows up in the HSRL profiles (Fig. 15) as highly heterogeneous cloud

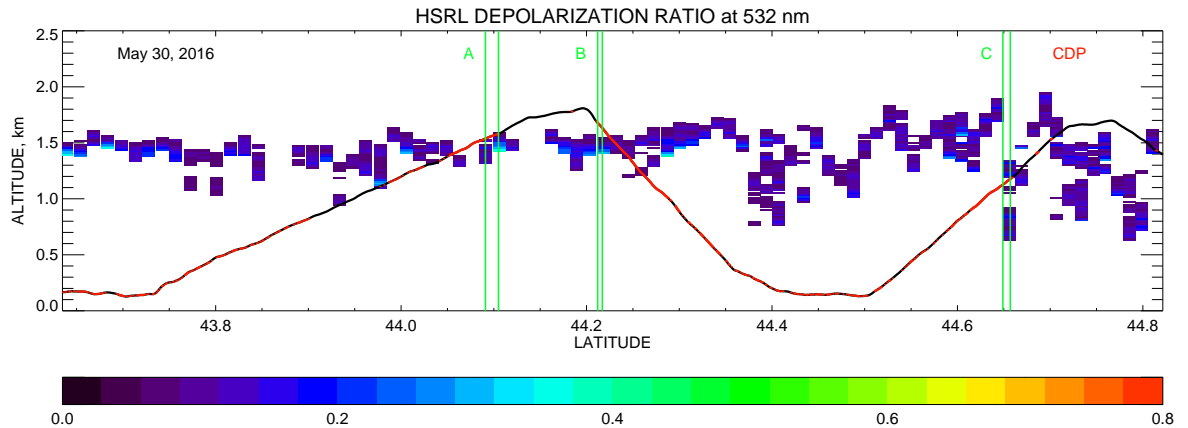


Figure 15: Same as in Fig. 3 but for May 30, 2016 case. The pairs of vertical green lines labeled A, B, and C indicate the intervals used for RSP-CDP intercomparisons presented in Table 1. The DSDs from the top points of these intervals are shown in Fig. 17.

544 top (especially in the second half of the segment), and in both RSP and CDP
 545 droplet size retrievals. Unlike mature marine stratocumulus clouds with very
 546 narrow DSDs at cloud top seen on May 18, 20, and 27, here we encounter very
 547 diverse cloud microphysical structure characterized by wide DSDs for which
 548 the parameters rapidly change from point to point (Figs. 16 and 17). Using
 549 such a dataset for an RSP-CDP intercomparison presents certain challenges
 550 because the spatial and temporal heterogeneity of cloud DSDs may lead to
 551 large discrepancies between the two types of retrievals due to greater than
 552 15 minute difference in observing times and/or ~ 200 m spatial mismatches
 553 between the observation locations. Thus, this case tests the limits of cloud
 554 system complexity under which we can still expect good agreement between
 555 remote sensing and *in situ* retrievals.

556 Despite the above concerns, the RSP-CDP agreement in the three speci-
 557 fied cloud-top cases appears to be reasonably good (Table 1). In cases A

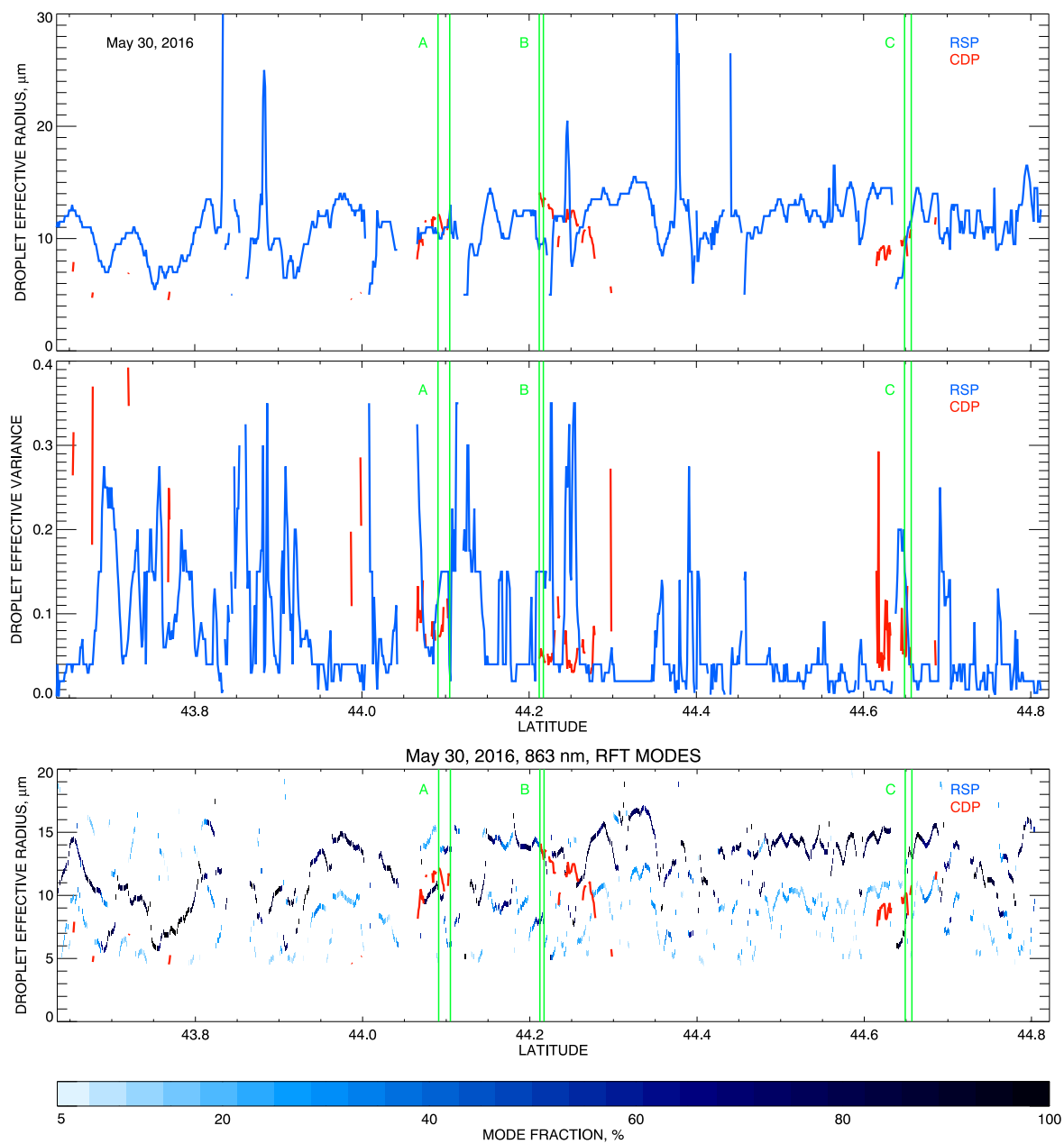


Figure 16: Same as in Fig. 4 but for May 30, 2016 case. The pairs of vertical green lines labeled A, B, and C indicate the intervals used for RSP-CDP intercomparisons presented in Table 1.

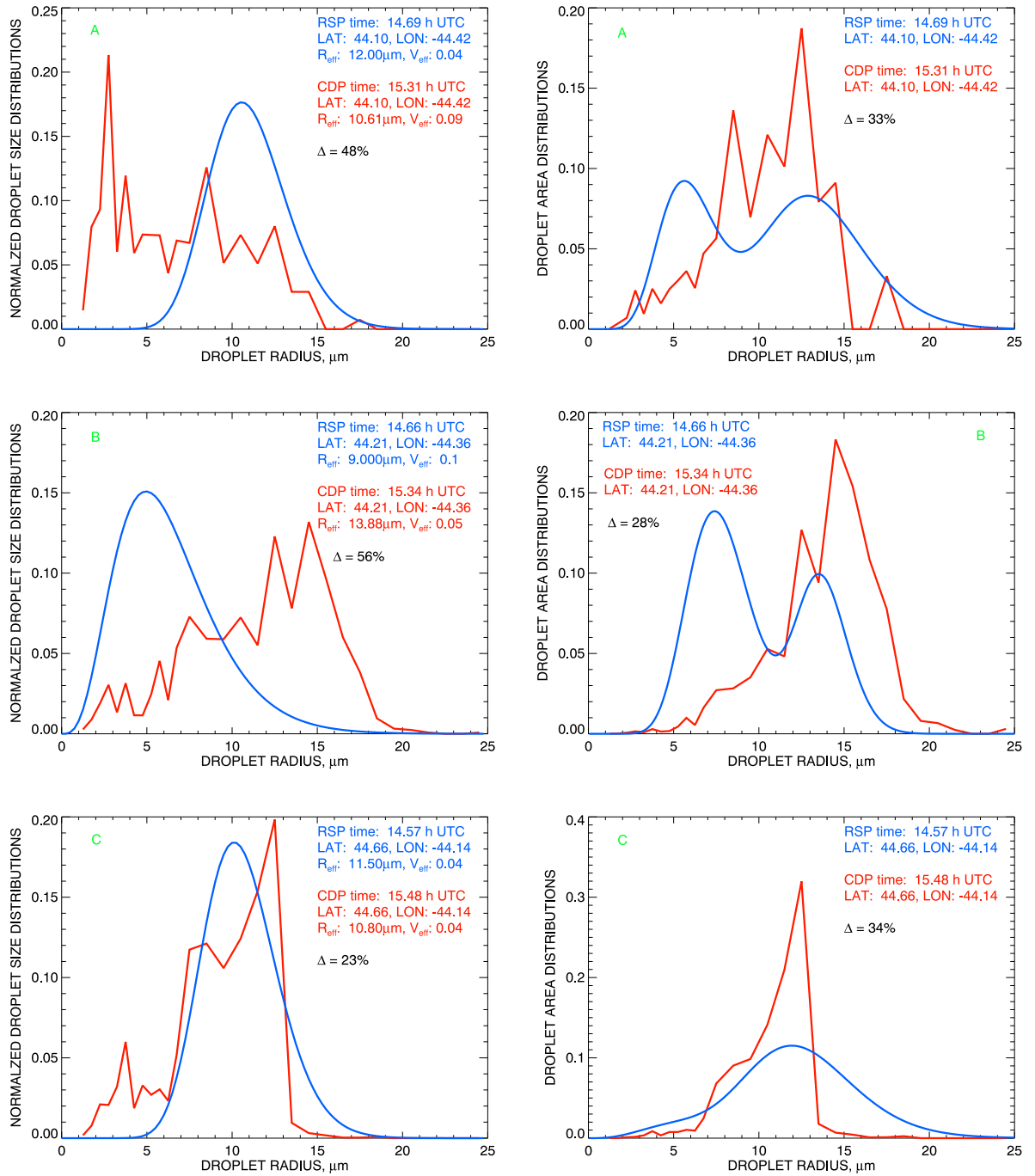


Figure 17: RSP- (blue) and CDP-derived (red) droplet radius (left) and area (right) distributions corresponding to the aircraft exiting the cloud top (A: 15.31 h UTC, top); entering the cloud from above (B: 15.34 h UTC, middle); and crossing a thin part of the cloud (C: 15.48 h UTC, bottom) in the May 30 case (see Fig. 15). The presented RSP retrievals are parametric in left plots and RFT-derived in right plots.

558 and C the RSP (parametric) and CDP results show relative biases in effective
559 radii of $\sim 0.5 \mu\text{m}$ with the standard deviations of the differences being ~ 1
560 μm . The RSP-derived v_{eff} appear to be larger on average than those in
561 CDP retrievals by 0.02–0.04 with standard deviations of the differences up
562 to 0.05, however, we should note that the effective variances themselves were
563 large (~ 0.1 on average) in both datasets. The magnitude of these differences
564 between RSP-derived and *in situ* DSD parameters, while being larger than on
565 other days, is still acceptable. The DSDs from the top points of the intervals
566 are shown in Fig. 17. We see from Fig. 17 (top right) that RFT analysis
567 in case A yields a distinctively bimodal distribution, while the CDP-derived
568 DSD shows no similarity to either one of the two modes, being rather in
569 between them. Similar situation is encountered in case C, while small mode
570 there is rather weak (and is not seen at all in the cloud-top DSD from Fig.
571 17 (bottom right)). In both cases A and C parametric RSP retrievals of r_{eff}
572 are in a better agreement with CDP data than the values from any RFT
573 mode, perhaps because two-layer structure is not well-defined in these cases.
574 (Comparisons of CDP-derived parameters with those of both RFT modes in
575 cases A and C can be found in Supplemental material.)

576 The RFT retrievals should be used instead of the parametric ones in
577 specific cases of distinctively two-layer cloud systems where the CDP makes
578 samples within one of the layers, while the RSP observes both. Cases A and
579 C do not fall into this category (probably due to the complex structure of
580 the clouds), however, case B seemingly does. DSD retrievals in this case very
581 much resemble those in case A from May 18, despite there being no two-layer
582 cloud structure seen in HSRL profiles from Fig. 15. In this case we again see

583 strongly bimodal DSD from RFT analysis with the CDP distribution being
584 close to its larger mode (Fig. 17 (middle right)), while parametric DSD in
585 Fig. 17 (middle left) has much larger v_{eff} (0.1 vs. 0.05) and smaller r_{eff} ($9 \mu\text{m}$
586 vs. $14 \mu\text{m}$) than its CDP counterpart (compare to Fig. 5 (top)). The same
587 situation is repeated for the whole interval B (see Table 1), where the average
588 large RFT mode's r_{eff} of $13.53 \mu\text{m}$ is much closer to the CDP value (13.51
589 μm) than the parametric effective radius ($9.40 \mu\text{m}$). The same is true for
590 the average values of effective variances: 0.15 for parametric RSP retrievals;
591 0.02 for RFT mode; and 0.05 for CDP.

592 5. Conclusions

593 We presented comparisons between cloud droplet size distributions de-
594 rived from RSP observations with those obtained from the measurements
595 made by the Cloud Droplet Probe. This is the first time that validation of
596 polarimetric droplet size retrievals has been done by direct comparison with
597 correlative *in situ* data. This validation dataset became available because of
598 the targeted flight planning during the NAAMES field campaign (May 2016)
599 when the NASA C-130 aircraft flew over the same ground track twice: one
600 time at high altitude making remote sensing measurements, and the other
601 time at low altitude facilitating *in situ* sampling. The presented compar-
602 isons show very good agreement in the cases when both remote and *in situ*
603 measurements were precisely co-located and the aircraft was at cloud top
604 during the sampling. This condition is very important for successful valida-
605 tion since RSP measurements of polarized reflectance are sensitive to cloud
606 droplet sizes only within a layer of unit optical depth (i.e., about 50 m thick)

607 at cloud top, while droplet sizes decrease and DSD widths increase rapidly
608 with depth into the cloud.

609 It should be noted that while the lack of vertical resolution is common to
610 all airborne passive remote sensing techniques, the localization of the polari-
611 metric retrievals near cloud top is an advantage compared to other methods
612 that provide a weighted average over a generally unknown DSD profile within
613 cloud. Weighting functions in such an averaging depend on optical transmit-
614 tance of the cloud layer between the altitude of the droplet and cloud top,
615 which itself depends on the unknown DSD profile. In distinction to this,
616 polarimetric measurements allow for direct retrieval of the actual microphys-
617 ical DSDs, the same as those measured *in situ* or found in the output of a
618 dynamical cloud model.

619 Four flight segments satisfying the cloud-top sampling condition were
620 selected for detailed intercomparisons. During three of them (May 18, 20,
621 and 30) the aircraft flew in a “porpoise” pattern during the *in situ* leg diving
622 into cloud several times. In such cases the CDP measurements suitable for
623 comparison with RSP were selected at the points within 50 m below the
624 aircraft’s entry or exit point at cloud top. In the fourth case (May 27) the
625 aircraft flew at cloud top for some period of time during the *in situ* leg. This
626 made it possible to collect a continuously sampled large dataset for more
627 extensive statistical comparisons with its RSP counterpart.

628 Two retrieval methods were applied to RSP observations of the polarized
629 rainbow: parametric fitting and non-parametric Rainbow Fourier Transform
630 (RFT), the latter allowing for analysis of complex (in particular, bimodal)
631 DSD shapes. The average values of the DSDs’ effective radii and variances

Table 1: Summary of intercomparisons between polarimetric RSP and *in situ* CDP retrievals of effective radii and variances of cloud droplet size distributions from the measurements made during NAAMES field experiment in May 2016. RSP values from parametric fitting algorithm are shown without parentheses, while those from the closest RFT mode are in parentheses. * Cases with two-layer cloud structure where parametric RSP values should not be used (these values are shown in *italics*).

Case No. of pts. CDP pattern at cld. top	CDP Start pt. coord. End pt. coord. Alt. range	RSP $\langle r_{\text{eff}} \rangle$, μm $\langle v_{\text{eff}} \rangle$ Time, UTC	CDP $\langle r_{\text{eff}} \rangle$, μm $\langle v_{\text{eff}} \rangle$ Time, UTC	$r_{\text{eff}}^{\text{RSP}} - r_{\text{eff}}^{\text{CDP}}$ mean, μm std. dev., μm	$v_{\text{eff}}^{\text{RSP}} - v_{\text{eff}}^{\text{CDP}}$ mean std. dev.
May 18, 2016					
A* 9 pts. ascent	56.89°N, 46.48°W 56.89°N, 46.50°W 749 – 796 m	<i>5.56</i> (10.75) <i>0.10</i> (0.01) 11:03	10.80 0.04 11:59	<i>-5.2</i> (-0.02) <i>0.85</i> (1.5)	<i>0.1</i> (-0.03) <i>0.1</i> (0.006)
B 15 pts. descent	56.94°N, 46.87°W 56.95°N, 46.90°W 798 – 838 m	10.80 (11.12) 0.02 (0.02) 11:00	10.77 0.03 12:02	0.035 (0.35) 0.26 (0.16)	-0.009 (-0.01) 0.002 (0.002)
May 20, 2016					
A 64 pts. asc/descent	53.57°N, 41.45°W 53.66°N, 41.55°W 679 - 729 m	8.66 (8.96) 0.02 (0.02) 12:52-53	8.51 0.03 13:23-25	0.15 (0.45) 0.44 (0.32)	-0.01 (-0.005) 0.007 (0.004)
B 9 pts. ascent	53.96°N, 41.92°W 53.97°N, 41.93°W 675 – 720 m	9.50 (9.51) 0.01 (0.02) 12:48	8.99 0.03 13:31	0.51 (0.51) 0.17 (0.13)	-0.02 (-0.01) 0.003 (0.003)
C 30 pts. descent	54.09°N, 42.07°W 54.15°N, 42.14°W 648 – 698 m	9.00 (9.24) 0.01 (0.02) 12:45-46	8.23 0.03 13:33-35	0.77 (1.00) 0.56 (0.49)	-0.02 (-0.007) 0.005 (0.003)
May 27, 2016					
A 166 pts. grazing	54.26°N, 41.31°W 54.06°N, 41.30°W 1384 – 1461 m	9.04 (8.70) 0.04 (0.03) 15:10-12	8.94 0.04 14:39-42	0.01 (-0.24) 0.82 (1.00)	0.005 (-0.009) 0.04 (0.02)
May 30, 2016					
A 11 pts. ascent	44.09°N, 44.43°W 44.11°N, 44.42°W 1539 – 1577 m	10.68 0.10 14:41	11.22 0.10 15:18-19	-0.54 0.99	0.04 0.04
B* 5 pts. descent	44.21°N, 44.36°W 44.22°N, 44.36°W 1635 – 1677 m	<i>9.40</i> (13.53) <i>0.15</i> (0.02) 14:40	13.51 0.05 15:22	<i>-4.10</i> (0.02) <i>0.63</i> (0.33)	<i>0.10</i> (-0.03) <i>0.004</i> (0.01)
C 7 pts. ascent	44.65°N, 44.14°W 44.66°N, 44.14°W 1126 – 1176 m	10.43 0.09 14:34	9.88 0.07 15:29	0.55 1.00	0.02 0.05

632 for each flight segment, as well as the means and standard deviations of
633 the differences between these parameters from RSP and CDP datasets are
634 presented in Table 1. The results of both RSP retrieval methods are shown
635 with RFT values placed in parentheses.

636 HSRL depolarization profiles co-located with RSP and CDP data indicate
637 that in some cases at least two separate layers of clouds are present in the
638 scene. In this situation if the top layer is optically thin (optical depth less
639 than one) the RSP retrievals are sensitive to droplet sizes in both layers (see
640 Alexandrov et al. (2012a) for details and simulations). This results in bimodal
641 DSD in RFT retrievals with each size mode associated with its own cloud
642 layer. Alexandrov et al. (2012a) demonstrated that the parametric retrieval
643 algorithm in such case either picks one (dominant) mode (if the other is weak)
644 or fits the whole DSD with a single wide mode having large (0.1 or more)
645 effective variance. The effective radius in the latter case is a weighted average
646 of those in the two modes. While such a wide DSD may be representative of
647 the two-layer system as a whole, it does not reflect microphysics in any one of
648 the layers. Understanding this is especially important for studies of marine
649 Sc clouds which are known to have very narrow DSDs at cloud top (formed
650 as a result of convection) with v_{eff} often smaller than 0.01 (corresponding to
651 about 1 μm standard deviation of radius in DSD) (Alexandrov et al., 2015;
652 Pawlowska et al., 2006). This means that in Sc cases detection of a large v_{eff}
653 should automatically raise suspicion that a multilayer structure is present.

654 Comparison of RSP retrievals with *in situ* measurements in two-layer
655 situations described above is challenging since the *in situ* DSDs reflect cloud
656 microphysics in a single layer (at a time), and, thus, cannot be directly

657 compared to RSP retrievals representing both layers at once. However, in
 658 such cases the RFT can be used to separate DSDs of different layers, one of
 659 which can be used for comparison with *in situ* data. In the NAAMES dataset
 660 we encountered very wide DSDs in parametric RSP retrievals (corresponding
 661 to distinctly bimodal RFT-derived DSDs) in two instances: case A from May
 662 18 and case B from May 30. In the May 18 case two cloud layers are clearly
 663 seen in HSRL profiles (Fig. 3). In this case CDP retrievals yield segment-
 664 averaged r_{eff} of $10.80 \mu\text{m}$ and v_{eff} of 0.04, which are quite different from
 665 the results of RSP’s parametric algorithm: $r_{\text{eff}} = 5.56 \mu\text{m}$ and $v_{\text{eff}} = 0.10$.
 666 However, the parameters of the larger mode in the RFT-derived distribution
 667 ($r_{\text{eff}} = 10.75 \mu\text{m}$ and $v_{\text{eff}} = 0.01$) are very close to the *in situ* values. A
 668 similar situation is seen in case B from May 30, where the averaged CDP-
 669 derived parameters ($r_{\text{eff}} = 13.51 \mu\text{m}$ and $v_{\text{eff}} = 0.05$) and those of the larger
 670 RFT mode ($r_{\text{eff}} = 13.53 \mu\text{m}$ and $v_{\text{eff}} = 0.02$) were close. In contrast the
 671 results from the RSP’s parametric algorithm were different ($r_{\text{eff}} = 9.40 \mu\text{m}$
 672 and $v_{\text{eff}} = 0.15$). The parametric RSP results in both of these cases, being
 673 not suitable for comparison with CDP data, are shown in italics in Table 1.

674 The clouds observed on May 18, 20, and 27 were well-developed stratocu-
 675 mulus with narrow DSDs at cloud tops. In six cases from these days (except
 676 case A from May 18 described above) both parametric and RFT retrievals
 677 were comparable with *in situ* data. In all of these cases the parameters of
 678 the dominant mode in the RFT-derived DSDs were close to those obtained
 679 using a parametric fit, being within $0.3 \mu\text{m}$ in r_{eff} and 0.01 in v_{eff} . Table 1
 680 shows that the RSP-CDP biases in r_{eff} for the well-developed Sc cases were
 681 mostly positive and within $0.5 \mu\text{m}$ (except for May 20, C: $0.77\text{--}1.00 \mu\text{m}$),

682 while the standard deviations were within $0.6 \mu\text{m}$ (except for May 18, A:
683 $1.50 \mu\text{m}$; and May 27, A: $0.82\text{--}1.00 \mu\text{m}$). The RSP-CDP biases in v_{eff} were
684 mostly negative and no larger than 0.02 in absolute value (except for May 18,
685 A: 0.03), while the standard deviations of v_{eff} in the segments were smaller
686 than 0.01 (except for May 27, A: 0.04).

687 The subject of our study on May 30 was a cloud with complex structure
688 (probably open-cell Sc) consistent with wide DSDs in both RSP and CDP
689 retrievals (v_{eff} of up to 0.1 on average). Case B for this day was described
690 above as having good agreement between *in situ* parameters and those of one
691 of the RFT-derived size modes. While RFT analysis produced bimodal DSDs
692 also in case C, and especially A, none of the modes showed similarity with
693 CDP-derived size distributions (so we do not show RFT data for these cases
694 in Table 1). Parametric RSP retrievals, on the other hand, showed reasonably
695 good agreement with *in situ* data in both cases: $\sim 0.55\text{-}\mu\text{m}$ biases and $1\text{-}\mu\text{m}$
696 standard deviation for r_{eff} , while for v_{eff} biases were below 0.04 and standard
697 deviations – below 0.05. The RSP-CDP comparisons were not expected to
698 be particularly good for this day because the substantial heterogeneity of
699 the cloud field increases spatial and temporal sampling errors. However,
700 the results appear to be quite satisfactory, showing that RSP can provide
701 accurate droplet size retrievals (with accuracy in r_{eff} of $1 \mu\text{m}$, and in v_{eff} –
702 of about 0.04) even for a complex cloud field like this.

703 The measurement accuracies of cloud DSD parameters required for a re-
704 liable quantification of indirect aerosol effect on clouds have been specified
705 by Mishchenko et al. (2004) as being the greater of $1 \mu\text{m}$ or 10% for r_{eff} and
706 greater of 0.05 or 50% for v_{eff} . These requirements are based on the need to

707 detect changes of cloud droplet size caused by increase in cloud condensation
708 nuclei concentrations and to determine the cloud droplet number concentra-
709 tion with at least 30% accuracy. The validation results presented in Table 1
710 demonstrate that the accuracy of RSP-based retrievals of DSD parameters
711 satisfy and in most cases exceed these requirements.

712 The validation of polarimetric cloud droplet size retrieval techniques pre-
713 sented in this study demonstrated the value of airborne (and potentially
714 satellite) polarimetric observations and that the resulting retrieved DSDs
715 are robust and accurate. We hope that validation experiments will be con-
716 tinued during future field campaigns and allow for an evaluation of how the
717 information in the remotely sensed DSDs can be used to understand the for-
718 mation of drizzle at cloud top. Our experience gained during this study will
719 help us to better plan future validation efforts. For example, we recommend
720 that the aircraft should periodically exit cloud when grazing cloud top, so
721 the cloud top height could be determined from *in situ* measurements. An-
722 other suggestion is to sample both layers in two-layer cloud structures, thus,
723 allowing for validation of bimodal DSDs.

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740 **Appendix A Droplet size statistics in remote sensing and in situ** 741 **measurements**

742 Remote sensing and *in situ* measurement communities traditionally use
743 different statistics for characterization of droplet size distributions. While
744 *in situ* measurements commonly report mean droplet diameter, its standard
745 deviation, and relative dispersion, optical remote sensing retrievals are usu-
746 ally expressed in terms of effective radius and variance. For the reference, we
747 present here definitions of these parameters and relationships between them
748 (for uniformity, all statistics is expressed in terms of droplet radius rather
749 than diameter).

750 Droplet size distribution $n(r)$ has moments

$$\langle r^k \rangle = \int_0^{\infty} r^k n(r) dr \quad (\text{A.1})$$

751 including the mean radius $\langle r \rangle$. The standard deviation σ is derived from the

752 dispersion

$$\sigma^2 = \int_0^{\infty} (r - \langle r \rangle)^2 n(r) dr = \langle r^2 \rangle - \langle r \rangle^2. \quad (\text{A.2})$$

753 Another commonly used parameter is relative standard deviation $d = \sigma/\langle r \rangle$
754 or relative dispersion

$$d^2 = \frac{\sigma^2}{\langle r \rangle^2} = \frac{\langle r^2 \rangle}{\langle r \rangle^2} - 1. \quad (\text{A.3})$$

755 The optically-driven effective radius and variance are defined as (Hansen &
756 Travis, 1974)

$$r_{\text{eff}} = \frac{\int_0^{\infty} r \pi r^2 n(r) dr}{\int_0^{\infty} \pi r^2 n(r) dr} = \frac{\langle r^3 \rangle}{\langle r^2 \rangle}, \quad (\text{A.4})$$

757 and

$$v_{\text{eff}} = \frac{1}{r_{\text{eff}}^2} \frac{\int_0^{\infty} (r - r_{\text{eff}})^2 \pi r^2 n(r) dr}{\int_0^{\infty} \pi r^2 n(r) dr} = \frac{\langle r^4 \rangle \langle r^2 \rangle}{\langle r^3 \rangle^2} - 1. \quad (\text{A.5})$$

758 Cloud DSDs often have the gamma distribution shape (Hansen & Travis,
759 1974):

$$n(r) = \frac{(ab)^{(2b-1)/b}}{\Gamma[(1-2b)/b]} r^{(1-3b)/b} e^{-r/ab}, \quad (\text{A.6})$$

760 where Γ is the gamma function. The parameters $a > 0$, and $b \in (0, 1/2)$ of

761 this distribution coincide with respectively the effective radius and variance:

$$r_{\text{eff}} = a, \quad v_{\text{eff}} = b. \quad (\text{A.7})$$

762 The mean radius and the standard deviation of gamma distribution are re-
763 spectively

$$\langle r \rangle = a(1 - 2b) \quad \text{and} \quad \sigma = a\sqrt{b(1 - 2b)}, \quad (\text{A.8})$$

764 thus, its relative dispersion is

$$d^2 = \frac{b}{1 - 2b}. \quad (\text{A.9})$$

765 This allows to express the effective radius and variance of gamma distribution
766 in terms of $\langle r \rangle$ and d :

$$a = \langle r \rangle (1 + 2d^2), \quad b = \frac{d^2}{1 + 2d^2}. \quad (\text{A.10})$$

767 For example, typical for Sc clouds values $r_{\text{eff}} = 10 \mu\text{m}$ and $v_{\text{eff}} = 0.02$
768 correspond to $\langle r \rangle = 9.6 \mu\text{m}$, $d = 0.14$, and $\sigma = 1.38 \mu\text{m}$.

769 Note that the mode radius of gamma distribution is

$$r_{\text{max}} = a(1 - 3b), \quad (\text{A.11})$$

770 indicating that gamma distribution has maximum only when $b < 1/3$.

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860 **List of Figure Captions**

861 **Figure 1.** CDP-derived vertical profiles of droplet effective radius (left)
862 and variance (right) for May 18, 2016 (see Fig. 3 for the location and CDP
863 altitude). Linear fits are provided to show how fast these parameters change
864 with altitude near cloud top.

865 **Figure 2.** GOES satellite image of North Atlantic ocean for 11:15 UTC
866 on May 18, 2016. The coastline of Newfoundland is shown in the West,
867 while that of Greenland – in the North. The vicinity of the validation flight
868 segments is depicted by red circle.

869 **Figure 3.** HSRL depolarization ratio profile for the May 18 case. Black curve
870 depicts the altitude of the aircraft during the *in situ* segment. Red points
871 on this curve indicate availability of CDP measurements with $r_{\text{eff}} > 4.5 \mu\text{m}$.
872 The pairs of vertical green lines labeled A and B indicate the intervals used
873 for RSP-CDP intercomparisons presented in Table 1. The DSDs from the
874 top points of these intervals are shown in Fig. 5.

875 **Figure 4.** Top and middle: effective radius and variance, respectively,
876 retrieved from the RSP data using the parametric fitting technique (blue
877 curves). The discretization seen in these plots is that of the LUTs used.
878 Bottom: the results of mode decomposition applied to distributions derived
879 from RSP data using RFT. The curves depicting the modes' effective radii are
880 colored according to the modes' respective weights in DSD. The red curves
881 in all panels depict the screened co-located CDP retrievals. The pairs of
882 vertical green lines labeled A and B indicate the intervals used for RSP-CDP
883 intercomparisons presented in Table 1.

884 **Figure 5.** RSP- (blue) and CDP-derived (red) droplet number (left) and

885 area (right) distributions corresponding to cloud exit (A: 11.98 h UTC, top)
886 and entrance (B: 12:03 h UTC, bottom) in the May 18 case (see Fig. 3).
887 The presented RSP retrievals are parametric in left plots and RFT-derived
888 in right plots.

889 **Figure 6.** Same as Fig. 2 but for 12:45 UTC on May 20, 2016.

890 **Figure 7.** Same as in Fig. 3 but for May 20, 2016 case. The pairs of vertical
891 green lines labeled A, B, and C indicate the intervals used for RSP-CDP
892 intercomparisons presented in Table 1. The DSDs from the top points of
893 these intervals are shown in Fig. 9.

894 **Figure 8.** Same as in Fig. 4 but for May 20, 2016 case. The pairs of vertical
895 green lines labeled A, B, and C indicate the intervals used for RSP-CDP
896 intercomparisons presented in Table 1.

897 **Figure 9.** RSP- (blue) and CDP-derived (red) droplet radius (left) and area
898 (right) distributions corresponding to cloud top (A: 13.40 h UTC, top); exit
899 (B: 13.52 h UTC, middle); and entrance (C: 13.56 h UTC, bottom) in the
900 May 20 case (see Fig. 7). The presented RSP retrievals are parametric in
901 left plots and RFT-derived in right plots.

902 **Figure 10.** Same as Fig. 2 but for 15:15 UTC on May 27, 2016.

903 **Figure 11.** Same as in Fig. 3 but for May 27, 2016 case. Two solid vertical
904 green lines bound the single interval (A) used for comparisons. This two lines
905 together with dashed line between them represent points used in DSD shape
906 comparisons shown in Fig. 13.

907 **Figure 12.** Same as in Fig. 4 but for May 27, 2016 case. Two solid
908 green lines bounding the comparison interval and dashed line between them
909 represent points used in DSD shape comparisons shown in Fig. 13.

910 **Figure 13.** RSP- (blue) and CDP-derived (red) droplet radius (left) and
911 area (right) distributions selected from May 27 data. The CDP time stamps
912 for these examples are 14.70 h UTC (top), 14.68 h UTC (middle), and 14.65
913 h UTC (bottom). The presented RSP retrievals are parametric in left plots
914 and RFT-derived in right plots. The top and bottom plots correspond to
915 the ends of the comparison interval (solid green lines in Figs. 11 and 12),
916 while the middle plots show distinctly bimodal DSD from the middle of the
917 interval (depicted by dashed line in Figs. 11 and 12).

918 **Figure 14.** Same as Fig. 2 but for 14:45 UTC on May 30, 2016.

919 **Figure 15.** Same as in Fig. 3 but for May 30, 2016 case. The pairs of
920 vertical green lines labeled A, B, and C indicate the intervals used for RSP-
921 CDP intercomparisons presented in Table 1. The DSDs from the top points
922 of these intervals are shown in Fig. 17.

923 **Figure 16.** Same as in Fig. 4 but for May 30, 2016 case. The pairs of
924 vertical green lines labeled A, B, and C indicate the intervals used for RSP-
925 CDP intercomparisons presented in Table 1.

926 **Figure 17.** RSP- (blue) and CDP-derived (red) droplet radius (left) and
927 area (right) distributions corresponding to the aircraft exiting the cloud top
928 (A: 15.31 h UTC, top); entering the cloud from above (B: 15.34 h UTC,
929 middle); and crossing a thin part of the cloud (C: 15.48 h UTC, bottom) in
930 the May 30 case (see Fig. 15). The presented RSP retrievals are parametric
931 in left plots and RFT-derived in right plots.