Comparison of GOES-retrieved and in-situ Measurements of Deep Convective Anvil Cloud Microphysical Properties During TC4

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For *Journal of Geophysical Research* Special Issue on TC4

September 2009

Abstract

One of the main goals of the Tropical Composition, Cloud and Climate Coupling Experiment (TC4) during July and August 2007 was to gain a better understanding of the formation and life cycle of cirrus clouds in the upper troposphere and lower stratosphere and how their presence affects the exchange of water vapor between these layers. Additionally, it is important to compare in-situ measurements taken by aircraft instruments with products derived from satellite observations and find a meaningful way to interpret the results. In this study, cloud properties derived using radiance measurements from the Geostationary Operational Environmental Satellite (GOES) imagers are compared to similar quantities from aircraft in situ observations and are examined for meaningful relationships. A new method using dual-angle satellite measurements is used to derive the ice water content (IWC) for the top portion of deep convective clouds and anvils. The results show the in-situ and remotely sensed mean microphysical properties agree to within ~10 μm in the top few kilometers of thick anvils despite the vastly different temporal and spatial resolutions of the aircraft and satellite instruments. Mean particle size and IWC are shown to increase with decreasing altitude in the top few kilometers of the cloud. Given these relationships, it is possible to derive parameterizations for effective particle size and IWC as a function of altitude from satellite observations.

1. Introduction

Clouds play a key role in the Earth's radiation budget and hydrological cycle. The horizontal and vertical distribution of cloud water affects atmospheric and surface heating rates as well as the distribution of precipitation. Accurate determination of the 3-D cloud field for a given domain is important, not only for understanding the role of clouds in weather and climate, but also for guiding the development and refinement of cloud process models and for use in initializing forecast models (e.g., *Benjamin et al.* [2004]). Active remote sensing instruments such as lidars and radars can provide vertical profiles of cloud hydrometeor concentrations (e.g., *Dong et al.* [2002], Wang and Sassen [2002]) and layering. Until the last few years, such information has been available only from fixed surface locations and limited aircraft measurements during field experiments. The launch of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite [*Winker et al.*, 2007] and CloudSat [*Stephens et al.*, 2008] have placed a cloud lidar and radar, respectively, into space producing global measurements of cloud vertical profiles. Yet, even with such advances, the active sensors still provide only cross-sections of the 3-D cloud fields at either two specific times of day (satellites) or at a single point on the Earth. Passive radiance measurements, limited as they are, remain necessary for taking measurements over all locations at all times of day. Scanning active sensors for observing clouds from a geostationary orbit are unlikely to be launched in the near future. Thus, it is important to continue researching new techniques for extracting 3-D cloud information from satellite imagers.

Recent advances in retrieving 3-D cloud information from passive imagery have resulted in multispectral methods for deriving profiles of cloud particle sizes (e.g., *Wang et al.* [2009]) and for detecting multi-layered clouds and retrieving their cloud properties (e.g., *Chang et al.*

[2009]). *Minnis et al.* [2008] used a combination of CALIPSO and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) data to improve the estimation of the physical cloud-top heights of optically thick ice clouds from infrared brightness temperature measurements, a quantity that has been subject to significant biases (e.g., *Sherwood et al.* [2004]). In the course of that analysis, *Minnis et al.*, [2008] suggested that it should be possible to retrieve ice water content (IWC) for the upper 2 km of optically thick ice clouds using passive radiance measurements from two satellite observations taken at different viewing zenith angles (VZA). The proposed method has yet to be tested. Knowing the IWC at the top of thick clouds might also be valuable for estimating the vertical distribution of IWC throughout the clouds, especially if used in conjunction with a technique like that of *Wang et al.* [2009] for profiling the effective particle sizes within the cloud.

The Tropical Composition, Cloud and Climate Coupling Experiment (TC4) [*Toon et al.*, 2009] conducted from San Jose, Costsa Rica during summer 2007 provides an opportunity for examining the new methods for inferring cloud-top IWC and validating retrievals of ice particle size and water path for deep convective clouds in the tropics during daytime. Being designed to study convectively generated cirrus clouds and transport of water vapor into the tropical tropopause layer (TTL), TC4 conducted numerous flights both within and above deep convective clouds. Cloud-top height and vertical profiles of cirrus clouds were observed with a high-altitude down-looking lidar, while in situ instruments measured particle sizes and IWC. In this paper, the dual-angle technique for retrieving IWC in the cloud tops is developed and applied to Geostationary Operational Environmental Satellite (GOES) data. The retrievals of IWC, cloud ice crystal effective size, and ice water path (IWP) are examined by comparing with the aircraft-based measurements of the same quantities. The results are discussed in light of the complexities of the cloud systems and the limitations of observational consistency among the measurements. The analysis should provide a better estimate of how these new methods can resolve parts of the 3-D cloud structure.

2. Data

The Tenth and Twelfth Geostationary Operational Environmental Satellites (GOES-10/12) provided valuable radiance measurements over the entire TC4 domain for the duration of the experiment. GOES-10 and GOES-12 are situated on the Equator at 60°W and 75°W, respectively, and have a nominal spatial resolution of 4 km at nadir. Four spectral channels are common to both satellites: visible (VIS, 0.65 µm), shortwave infrared (SIR, 3.9 µm), water vapor (WV, 6.7 µm), and infrared (IR, 10.8 µm). The fifth channels on GOES-10 and 12, respectively, are the split window (SPW, 12.0 µm) and CO2-slicing (COS, 13.3 µm, 8-km resolution). GOES imagery typically had temporal resolution of 15-30 minutes over the TC4 domain.

The NASA DC-8 aircraft, managed during TC4 by the University of North Dakota, was equipped with an array of sensors designed to take remote and in-situ measurements of clouds, aerosols, and gases [*Toon et al*, 2009]. The aircraft is capable of flights to an altitude of 12 km for durations exceeding 10 hours and made a total of 13 science flights during TC4. The DC-8 flew through both low- and high-level clouds taking measurements at different levels within clouds and occasionally obtaining profiles of various properties from cloud top to base. Of particular interest for this study are measurements of cloud particle size and frozen water content. During TC4, the DC-8 was equipped with two cloud probes, the two-dimensional cloud-imaging probe (2D-CIP) and precipitation-imaging probe (2D-PIP), designed to measure the size of cloud and precipitation particles. Combined, CIP and PIP, simply referred to hereafter as CIP, have a dynamic range of 25-6400 μm and have resolutions of 25 μm and 100 μm, respectively [*Kingsmill et al.*, 2004].

The NASA ER-2 high altitude aircraft flew a total of 13 science flights during TC4 carrying a variety of remote sensors. Among these sensors was the Cloud Physics Lidar (CPL), an active remote sensor designed to take multispectral measurements of cirrus, subvisual cirrus, and aerosols with high temporal and spatial resolution [*McGill et al.*, 2002]. Measurements of backscatter from the 355-, 532-, and 1064-nm channels are used to determine the altitude and optical depth of up to 10 cloud or aerosol layers. The lidar beam is completely attenuated by features with optical depths greater than ~3 and is unable to detect cloud and aerosol features beyond this limit. Because of its sensitivity to weakly scattering particles, high temporal and spatial resolution, and range-resolving ability, the CPL is a valuable instrument for validating cloud-top heights derived from passive satellite radiance measurements.

3. Methodology

Aircraft instruments often measure cloud properties that are not directly comparable to quantities derived from satellite instruments. Typically, they measure instantaneous quantities that may vary significantly in time and space while passive spaceborne sensors usually provide column-integrated quantities. In the case of optically thick anvils, satellite derived cloud properties tend to be representative of conditions near cloud top while aircraft are capable of profiling the entire cloud. In this section, we describe methods to derive quantities from aircraft and satellites observations that are more analogous to each other. This makes the comparison of aircraft- and satellite-derived cloud properties a more feasible task.

3.1 Satellite retrievals

All satellite cloud properties in this study were derived from GOES data as described by *Minnis et al.* [2009a]. During daytime, defined as solar zenith angle SZA < 82°, the Visible-Infrared-Shortwave-infrared-Split-window Technique (VISST) is used to retrieve cloud properties including cloud effective temperature T_{eff}, effective cloud height Z_{eff}, cloud top height Z_t, thermodynamic phase (water or ice), optical depth τ, effective droplet radius r_e, and effective ice crystal diameter D_e [*Minnis et al.*, 2009b]. Liquid water path (LWP) and IWP are computed from the effective particle size and optical depth. During TC4, cloud properties were derived in near-real time from GOES imagery in order to help mission teams plan safe flight routes and maximize success in meeting science objectives [*Minnis et al.*, 2009a]. The data were later reprocessed using a revised set of algorithms and matched temporally and spatially to the flight tracks of the DC-8 and ER-2. Each sampling time from the CIP was matched to the nearest 4 GOES pixels. Because high-altitude clouds can cause slight spatial mismatches when comparing cloud properties, a parallax correction was made when searching for the nearest satellite pixels. Cloud-top heights from the CPL were used to make this correction where they were available. Where no CPL data were available, the cloud-top height from VISST was used. On 17, 22, and 31 July and 5 and 8 August, the DC-8 and ER-2 coordinated their flight paths and the two planes flew over the same locations within seconds of each other. For these coordinated DC-8 and ER-2 flights, the DC-8 flight track was first matched to the satellite pixels. Matched data from the CPL were then found by taking the mean of the properties within 4 km of the location of the DC-8 and within 2 minutes of the CIP sampling time.

3.2 Computation of D_e

For spherical cloud droplets, size distributions $n(r)$ are expressed as the number of particles n having a radius between r and $r + \Delta r$, where Δr is the width of the size bin. However, ice particles are known to take a variety of shapes that are highly irregular and poorly represented by spheres in radiative transfer calculations [*Yang et al.*, 2003]. Instead, it is common to classify ice crystals by their length or maximum dimension L and the size distribution is therefore expressed as $n(L)$. To be consistent with the VISST cloud retrieval algorithms, we assume that all ice particles are hexagonal columns with length L and width D. *Wyser and Yang* [1998] determined a functional relationship between L and D for the case of hexagonal columns given by $D = 2.5L^{0.6}$. The equation used to compute D_e in this study is

$$D_e = \frac{\int D \times LDn(L)dL}{\int D \times Ln(L)dL}, \tag{1}$$

following *Minnis et al.* [1998]. Computing D_e this way gives a quantity that is analogous to the particle size retrieved from satellite radiance measurements.

3.3 Computation of IWC

In-situ measurements from CIP provide estimates of IWC along the path of the airplane, and the VISST estimates IWP over an area including the flight path. These two values are not directly comparable, even if the IWP were uniform over the pixel area, since IWP is a column-integrated quantity. Only occasionally did the DC-8 make spiral descents through clouds to get a full IWC profile, which can then be integrated over the depth of the layer to obtain IWP. On the other hand, it may be possible to estimate IWC near cloud top if the proper set of satellite measurements was available. *Sherwood et al.* [2004] and *Minnis et al.* [2008] demonstrated that the physical top of even optically thick ice clouds is underestimated when using a standard IR cloud-top retrieval method. Instead, the height retrieved by IR-based methods typically lies 1-2 km below the actual physical top. Based on this difference between the physical and radiating top of the cloud, *Minnis et al.* [2008] suggested that IWC could be retrieved from passive radiance measurements given two satellite observations that observe a given scene from different VZAs. IWC is defined as

$$IWC = \frac{2\rho_i \tau D_e}{3Q_e \Delta z}, \tag{2}$$

where $\rho_I = 0.9$ g cm^{-3} is the bulk density of ice, τ is the optical depth of the cloud layer in the VIS channel, $Q_e = 2.0$ is the extinction efficiency, and Δz is the thickness of the cloud layer. For two satellites viewing the same cloud, there are two retrievals of cloud effective temperature T_{eff1} and T_{eff2} from two different viewing angles θ_1 and θ_2. If $\theta_1 > \theta_2$, then $T_{eff1} < T_{eff2}$ because more of the upper, colder portion of the cloud is along the line-of-sight of the satellite viewing at θ_1, while the one viewing at θ_2 detects more IR radiance from deeper in the cloud, where the temperature should be greater than near cloud top. Thus T_{eff1} will be observed at a higher altitude Z_{eff1} , in a local temperature sounding than T_{eff2}, observed at altitude Z_{eff2}. If it is assumed that the difference between the heights $\Delta Z_{eff} = Z_{eff1} - Z_{eff2}$ is due entirely to different VZAs, then it is possible to estimate IWC in the cloud layer as represented by ΔZ_{eff} given by

$$IWC = \frac{2\rho_i \Delta\tau D_e}{3Q_e \Delta Z_{eff}} \tag{3}$$

where

$$\Delta\tau = l(\cos\,\theta_2 - \cos\,\theta_1), \tag{4}$$

and $l \approx 1.3$ as discussed in *Minnis et al.* [2008]. *Coakley and Davies* [1986] referred to l as the diffusion length. Substituting (4) into (3), the equation for IWC becomes

$$IWC = lD_e \frac{2\rho_i}{3Q_e} \frac{\mu_2 - \mu_1}{Z_{eff1} - Z_{eff2}}, \tag{5}$$

where μ_1 and μ_2 are the cosines of θ_1 and θ_2, respectively. It follows that if $\mu_1 = \mu_2$ or $Z_{eff1} = Z_{eff2}$, then no IWC retrieval is possible. Furthermore, there is more confidence in the retrieval when the difference between μ_1 and μ_2 is not small. In practice, the average value of D_e from the two angles is used in Eq (5). Here, equation (5) is used to retrieve IWC from simultaneous satellite observations near cloud top along the DC-8 flight track. In the next section, this retrieval is compared to in-situ measurements taken by the CIP near cloud top.

4. Results

4.1 31 July, 2007

To provide the large-scale context, Figure 1 shows a composite GOES-10/12 visible-channel image from 1528 UTC, 31 July 2007. A large mesoscale complex developed off Costa Rica's Pacific coast and produced widespread anvil clouds. Plotted over the GOES imagery in red and cyan are the flight tracks of the DC-8 and ER-2, respectively. Between 1330-1600 UTC, the DC-8 and ER-2 flew a coordinated flight pattern among these convective cores and anvils. The

ER-2 flew over the system at altitudes of ~20 km allowing the CPL to observe the highest cloud tops, while the DC-8 flew directly beneath the ER-2 at altitudes below 12 km taking in-situ particle size and IWC measurements.

Cloud properties derived along the aircraft flight track between 1330-1600 UTC are summarized in Figure 2. Figure 2a displays the 532-nm backscatter profiles obtained by the CPL aboard the ER-2. Weak molecular scattering is shown as shades of purple while successively stronger scattering due to clouds is shown as greens, blues, reds, and white. Cloud-top altitudes are between 15-18 km throughout this segment of the flight, well above the altitude of the DC-8. Most of the clouds observed along this segment were thick enough to fully attenuate the lidar beam although optically thin cirrus often overlay the thick anvils, which topped out around 14 km. Complete attenuation of the lidar beam is indicated in Figure 2a as "shadows" beneath strongly scattering features. The yellow and blue lines in Figure 2a indicate retrievals of Z_{eff} and Z_t, respectively, derived by VISST from the GOES-10 imagery. Plotted in red is the altitude of the DC-8 throughout its flight. On this day, the DC-8 maintained its altitude several kilometers below the highest anvil top observed by the CPL. The VISST Z_{eff} very closely matches the altitude at which the CPL beam was completely attenuated and VISST Z_t lies 1-2 km above Z_{eff}. When the CPL beam is not completely attenuated by thick cirrus and detects both high and low cloud layers such as between 1530-1550 UTC, the VISST Z_{eff} and Z_t lie between the two cloud layers. Gaps appear in the VISST cloud heights and DC-8 altitude where the ER-2 briefly deviated from the flight path of the DC-8 and hence no spatially matched data are available. Figure 2b shows the VZAs for GOES-10 and 12. The GOES-10 VZA were always larger than the GOES-12 VZA by ~15°. The VZA never exceeds 35° for either GOES, so errors introduced by distorted or overlapping pixels due to extreme viewing angles are expected to be minimal.

Figure 2c shows the D_e derived from CIP, GOES-10, and GOES-12 in black, magenta, and aquamarine, respectively. The GOES retrievals generally follow the same trends, while the D_e values from CIP vary widely as the plane changes altitude within the cloud. Figure 2d shows the IWC retrieved from CIP and GOES-10 and 12. A range of IWC values from < 0.0001 g m^{-3} to ~1.0 g m^{-3} is obtained by both methods but values from CIP tend to be much higher, often by an order of magnitude. Although an IWC retrieval was attempted for optically thin and thick clouds, the retrieval should be more reliable for optically thick cirrus. The gray shading in Figure 2 highlights areas where a dual-satellite IWC retrieval was attempted and the cloud optical depth $\tau_c > 8$.

Figures 3a and b show scatter plots of D_e estimates from CIP and GOES-10 and GOES-12, respectively. While there is a considerable amount of scatter, the mean difference (CIP minus GOES) between the CIP and GOES estimates of D_e is less than 20 μm. The CIP tends to retrieve larger particle sizes because the DC-8 was flying well below the cloud top and particle size has been shown to increase from cloud top to base [e.g., *Wang et al.*, 2009]. Figure 4 shows the IWC retrievals from GOES-10/12. The in-situ IWC is often an order of magnitude greater than the GOES value, probably because IWC is greater deeper in the cloud where the DC-8 was flying. Nevertheless, the CIP and GOES IWC values are fairly well correlated with a squared correlation coefficient $R^2 = 0.41$.

4.2 5 August, 2007

Figure 5 shows visible GOES imagery from 5 August, 2007 at 1558 UTC, From 1445 to 1615 UTC, the ER-2 and DC-8 flew a coordinated path just south of the Gulf of Panama to obtain measurements of the properties of the anvils over that area. During this flight segment, the DC-8 maintained a fairly constant altitude near 12 km which was also near the level of complete attenuation of the CPL as shown in Figure 6a. For optically thick clouds, the VISST Z_{eff} closely matches the altitude at which complete beam attenuation occurs. When thin cirrus overlies another cloud layer, Z_{eff} is located between the two cloud layers. The difference between the GOES-10 and GOES-12 VZA was ~15° (Figure 6b) and the maximum VZA is ~25° so errors due to pixel distortion should be small in this case as well. Again the in-situ and GOES D_e follow similar trends with the largest particle sizes coinciding with optically thicker clouds (Figure 6c). The in-situ and remotely sensed IWC values vary in the same way but are offset in magnitude (Figure 6d). The DC-8 was typically 2-3 km below cloud-top where the cloud ice concentrations tend to be higher.

Scatter plots of D_e for 5 August show more correlation than the July 31 case (Figure 7). The mean differences between the CIP and GOES-10 and GOES-12 D_e values are 15 µm or less and are comparable to the previous case. The correlation is stronger here than in the previous case. For GOES-10 and GOES-12, R^2 = 0.12 and 0.19, respectively. A scatter plot of the in-situ and remotely sensed IWC shows that CIP again generally finds larger IWC values. The mean difference is small, but unlike the previous case, the CIP and GOES IWC retrievals are uncorrelated. The increased scatter may be due to errors in the retrieved cloud optical depth.

4.3 All flight days

Much of the scatter in Figures 3, 4, 7, and 8 is partially a result of comparing measurements obtained by instruments with very different spatial resolutions and sampling schemes. GOES pixels have a nominal spatial resolution of 4 km at nadir while the CIP samples an extremely narrow swath along the path of the DC-8. Furthermore, the DC-8 often flew several kilometers below cloud-top and therefore potentially encountered very different cloud properties than those observed by space-based instruments. Because particle size and IWC can vary significantly on small horizontal and vertical spatial scales, finding a meaningful way to validate space-based estimates of these cloud properties with in-situ measurements is imperative and was one of the major science questions to be addressed by TC4 [*Toon et al.*, 2009].

Because the two different spatial resolutions of GOES and the CIP make comparison of instantaneous values of D_e and IWC difficult, a comparison of the mean properties is appropriate. The D_e values from CIP were binned according to the difference between the cloud top altitude observed by the CPL Z_{topCPL} and the altitude of the DC-8 Z_{DC8} using a 2-km bin size. The corresponding D_e values from VISST were binned in the same way. This procedure was performed for each of the flight days when there was a significant amount of coordination between the DC-8 and ER-2. Figure 9a shows the mean CIP and GOES D_e as a function of $Z_{topCPL} - Z_{DC8}$, where the midpoint of each 2-km bin is the abscissa. CIP values are represented by circles and the mean GOES-10/12 D_e are represented by squares. Surprisingly, the CIP and GOES mean D_e both increase with the DC-8 depth below cloud-top and are well correlated (R^2 = 0.84). When $Z_{topCPL} - Z_{DC8} < 4$ km, the mean GOES D_e is larger than the CIP D_e while the opposite is true when $Z_{topCPL} - Z_{DC8} > 4$ km. When the DC-8 was near cloud-top, the CIP was only sampling small particles while the satellite is sensitive to larger particles somewhat deeper in the cloud. Therefore, the mean D_e from CIP is smaller than the mean GOES D_e. At a certain depth below cloud-top, in this case ~4 km, the DC-8 encountered larger ice particles from which the GOES satellites received no signal. Therefore, the CIP D_e is larger than the GOES D_e. Despite the fact the GOES D_e represents an integrated quantity in the top few kilometers of the cloud, it seems to give an accurate representation, to within ~10 μm, of the in-situ particle size.

The same binning procedure described above in the particle size analysis was also carried out for IWC. The CIP measurements clearly demonstrate that mean IWC increases rapidly below cloud-top (Figure 9b). The smallest difference between the mean GOES and CIP IWC is near cloud-top where the difference between the means is 0.043 g m^{-3}. Below cloud-top, IWC increases rapidly, while the satellite-retrieved IWC remains relatively constant since the GOES represents only the top few kilometers of the cloud.

The same analysis was performed again for all DC-8 flights using Z_{eff} as the reference altitude instead of Z_{topCPL} and the results are shown in Figure 10. Note that although the DC-8 rarely flew above Z_{topCPL}, it frequently flew above Z_{eff} as indicated by the negative values. CIP mean D_e increases monotonically from 40 to 180 μm over a depth of ~12 km (Figure 10a). The smallest particles are found close to cloud top ($Z_{eff} - Z_{DC8}$ = -5). The GOES mean D_e are, of course, independent of the DC-8's altitude and show a less defined trend than the CIP retrievals. The best agreement between the CIP and GOES is attained when the DC-8 was near Z_{eff} itself (i.e., $Z_{eff} - Z_{DC8} = 0$) where the two mean are within one standard deviation of each other. Note that the error bars for the CIP values become larger as $Z_{eff} - Z_{DC8}$ increases indicating that the ice crystal size distribution broadens with altitude beneath cloud top. Similarly, the GOES IWC means are closest to their CIP counterparts and within one standard deviation of each other above Z_{eff}, as expected (Figure 10b). Like D_e, IWC exhibits increasing variability below cloud-top.

4.4 Spirals

The DC-8, with its array of cloud probes, has the unique ability to obtain vertical profiles of

D_e and IWC by spiraling up or down through the entire depth of a cloud. On 24 July, the DC-8 executed an upward spiral near a developing convective core which eventually merged with another storm to the west (Figure 11). Starting around 1448 UTC the ascent was fairly gradual, taking about 35 minutes to complete (Figure 11a). Retrievals of Z_t, D_e, and IWC from GOES-10, GOES-12, and the CIP are summarized in Table 1. The CIP Z_t was located less than 1 km above that from both GOES retrievals. The CIP Z_t is taken to be the last altitude where measureable IWC was encountered and, because it is a single value, no standard deviation is given in Table 1. The D_e retrievals agree very well, ranging from 76.6 to 80.3 μm with standard deviations less than 20 μm. Since the CIP measures IWC, integration over cloud depth is required to obtain IWP, which can then be compared to the GOES retrievals. Integration of IWC for this case yields IWP = 956 g m^{-2} and since it is a single value no standard deviation is given in the table. The CIP IWP is well within the range of 796-1260 g m^{-2} given by the GOES-10 and GOES-12 means, respectively. The GOES scanned this area twice, once at 1445 and again at 1515 UTC, while the DC-8 was making its ascent. During this time, the cloud evolved considerably and the sampled scene was highly variable (Figures 11b-d), which together explain why the GOES Z_t and IWP standard deviations are so high.

Another spiral was performed on 3 August through a cirrus anvil over the Gulf of Panama (Figure 12). At 1705 UTC, the DC-8 began its descent from an altitude of 12 km, corresponding to cloud-top. This spiral was completed in 19 minutes, about half the time of the previous case. As seen in Figure 12a, the spiral was conducted near the edge of the anvil where the variability in cloud properties (Figures 11b-d) were significant. GOES-10 scanned this area at 1658 and 1715 UTC and GOES-12 scanned at 1645 and 1715, but most of the pixels matched to the flight track came from the 1715 UTC scans. The CIP measurements indicate that ice crystals were detected down to 6 km which is taken to be cloud base. Table 2 summarizes the cloud properties obtained for this case. There is relatively good agreement between the DC-8 and GOES-derived cloud-top heights with the former falling just within one standard deviation of the satellite values. Values of D_e are also fairly close especially for GOES-12. The CIP and GOES-12 mean values differ by only 4 μm, or 5%. The IWP values are well within one standard deviation. Again, the agreement is best between the CIP and GOES-12 with differences of -47 gm^{-2} or 15%. These results and those in Table 1 are only two data points, but they confirm, as suggested by the other analyses in section 4.3, that the VISST retrievals of D_e, Z_t, and IWP, and by definition, τ, are representative of the anvil clouds over the TC4 domain.

5. Summary and Future Work

Careful analysis is required when comparing in-situ and remotely sensed cloud properties because these quantities are often not directly comparable. In this study, estimates of D_e were computed from ice crystal size distributions collected by the CIP aboard the DC-8 aircraft and compared to GOES retrievals matched in space and time. A new method to estimate IWC near cloud-top with coincident satellite observations was developed and the resulting values were compared with in-situ measurements taken by CIP. Instantaneous comparisons of both D_e and IWC show significant differences although there is some correlation between the in-situ and remotely sensed properties. On average, the D_e retrievals from GOES are an accurate representation of the in-situ particle size as measured by the CIP. The two comparisons with CIP-derived IWP indicate that the GOES-retrieved ice water path is a reasonable representation of the scene. These results are consistent with other comparisons [*Mace et al.*, 2005; *Waliser et al.*, 2009], which show that the VISST, on average, provides accurate estimates of IWP. The results are encouraging for using the new method for retrieving cloud-top IWC using dual-angle views. While the mean GOES-retrieved IWC is in agreement with its DC-8 counterpart near cloud-top, the IWC increases rapidly with decreasing height in the cloud. The results, for at least one flight, show that the IWC near cloud top is related to that deeper in the cloud. If that correlation is common, then it becomes more likely that reasonably accurate profiles of D_e and IWC below cloud-top can be estimated from passive satellite observations alone, especially if additional spectral information is available [e.g., *Wang et al.*, 2009].

Knowledge of the vertical profiles of particle size and IWC are important for validating, initializing, and improving cloud process and other less sophisticated weather and climate models that explicitly include cloud microphysical properties. Thus, accurate retrievals of those quantities from geostationary satellite data should be valuable for improving numerical weather analyses and forecasts. The retrievals could also be valuable for aviation safety. Areas of large concentrations of ice (IWC > 1 g m^{-3}) in convective cloud systems pose a threat to aviation because ingest of too much ice in a jet engine can induce engine rollback and failure [*Lawson et al.*, 1998; *Mason et al.*, 2006]. If techniques can be developed to detect areas of potentially high IWC, it may be possible to provide warnings to air traffic controllers so that such incidents can be avoided. A correlation between IWC at cloud top and the IWC deeper in the cloud may be the basis for such a technique. The approach developed in this paper requires two satellites, or, at least, two different viewing zenith angles to retrieve IWC near cloud top. Thus, it would be practical for application over much of North America, which is viewed by two GOES, or for any other region where the satellite images overlap within a few minutes of each other. When the new GOES-R series of imagers [*Schmit et al.*, 2005] become available later in this decade, the extra channels needed to estimate the vertical profile of D_e will be available and the technique could be further refined.

The results presented here represent only a first step in retrieving cloud-top IWC from passive satellite data. Much additional research is required to validate and improve the technique and to define its limits. Similarly, additional validations of the retrieved values of D_e and IWP are required to establish reliable uncertainty bounds. Those validations will require extensive comparisons with data from instruments such those on CloudSat and CALIPSO and at the Atmospheric Radiation Measurement Program sites [*Ackerman and Stokes*, 2003]. Comparisons with in situ measurements in various conditions will also be necessary for complete evaluation of the retrievals. Such efforts are currently ongoing.

Acknowledgments

This research was supported by the NASA Applied Sciences Program, the Department of Energy Atmospheric Radiation Measurement Program through Interagency Agreement, DE-AI02-07ER64546, and the NOAA Center for Satellite Applications and Research GOES-R Program.

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Table 1. Satellite and in-situ cloud properties derived from the DC-8 spiral at ~1500 UTC, 24 July 2007.

	GOES-10		GOES-12		CIP	
	Mean	SD	Mean	SD	Mean	SD
Z_t (km)	11.1	3.8	10.9	4.1	11.3	-
D_e (μm)	76.6	15.9	78.6	19.2	80.3	19.2
IWP (g m^{-2})	795.6	795.8	1260.4	1145.6	955.6	-

Table 2. Satellite and in-situ cloud properties derived from the DC-8 spiral at ~1705 UTC, 3 August 2007.

	GOES-10		GOES-12		CIP	
	Mean	SD	Mean	SD	Mean	SD
Z_t (km)	12.2	0.6	12.3	0.7	11.6	-
D_e (μm)	72.8	14.5	90.6	33.6	87.0	50.3
IWP (g m^{-2})	185.7	102.0	276.2	188.2	322.9	-

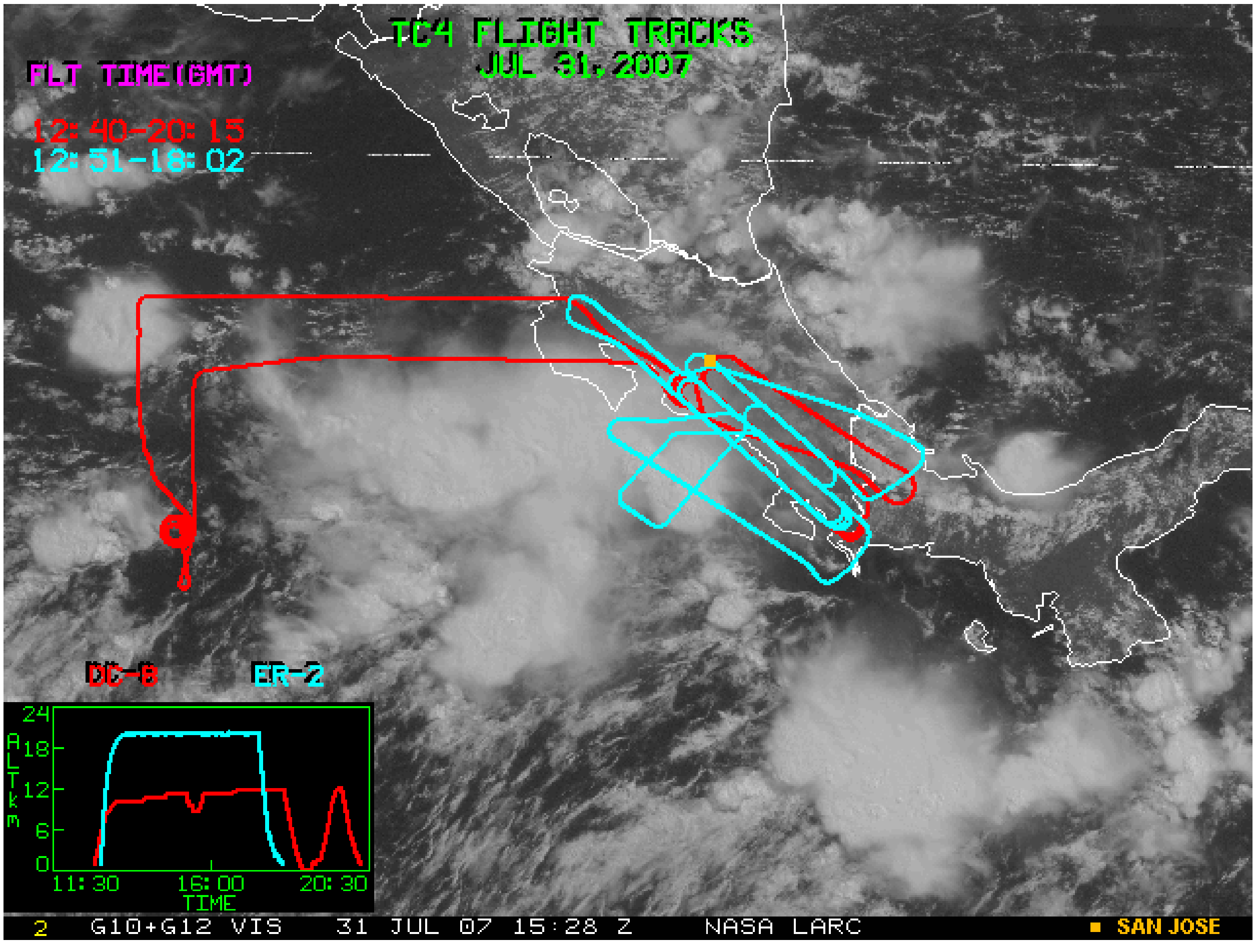

Figure 1. Composite GOES-10/GOES-12 visible image over the TC4 domain at 1528 UTC, 31 July 2007. The flight tracks of the DC-8 and ER-2 are plotted over the image. Time series of the planes' altitudes are shown in the lower left inset.

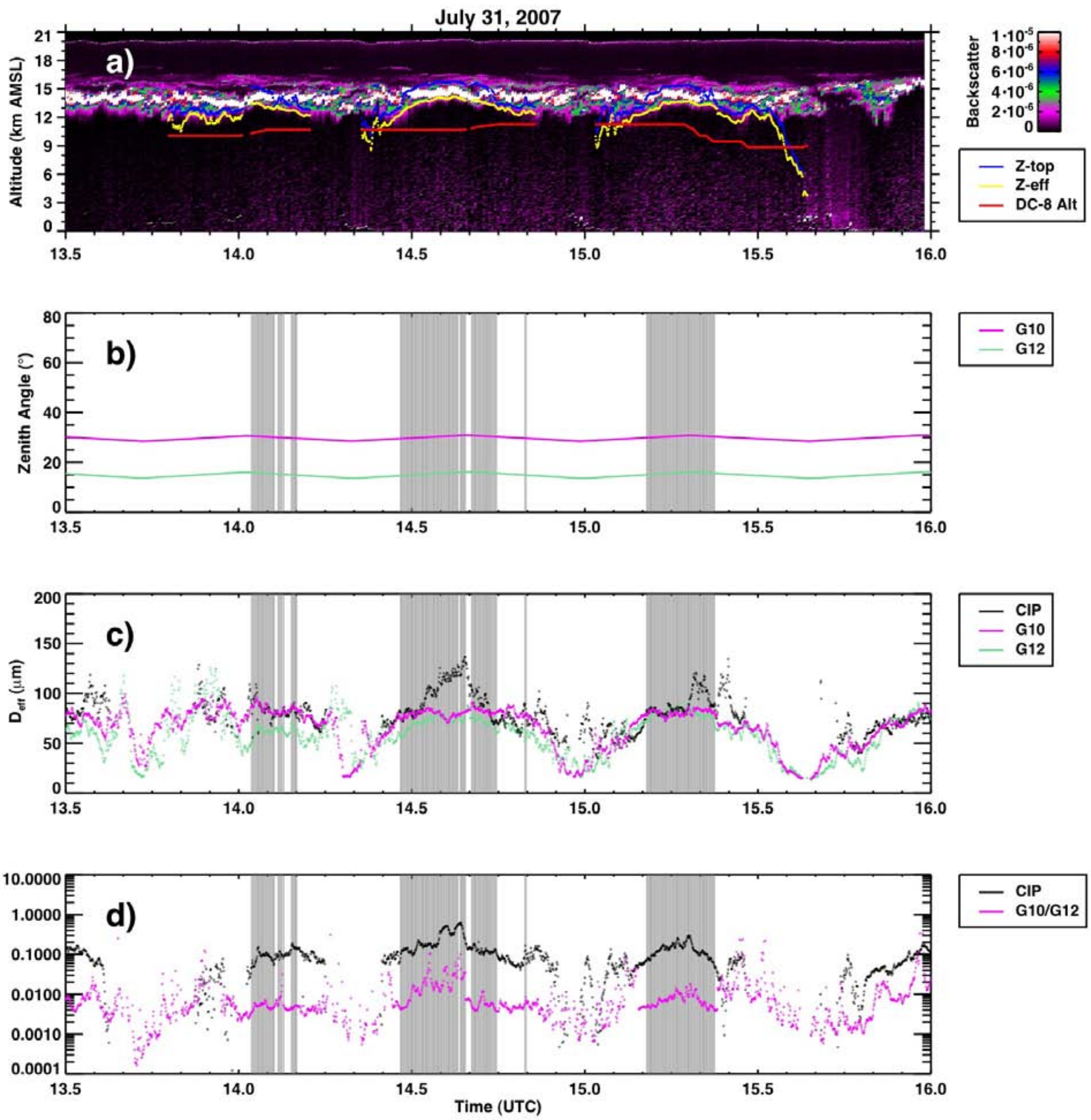

Figure 2. Time series of (a) cloud-top, effective radiating, and aircraft altitude plotted over CPL 532-nm backscatter profiles, (b) satellite VZA, (c) effective ice crystal diameter, and (d) ice water content for 31 July 2007.

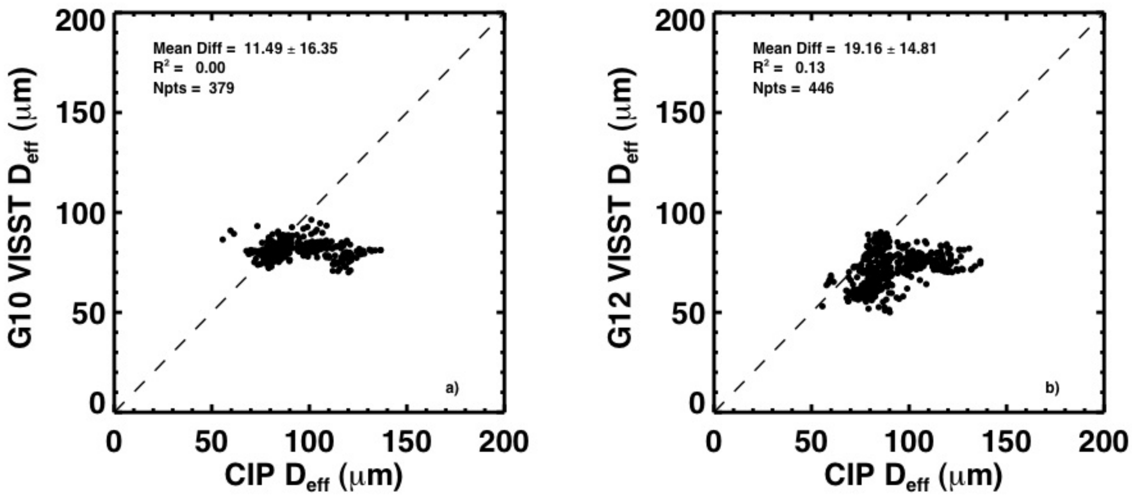

Figure 3. Scatter plots of D_e estimated from CIP and (a) GOES-10 and (b) GOES-12 for 31 July 2007.

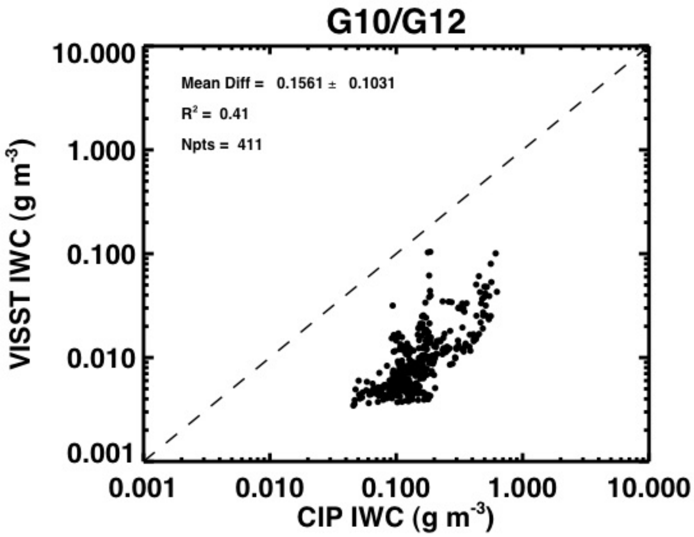

Figure 4. Scatter plot of IWC estimated from CIP and a combination of GOES-10/GOES-12 data for 31 July 2007.

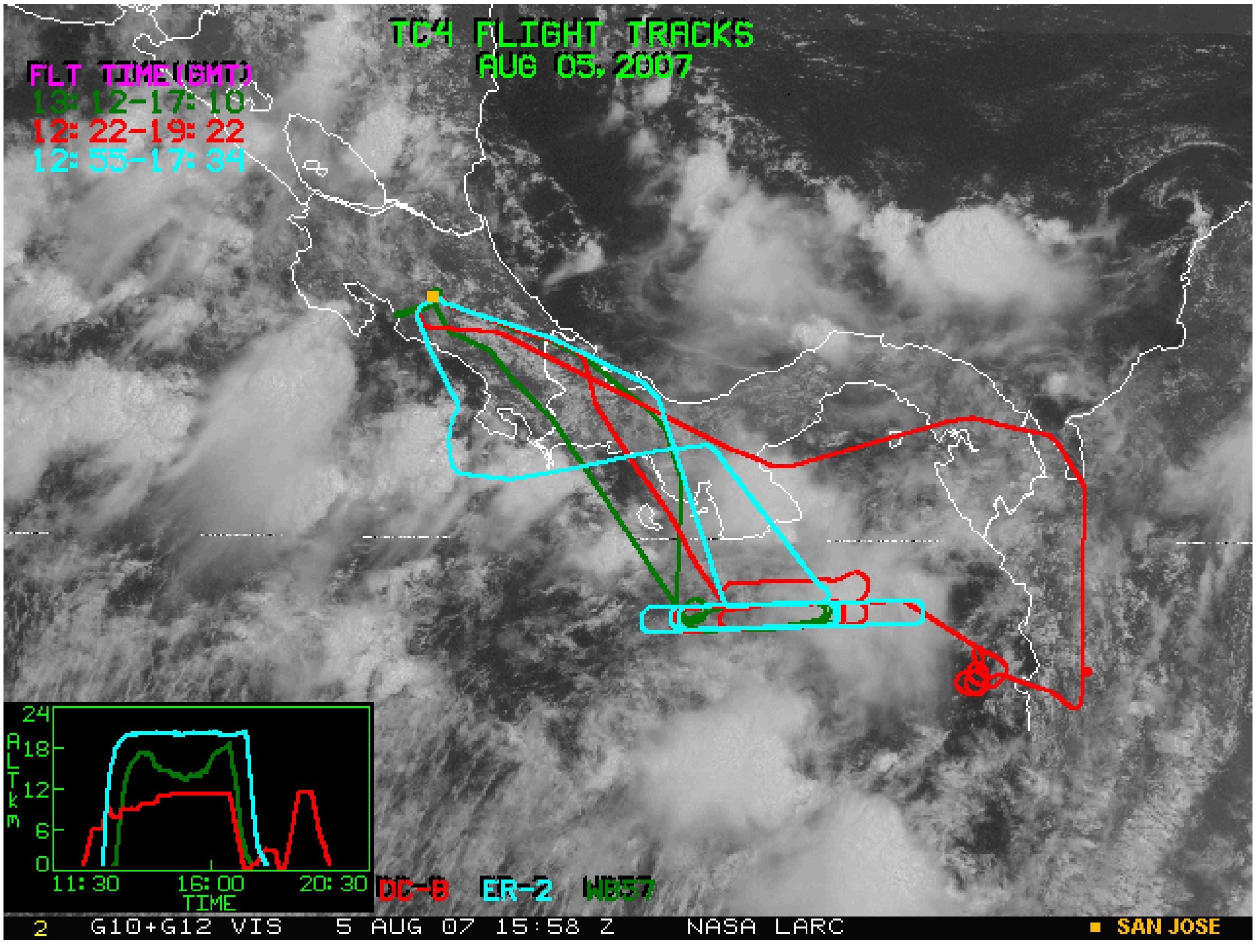

Figure 5. Composite GOES-10/GOES-12 visible image over the TC4 domain at 1558 UTC, 5 August 2007. The flight tracks of the DC-8 and ER-2 are plotted over the image. Time series of the planes' altitudes are shown in the lower left inset.

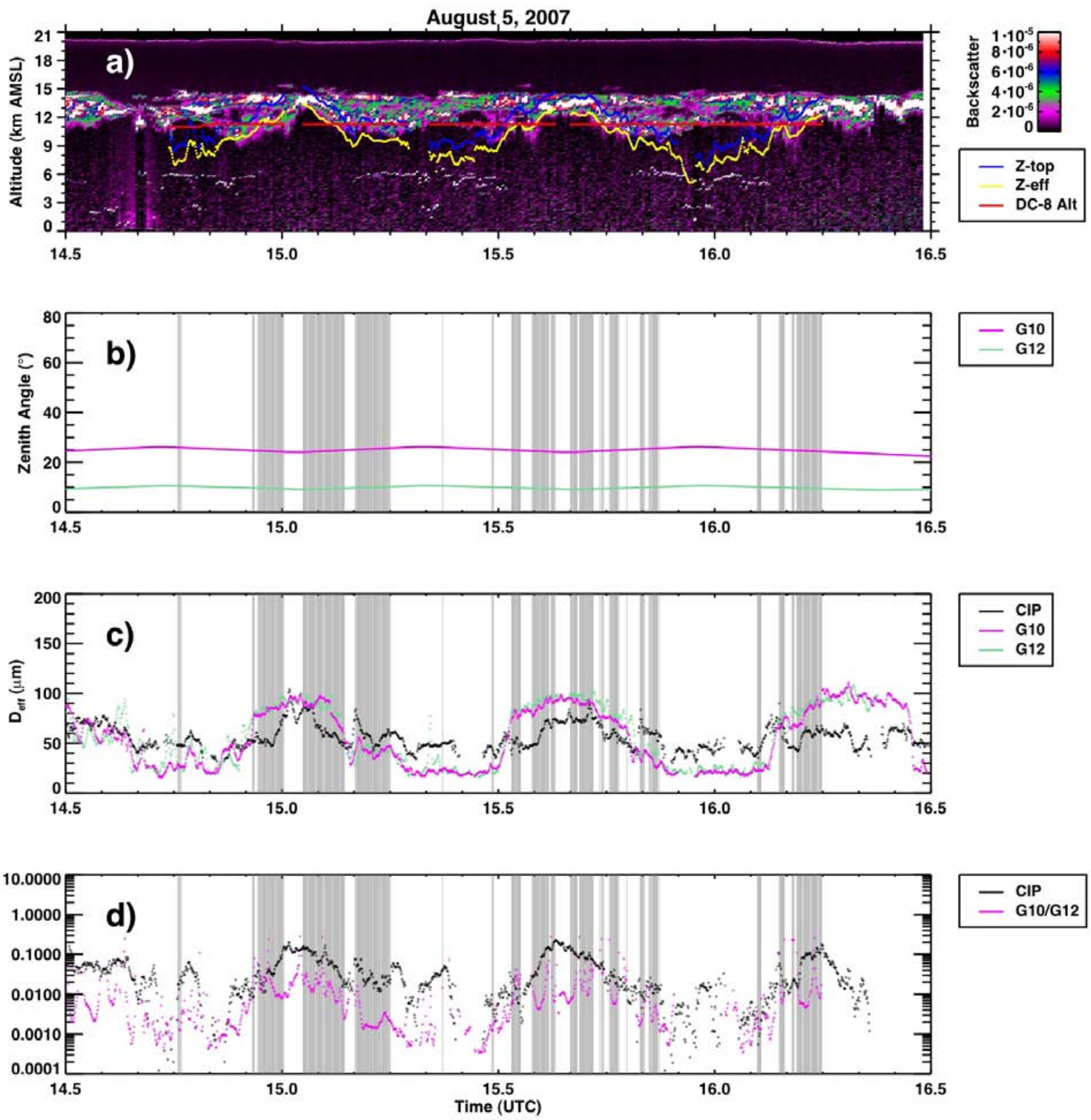

Figure 6. Time series of (a) cloud-top, effective radiating, and aircraft altitude plotted over CPL 532-nm backscatter profiles, (b) satellite VZA, (c) effective ice crystal diameter, and (d) ice water content for 5 August 2007.

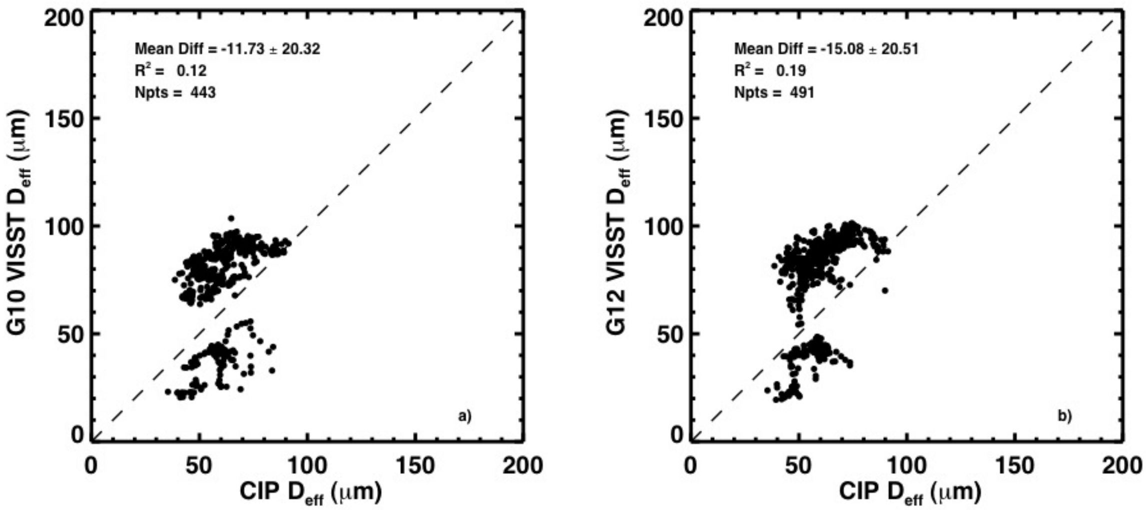

Figure 7. Scatter plots of D_e estimated from CIP and GOES-10 (a), GOES-12 (b) for August 5, 2007.

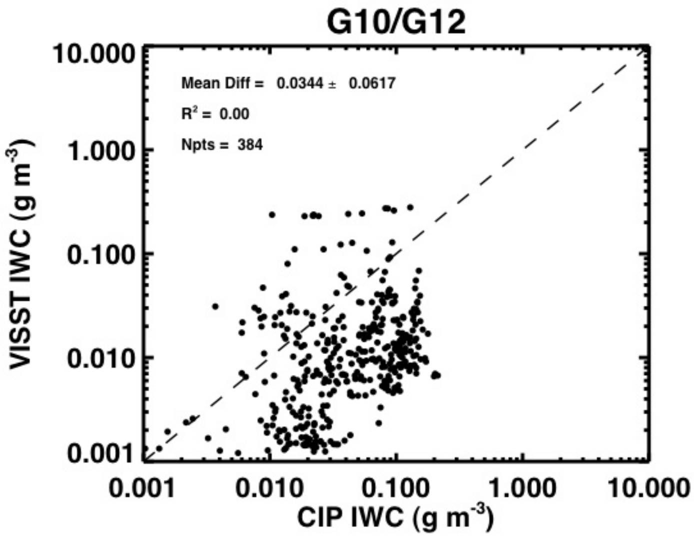

Figure 8. Scatter plot of IWC estimated from CIP and a combination of GOES-10/GOES-12 data for 5 August 2007.

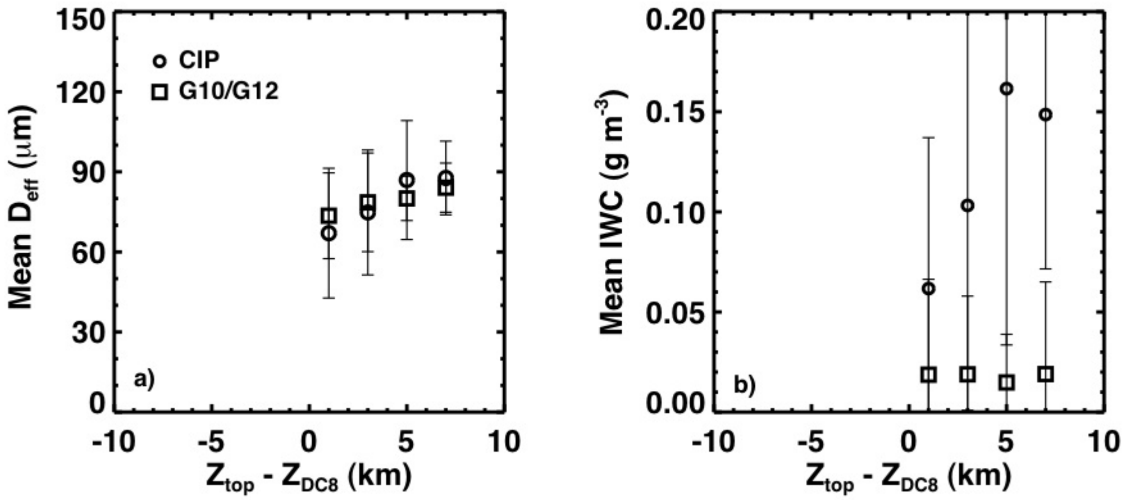

Figure 9. Mean (a) D_e and (a) IWC as a function of the vertical position of the DC-8 relative to the CPL Z_t for all coordinated flights with the DC-8 and ER-2.

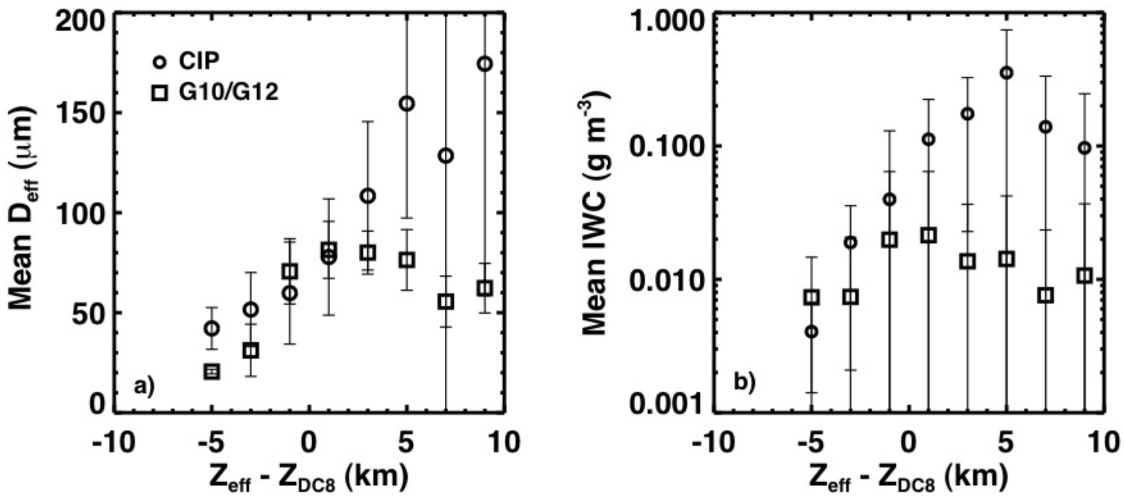

Figure 10. Mean (a) D_e and (b) IWC as a function of the vertical position of the DC-8 relative to Z_{eff} for all DC-8 flights. The bars indicate the standard deviations of the measurements.

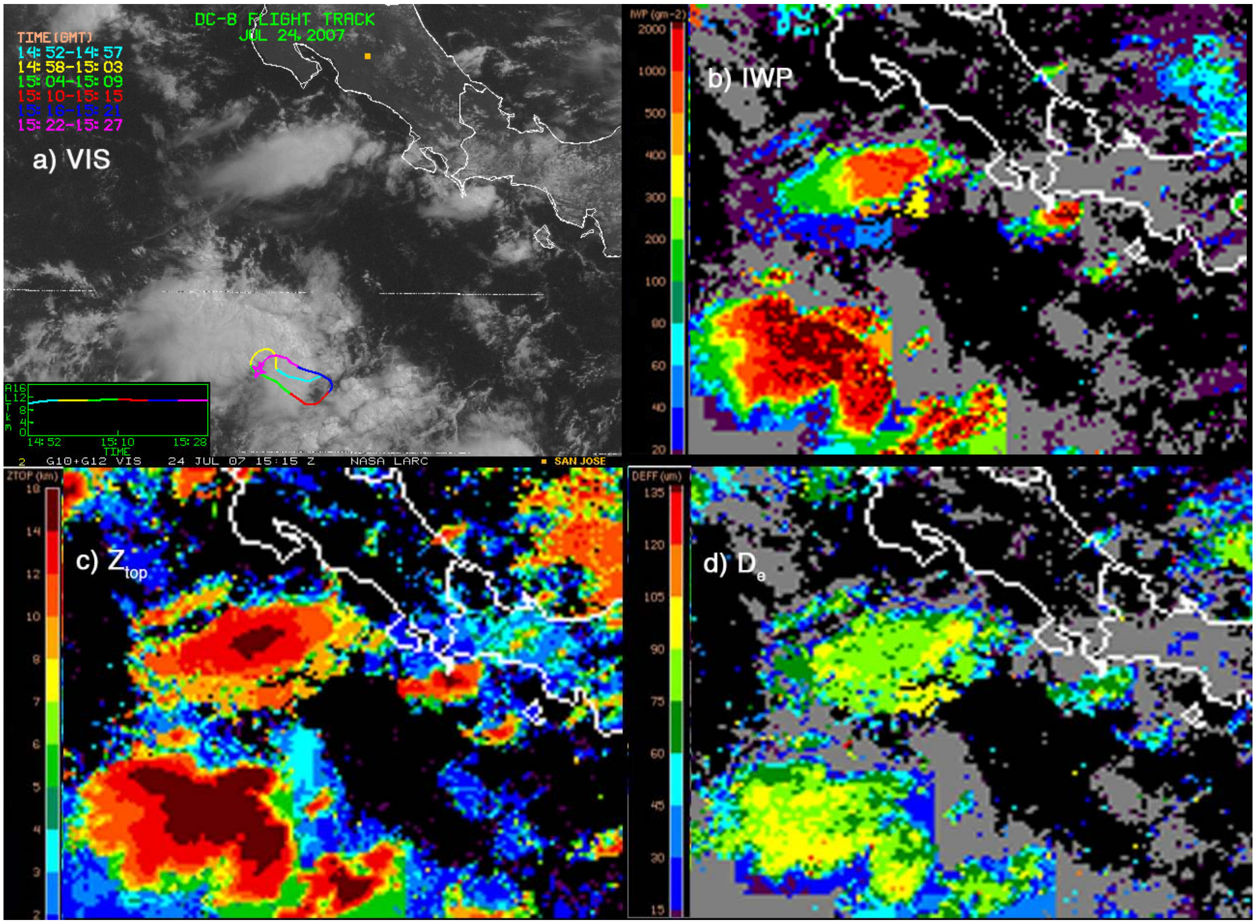

Figure 11. GOES-12 imagery and VISST cloud products for 1515 UTC, 24 July 2007. (a) VIS channel image with DC-8 flight track overlay; (b) IWP (gm^{-2}), grey areas indicate water clouds; (c) Cloud –top height (km); and (d) D_e (μm).

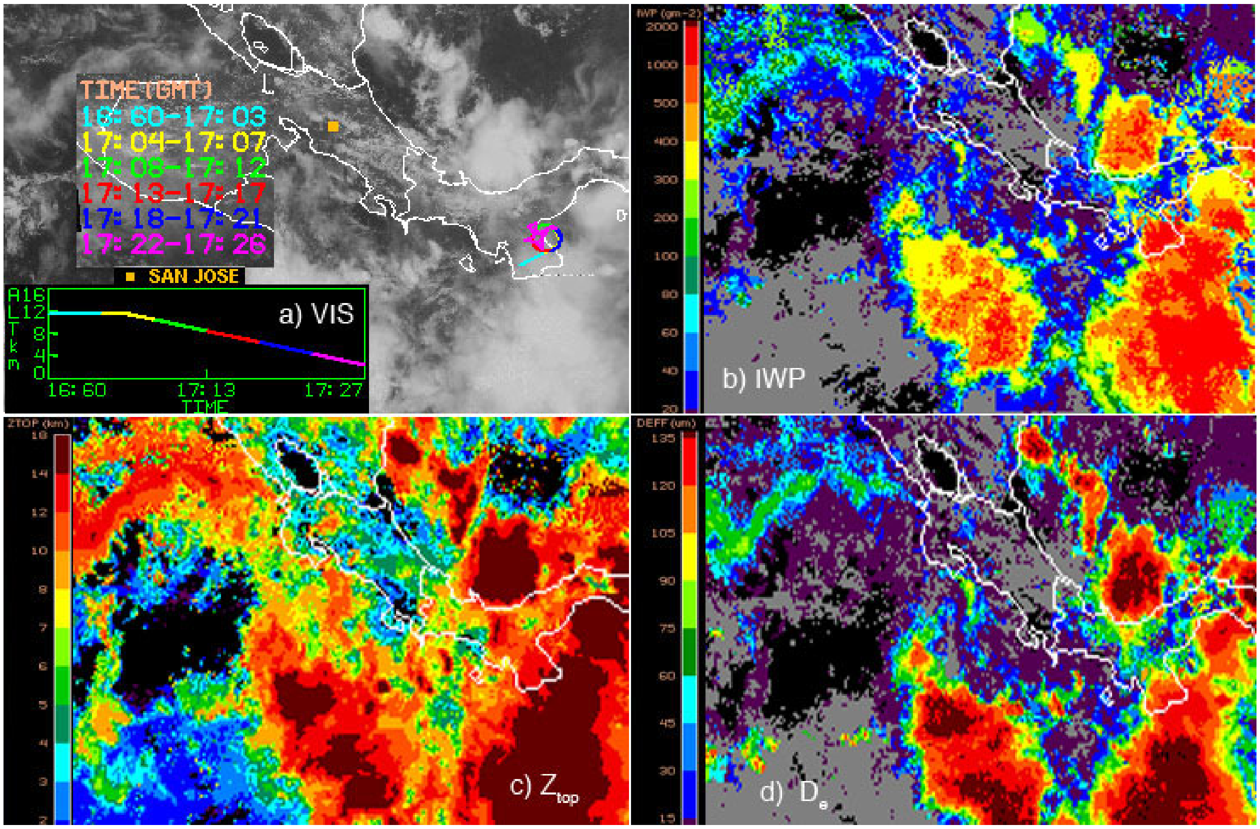

Figure 12. Same as Figure 11, except for 1715 UTC, 3 August 2007.