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An evaluation of the liquid cloud droplet effective radius derived from MODIS, airborne remote sensing, and in situ measurements from CAMP^{2}Ex

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Supplemental Materials

S1 Additional individual case studies

S1.1 09 Sep. 2019 research flight 7

RF07 sampled the first cold pool targeted during CAMP^{2}Ex. Around 01:00UTC Sep. 9th, the NASA P-3 entered the cold pool region around 18.8° N, 122.8° E. The P-3 conducted multiple back and forth remote sensing legs at around 5.5 – 6.0 km altitude, targeting clouds along the cold pool front, followed by downward box spirals along and outside the front. The P-3 switched to in situ sampling near cloud base between 03:00 UTC to 04:00 UTC, finally exiting the region around 04:10 UTC. The SPEC Learjet provided additional in situ measurements as it conducted downward sampling of the cold pool and associated clouds from ~4.5 km to 0.4 km between 01:40 UTC and 02:20 UTC. A Terra MODIS overpass occurred at 02:47 UTC. At the MODIS overpass time, the P-3 was positioned to the west of the area shown in Fig. S1(a). As seen from the MODIS RGB reflectance image in Fig. S1(a), the cold pool at this stage became mature (as evident from AHI 10-minute imagery), with a clearly discernible convective line along the gust front, and a deeper (CTH ~12 km) convective cloud structure next to the cold pool. Here we again only focus on warm cumulus clouds, so only the cold pool clouds with liquid phase tops as indicated by the MODIS cloud flag are included. As indicated from MODIS L2 CTH, the congestus and deeper convective clouds have cloud tops around 3 to 6 km altitude, with shallower clouds along the gust front. The MODIS *Re* shows a range of 8 to 20 μm for the shallower clouds (with optical depth 1-15), and 20 to 30 μm for the deeper clouds (with optical depth > 40). Again, this is closely in line with the RSP bi-spectral *Re* in the range of 7 to 30 μm. Bias-adjusted MODIS *Re* and polarimetric *Re* agrees on the range of 4 to 25 μm. The P-3 in situ *Re* values are in the ~5 to 6 μm range, whereas Learjet in situ *Re* suggests a range from 10 μm to beyond 30 μm. This large contrast between Learjet and P-3 was primarily due to different sampling strategies: The Learjet entered the cold pool convective core at an earlier stage (~1:50 UTC), sampling through the top of the convective clouds ~4.5 km that was heavy precipitating, as large splashing on the Learjet windshield was observed according to the forward video. The P-3, however, sampled near cloud base (~0.5 km) at a much later stage (~3:30 UTC) as clouds start to dissipate (as observed from the AHI 10 min imagery). No clear drizzle was observed from the P-3 forward video. The APR-3 W-band maximum reflectivity also indicates considerable precipitation (maximum reflectivity ~25 dBZ in Fig. S1(h)) during the time periods which was sampled by RSP and Learjet.

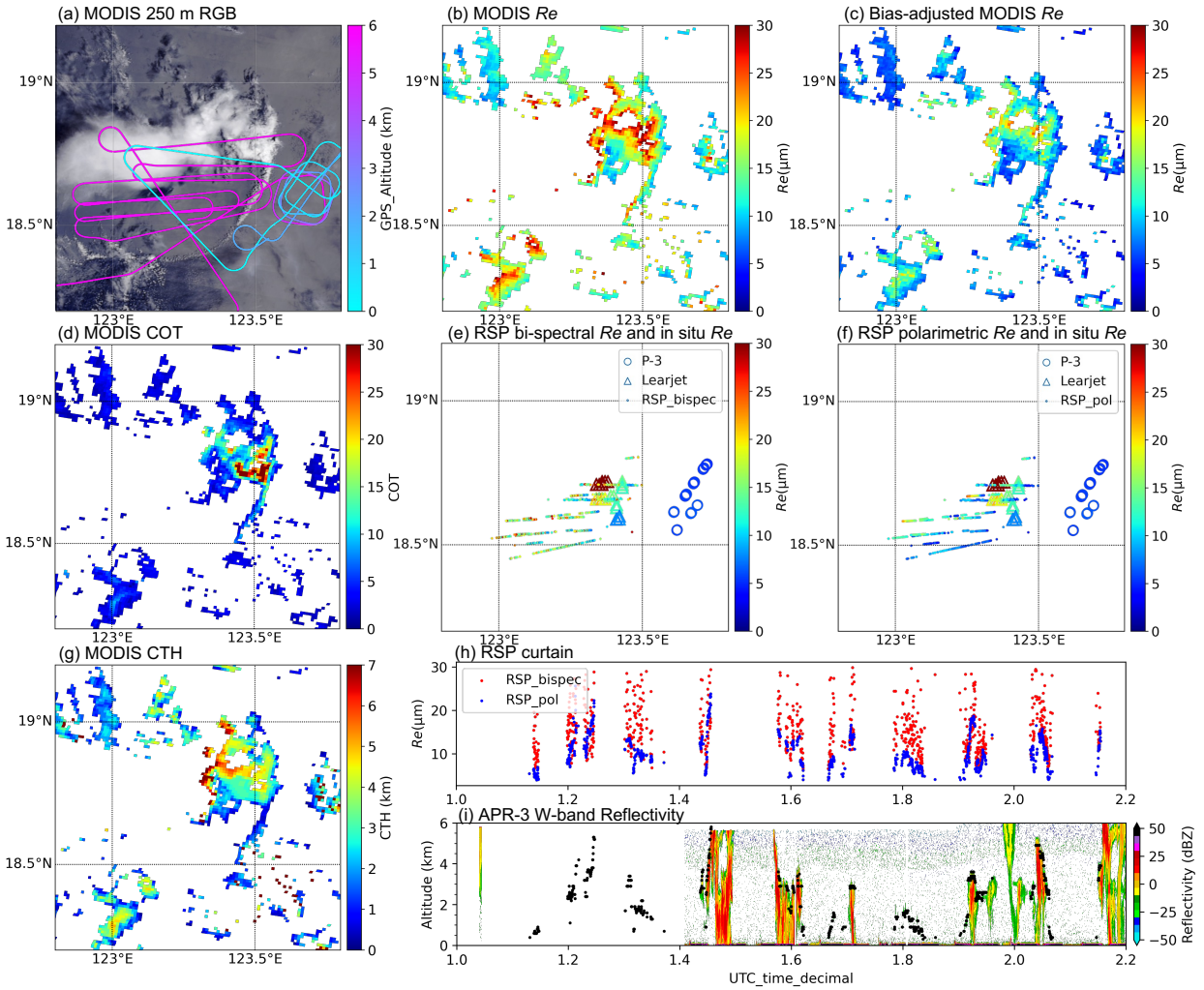

Figure S1. (a) MODIS RGB reflectance at 2:34UTC during RF07 on 09 Sep. 2019. Color bar indicates P-3 altitude and flight track within ±1.5 hours of MODIS overpass time. (b) MODIS Level-2 1 km Re retrievals from 2.1 μm channel. (c) MODIS Level-2 1 km bias-adjusted *Re* retrievals from 2.1 μm channel after applying Fu et al. (2019) correction factors. (d) MODIS Level-2 1 km COT from 2.1 μm channel. (e) RSP bi-spectral *Re* retrievals from 2.26 μm channel. In situ *Re* from P-3 (Learjet) is displayed in circles (triangles). (f) RSP polarimetric *Re* retrievals from 0.86 μm channel. In situ from P-3 is displayed in circles. (g) MODIS Level-2 1 km CTH retrievals. (h) RSP *Re* curtain between 01:00 UTC and 02:12 UTC. (i) APR-3 W-band reflectivity and RSP cloud top height (black dots) between 01:00 UTC and 02:12 UTC.

Figure S2 is constructed using the same approach as mentioned in Section 3.3.1 of the main manuscript and shows an increasing *Re* profile with height for all six techniques, but with significant differences. While the RSP polarimetric *Re* shows a clear increasing trend up to ~3.5 km, the RSP bi-spectral *Re* shows much more variability in the *Re* mean values throughout various CTH bins. Both MODIS profiles (original and bias-adjusted) exhibit a small increasing trend of *Re* profile below ~2 km, above which the trend becomes larger. The in situ profile from the Learjet also shows a clear increasing *Re* profile. When the Learjet in situ *Re* profile is compared to the remote sensing *Re* profiles, the difference between the two becomes more prominent at higher altitudes. In situ measurements may be penetrating

through deeper convective clouds than those sampled by remote sensing with CTH of similar altitude. As indicated in Fig. S2, for the shallower clouds below 2 km the Learjet and P-3 in situ *Re* are in very good agreement with the RSP polarimetric *Re* (e.g., mean bias between RSP polarimetric and Learjet in situ *Re* is 0.8 μm), but as the height exceeds 2 km, Learjet-derived *Re* mean values exceed 20 μm and increase to 40 μm at ~ 4.5 km altitude. These very large *Re* values are associated with the heavy precipitation observed during the RF07. According to the Learjet forward video, at ~1:47 UTC the Learjet penetrated through the side of a raining congestus that is close to the convective core at approximately ~ 4.5 km in altitude. Heavy splashing on the Learjet windshield was observed from the forward video. The Learjet then descended while penetrating through raining clouds (indicated by apparent splashing on windshield through the forward video) until ~ 2:10 UTC at an altitude of ~1 km. RSP polarimetric *Re* appears to be in good agreement with bias-adjusted MODIS *Re* with a mean bias of 1.6 μm. Again, MODIS *Re* and RSP bi-spectral *Re* appear to be much larger than RSP polarimetric *Re* (mean bias between RSP polarimetric *Re* and MODIS *Re* / RSP bi-spectral *Re* is 6.1 μm / 5.0 μm). The abundance of precipitation in this cloud scene for higher cloud-top clouds (Fig. S1(h)) leads to larger *Re* retrievals from both RSP polarimetric and bi-spectral techniques that are closer between each other at altitudes between 3 - 4.5 km.

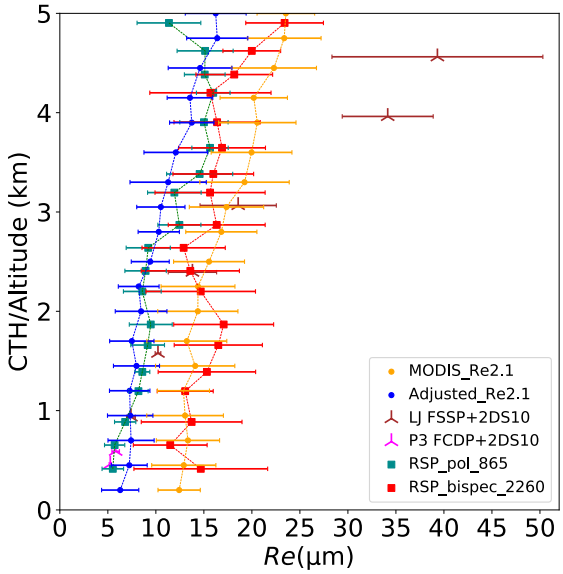

Figure S2. *Re* profile (mean *Re* vs. mean height) of vertically binned MODIS *Re*, bias-adjusted MODIS *Re* (after applying Fu et al. (2019) correction factors), RSP polarimetric *Re*, RSP bi-spectral *Re*, P-3 and Learjet in-situ derived *Re* for the RF07 case. Horizontal whiskers indicate standard deviation of data within each 250m altitude bin.

S1.2 22 Sep. 2019 research flight 12

RF12 observed another cold pool system. At around 1:40UTC on Sep. 22nd, the P-3 entered the scene depicted in Fig. S3 on a ~0.7 km low altitude leg, where it then started to perform back and forth in situ measurements near the cloud base at the cold front region. Around 02:00 UTC, the P-3 platform started to ascend in an upward spiral and then switched into remote sensing legs at ~4.5 km altitude as it flew westward to sample cumulus turrets. After repeated remote sensing legs were conducted, the P-3 left the scene at ~03:15 UTC, exiting the right of the domain in

Fig. S3(a). The Learjet entered the scene at ~01:00 UTC at approximately 5 km altitude. As it flew westward, it gradually spiraled to cloud base to sample the lifecycle of the cumulus turrets until ~01:42 UTC, when it exited the region at the bottom left of the scene. The Learjet forward video indicates that the platform encountered precipitation as it penetrated throughout the cumulus cloud field. Terra MODIS overpass at 2:03 UTC observed the cold pool in its mature stage (as evident from AHI). The MODIS RGB image (Fig. S3(a)) shows cirrus clouds to the south and east and north of the cold pool system. MODIS liquid cloud *Re* shows a range of ~8 to 25 μm, with COT ranging from ~1 to 40. RSP bi-spectral *Re* suggests a similar range of 7 to 30 μm. The RSP polarimetric and P-3 in situ *Re* shows values of ~4 to 10 μm, and the bias-adjusted and Learjet in situ *Re* shows slightly higher values of 5 to 15 μm. APR-3 curtain suggests precipitation for the deeper convective clouds (Fig. S3(h)).

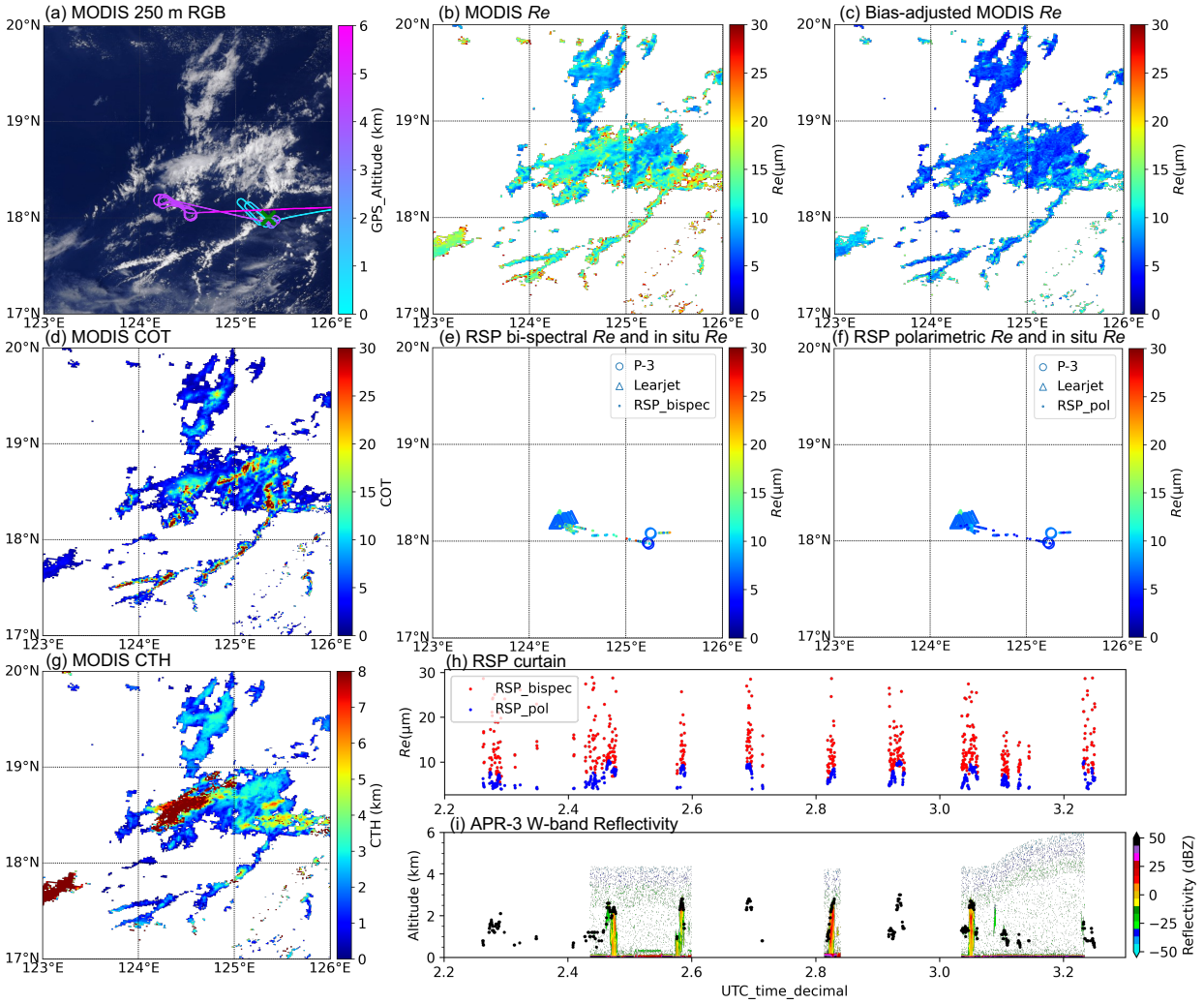

Figure S3. Similar with Fig. S1, but for cold pool case during RF12 on 22 Sep. 2019.

Figure S4 shows much smaller vertical variations of *Re* with height when compared to the previous two cases (RF02 and RF07 cases). The in situ derived *Re* from the Learjet and P-3 line up with each other. They both agree with RSP polarimetric *Re* especially below 2 km (mean bias ~ 1 μm). The Learjet derived *Re* above 3 km shows slightly larger *Re* mean values of ~14 μm resulting from the precipitation within the cumulus cloud field. Throughout all CTH

levels, bias-adjusted *Re* is in good agreement with RSP polarimetric *Re* (mean bias ~ 1.6 μm). The MODIS *Re* and RSP bi-spectral *Re* both suggest much larger mean *Re* values. Their mean biases with respect to RSP polarimetric *Re* are 6.0 μm for the RSP bi-spectral and 7.2 μm for the MODIS, respectively.

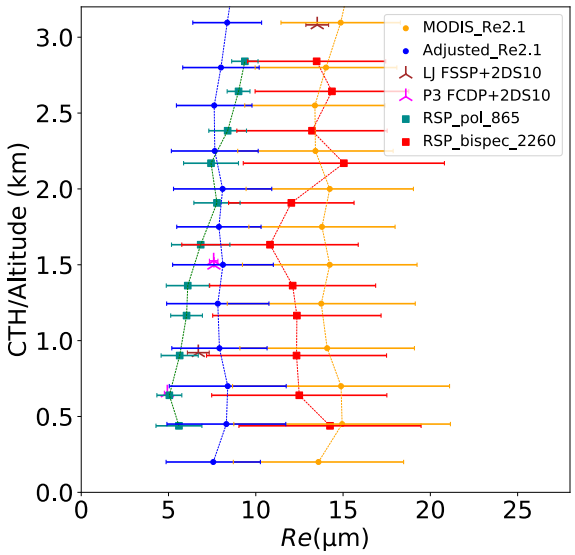

Figure S4. Same as Fig. S2, but for the RF12 case study.

S1.3 02 Oct 2019 research flight 17

RF17 sampled a field of small, shallow cumuli that appear very different than the previous three cases. The most prominent feature for this case is the abundance of small broken cumulus clouds in this domain. On October 2nd around 01:00UTC, the P-3 platform entered the region at around 1.5 km altitude and then descended to ~100 m above sea level to begin in situ measurements below cloud base and at various levels within clouds. Around 02:00 UTC, the P-3 started climbing from 1 km to 5 km altitude to perform remote sensing sampling, with long stretches of straight legs as shown in Fig. S5(a). The aircraft exited the region around 04:30UTC. A MODIS overpass took place at 02:40UTC. The MODIS retrievals indicate that clouds in this case were very shallow, broken (CTH below 1.5 km) and optically thin (COT below 10, mostly between 1 to 4), with *Re* values between 10 to 30 μm. Like MODIS, the RSP bi-spectral retrievals show a range of 6 to 30 μm. RSP polarimetric *Re*, however, show much smaller values of 4 to 7 μm that also agrees with the P-3 in situ *Re*. Bias-adjusted MODIS *Re* also shows a similar *Re* range of ~5 to 10 μm. Only some slight drizzle was observed for the cloud ~1 km from the P-3 forward video.

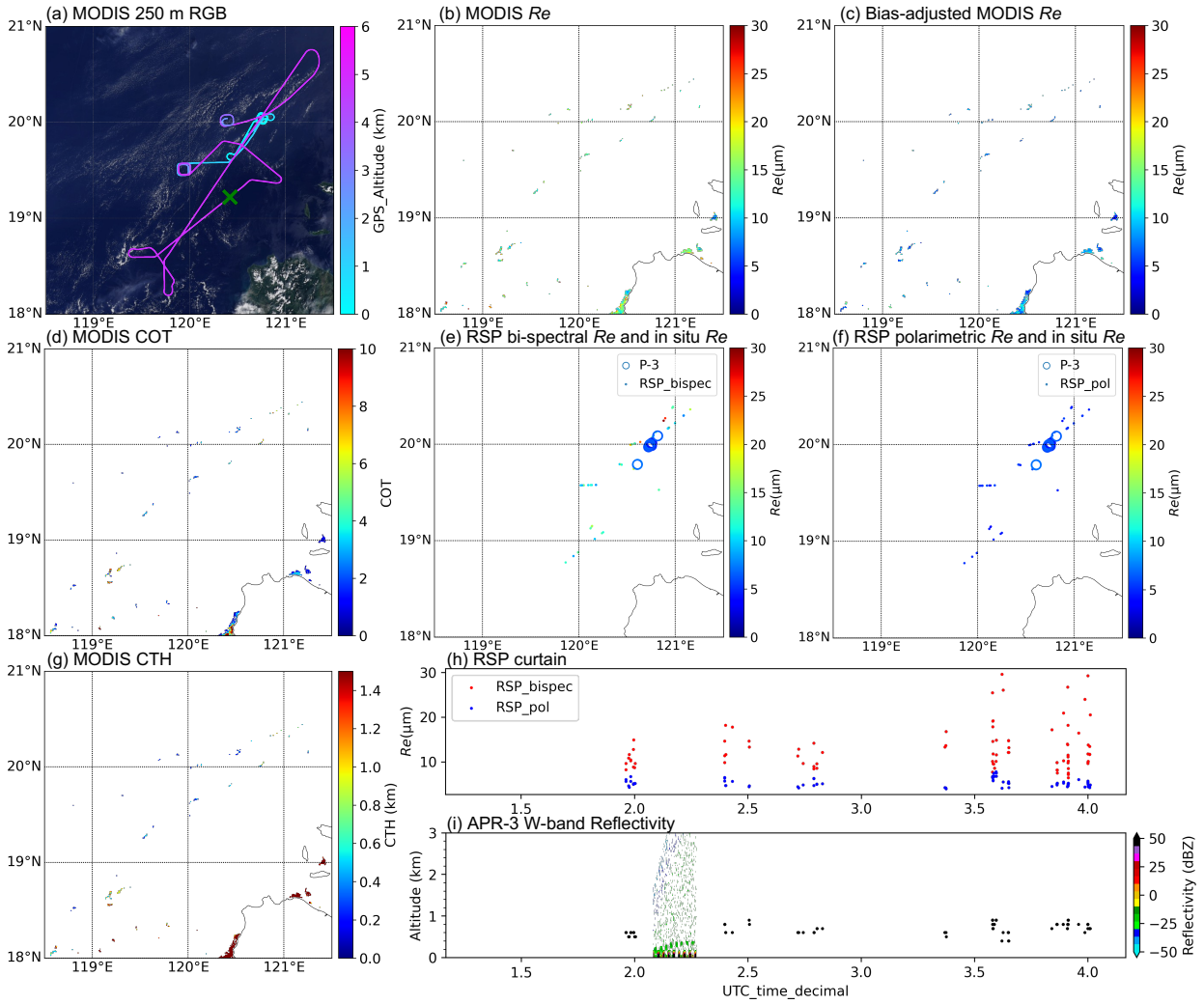

Figure S5. Similar with Fig. S1, but for broken shallow cumulus case during RF17 on 02 Oct. 2019.

Figure S6 shows that the *Re* profiles of P-3 in situ and RSP polarimetric *Re* are very consistent, both suggesting an increasing *Re* profile with height (with a range of 5 - 7 μm). The mean bias between RSP polarimetric and P-3 in situ is 0.1 μm. The MODIS Re and RSP bi-spectral *Re* also share similar *Re* mean values (13 to 16 μm), with the RSP bi-spectral *Re* showing much more variability. The MODIS bias-adjusted *Re* are close in values with the in situ and RSP polarimetric *Re* values, but biased high by ~2 to 3 μm (mean bias between RSP polarimetric and bias-adjusted MODIS *Re* is 2.6 μm). Figure S6 shows the two bi-spectral *Re* profiles are much larger than the other three *Re* profiles, e.g., the mean biases with respect to RSP polarimetric for RSP bi-spectral *Re* and MODIS *Re* are 9.8 μm and 8.3 μm, respectively.

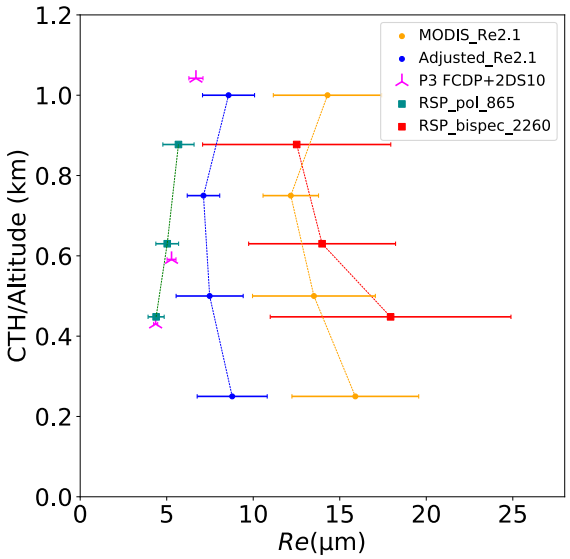

Figure S6. Same as Figure S2, but for the RF17 case study.