Droplet Growth in Warm Water Clouds Observed by the A-Train. Part II: A Multisensor View

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ABSTRACT

Hydrometeor droplet growth processes are inferred from a combination of Aqua/Moderate Resolution Imaging Spectroradiometer (MODIS) cloud particle size observations and CloudSat/Cloud Profiling Radar (CPR) observations of warm water clouds. This study supports the inferences of a related paper (Part I) (i) that MODIS-retrieved cloud droplet radii (CDR) from the 3.7-μm channel (R37) are influenced by the existence of small droplets at cloud top and (ii) that the CDR obtained from 1.6- (R16) and 2.1-μm (R21) channels contain information about drizzle droplets deeper into the cloud as well as cloud droplets. This interpretation is shown to be consistent with radar reflectivities when matched to CDR that were retrieved from MODIS data. This study demonstrates that the droplet growth process from cloud to rain via drizzle proceeds monotonically with the evolution of R16 or R21 from small cloud drops (on the order of 10–12 μm) to drizzle (CDR greater than 14 μm) to rain (CDR greater than 20 μm). Thus, R16 or R21 is an indicator of hydrometeor droplet growth processes whereas R37 does not contain information about coalescence. A new composite analysis, the contoured frequency diagram, is introduced to combine CloudSat/CPR reflectivity profiles and reveals a distinct trimodal population of reflectivities corresponding to cloud, drizzle, and rain modes.

1. Introduction

Clouds exert an important influence on the planet's water and energy balances and processes related to clouds underpin key climate feedbacks that influence how much warming is expected with the building of greenhouse gas concentrations. Changes to low clouds in particular alter the warming effects of carbon dioxide (Bony and Dufresne 2005) via changes in cloud amount that alter the albedo of cloud regions. Cloud optical property changes can also alter the expected warming effects and the influence of aerosol on these cloud properties, referred to as aerosol indirect effects, is one of the major sources of uncertainty in global warming projections.

Studying the effects of increasing anthropogenic aerosols on the cloud radiative properties has been an active area of research over the past 20–30 years (e.g., Twomey 1976; Coakley et al. 1987; Radke et al. 1989; Lohmann and Feichter 2005, among many others). Despite the amount of ongoing research, our understanding of cloud–aerosol interactions remains rudimentary, generally limited by a lack of observations that are able to identify aerosol influences on key cloud droplet growth processes. More advanced global-scale observing tools that provide a way of detecting these processes, together with advanced models of cloud–aerosol interactions, are important needed to make the necessary advances in our understanding of this problem.

One piece of information provided by satellite-borne sensors that is important for most aerosol indirect studies is the cloud droplet radii (CDR) retrieved from measurements of reflected sunlight. Nakajima et al. (2010, hereafter Part I) provide new interpretations of the CDR retrieved using different spectral channels of Moderate Resolution Imaging Spectroradiometer (MODIS) centered on 1.6 (R16), 2.1 (R21), and 3.7 μm (R37), extending the earlier ideas of Nakajima et al. (1991) and...
In Part I, we suggested that these different measures of particle sizes might differentiate effects of different droplet growth processes. In particular, that study examined the effects of cloud vertical structure on the interpretation of CDR. Part I focused on addressing the following questions: What do R16, R21, and R37 represent in terms of cloud microphysical properties? Why are most R37/R21 values less than unity, and why is the R16/R21 mode near unity? Does the vertical inhomogeneity of cloud droplet sizes explain the ratio values R37/R21 and R16/R21? The fact that these different CDR represent vertically averaged particle sizes over different depths of cloud, together with the existence of drizzle particles in clouds, suggests they may also reflect different characteristics of the drop growth processes.

In this study, we further examine the character of these different retrieved CDR and explore the possible insights they offer into different cloud drop growth processes. We combine the CDR information with CloudSat radar information (e.g., Stephens et al. 2008) to demonstrate how the variation of R21 reflects the existence of drizzle and rain in low warm clouds. In so doing, we will show how the radar reflectivity information relates to different aspects of the droplet growth process in warm water clouds, much as Suzuki and Stephens (2008) have done. The radiative transfer simulations of Part I showed that the retrieved CDR are influenced by the vertical inhomogeneity of droplet size, including (i) the existence of small cloud droplets at the cloud top and (ii) the existence of the drizzle mode. The influence of smaller droplets at cloud top affects the 3.7-μm channel most, whereas the presence of drizzle influences the 2.1- and 1.6-μm channels more than the 3.7-μm channel. We assume that evaporation at the cloud top is one possible source of such small particles.

In this paper we match the retrieved CDR of warm water clouds obtained from one month of Aqua/MODIS data with the CloudSat/Cloud Profiling Radar (CPR) footprint to examine the effects of cloud vertical structure on the retrieved CDR. The results of this analysis support the interpretations of Part I and suggest that the R21 particle size and the ratio of R37/R21 contain information about cloud droplets, drizzle, and rain and the vertical structure of these different modes revealed by the radar hint at the growth processes taking place in warm clouds. Inherent to the interpretation of observations is the assumption that the snapshots provided by satellite data, when collected over time and space, represent the spectrum of stages of droplet evolution. The datasets and the data analysis algorithms are presented in the next section. The individual analyses from Aqua/MODIS are presented in section 3. A new contoured frequency diagram of the radar reflectivities classified as R21 is offered in section 4 and used to interpret the observations in terms of growth processes. The paper concludes in section 5 with a discussion and summary of key results.

## 2. Satellite data and algorithms

The CloudSat project provides several standard products (Stephens et al. 2008), including the MODIS-Aux dataset (Partain 2007a), CPR 2B-Tau dataset (Polinsky 2008), CPR 2B-GEOPROF dataset (Mace 2007), and European Centre for Medium-Range Weather Forecasts (ECMWF)-Aux dataset (Partain 2007b). These datasets are available from the CloudSat Data Processing Center (DPC) located at Colorado State University (CSU). The MODIS-Aux data contain a subset of MODIS radiances and some ancillary data such as the cloud mask that overlaps and surrounds each CloudSat CPR footprint. We retrieved R16, R21, and R37 using the MODIS-Aux radiances data as input to the Comprehensive Analysis Program for Cloud Optical Measurements (CAPCOM) retrieval algorithm (Nakajima and Nakajima 1995; Kawamoto et al. 2001). CAPCOM is the standard algorithm for the Advanced Earth Observing Satellite II (ADEOS-II) Global Imager (GLI) science mission operated by the Japan Aerospace Exploration Agency (JAXA) (Nakajima et al. 2009). The CloudSat 2B-Tau product contains the MODIS-based optical depth for each CPR ray and proportions this optical depth into 240-m layers in a way that is proportional to the CPR reflectivity of that layer. This is a crude attempt to provide more information about the vertical extinction. This layered optical depth is used below.

The 2B-Tau column optical depth employs a Bayesian estimation approach with forward calculations that are performed to simulate two MODIS bands with the a priori vector of the optical depths that were obtained from CPR-derived liquid water contents. The 2B-Tau optical depth and R21 particle size of low clouds are essentially the same as those of the standard MODIS products and the same as those from CAPCOM. The CPR 2B-GEOPROF data contains the radar reflectivities of the CPR bins along the CloudSat footprints, as well as several flags such as CPR cloud mask, MODIS cloud mask, CPR echo top characterization, CloudSat scene variability designation, and so on. The ECMWF-Aux dataset is the objective analysis data from ECMWF collocated and coincidentally matched up along the CloudSat footprint. The ECMWF-Aux data were used in the CAPCOM retrievals of cloud properties from MODIS-Aux. The above datasets are useful because the data are consistently collocated and essentially coincident.
within approximately 60 s). In the following data analysis, we selected clouds that returned unambiguous CPR echoes and are horizontally uniform, nonmultilayered, water-phase clouds. Ishida and Nakajima’s (2009) cloud screening algorithm performed on the MODIS-Aux retrievals was used to identify water-phase clouds. Data for July 2006 were analyzed in this study.

3. Aqua/MODIS CDR results and discussion

In this section, we examine relationships between the CDR (R16, R21, and R37) that were retrieved from the CAPCOM retrieval algorithm and examine the ratios of these radii under the perspective that these relationships of cloud microphysics will show specific stages of cloud evolutions. As mentioned in Part I and other studies, solar radiation in the 1.6-, 2.1-, and 3.7-μm spectral regions is expected to penetrate into the cloud at different optical depths. In Part I, we showed that these penetration depths correspond to ~28, ~15, and ~8 from the cloud top for 1.6-, 2.1-, and 3.7-μm radiation, respectively. These are the optical depths for each spectral region above which the reflectances and thus the respective CDR become independent of the column optical depth of cloud. The analysis presented below applies to optically thick clouds that have optical depths larger than these specific values in order to avoid fluctuations in ratios of R16/R21 and R37/R21 that arise from variations in optical depth.

Figure 1 illustrates the joint probability density function (JPDF) of (top) R37/R21 against R21 and (bottom) R37/R21 against R37 for (left) ocean area only and (right) land area only for clouds of optical depth greater than 15. For R21 < 14 μm, R37/R21 increases as R21 increases to ~14 μm [Fig. 1a along the line from (i) to (ii)]. The ratio then decreases with increasing R21 [from (ii) to (iii)]. These features can be interpreted in terms of microphysical particle growth processes whose signatures may appear as various relationships in this diagram. When the condensation process dominates the particle growth, for example, the particle size tends to increase upward and thus R37 tends to grow faster than R21 since R37 reflects the particle size in the upper layer (Part I). This provides an increasing tendency of R37/R21 with increasing R21 as shown by the positive tendency from (i) to (ii). The fact that R37/R21 is less than unity may be explained by the existence of small cloud droplets at the top of cloud as discussed in section 2a of Part I. When the coalescence process dominates the particle growth, on the other hand, R21 grows much faster than R37 since the former is more sensitive to the existence of drizzle particles than the latter (Part I). The ratio R37/R21 then tends to decrease with R21 increasing in this case. The negative tendency may thus be interpreted as being dominated by the coalescence process.

Figure 1c is more complicated than Fig. 1a. The path from (ii) to (iii) appears to spread broadly in Fig. 1c compared with Fig. 1a. This difference between Figs. 1a and 1c may be due to the microphysical processes involving the small particles near the cloud top that is represented by R37 and R37/R21 in a more complicated manner. To interpret the observed characteristics in Fig. 1c, we assume several types of transitions from state (ii) to (iii). In case 1 the collision-growth process takes place near cloud top, in case 2 the coalescence occurs deeper down from the cloud top, and case 3 is characterized by the simultaneous occurrence of collision growth in a deeper layer of clouds and evaporation of cloud droplets at the cloud top. In case 1, R37/R21 should only weakly decrease with increasing R37—schematically shown as (ii) to (iiia)—since both R21 and R37 represent the larger particles formed by the collision-growth process taking place near cloud top and the sensitivity of R21 to drizzle droplets is greater than R37 (Part I). In case 2, R21 tends to increase more rapidly because of the existence of drizzle droplet in deeper layers, whereas R37 increases only slightly. The ratio R37/R21 decreases with R21 more rapidly in this case [(ii) to (iiib)] than in case 1. For case 3, R37/R21 will decrease very quickly because of a rapid decrease of R37 as a result of evaporation near the cloud top and also because of an increase of R21 representing the growth of drizzle particles in the deeper layer. Our interpretation of these results is that Fig. 1c may contain these cases that are mixed in a complicated way. It is interesting to find that the paths toward (iiib) and (iiic) are apparent for clouds over oceans but not as obvious for clouds over land (see Fig. 1d). It is hypothesized that drizzle may form lower down in oceanic clouds and form higher up in land-based clouds, respectively. If this interpretation is true, then we expect a corresponding contrast between ocean and land reflectivity structures observed by the CloudSat/CPR and discussed below. Another relevant aspect in Fig. 1 is that R37/R21 is multivalued and its behavior is complex. By contrast, R21 varies in a monotonic fashion as droplet growth process change. For brevity, we do not show the equivalent R37/R16 versus R16 JPDF because the behavior is similar to those shown in Fig. 1. Also, R16/R21 values generally range from 0.8 to 1 for all values of R21. For a limited numbers of cases, the ratio R16/R21 is larger than unity because of the presence of drizzle and rain in the low portion of clouds.

In summary, the results shown in the JPDFs of Fig. 1 are consistent with predictions from radiative transfer
simulations of Part I. The ratios R37/R21 and R16/R21 (not shown) vary according to the presence of drizzle and according to the vertical inhomogeneity of cloud droplets. One of the new aspects of the results shown is that R21 \textasciitilde 14 \textmu m approximately divides the condensation and collision growth processes, as has been suggested in other studies (Rosenfeld and Gutman 1994). Three pathways of droplet growth—illustrated in Fig. 1c as movement from (ii) to (iiia), (iiib), and (iiic), respectively—can be interpreted as three different characteristics of growth by coalescence. It is demonstrated that the hydrometeor droplet growth from cloud to drizzle proceeds monotonically with increasing R16 or R21 and that R37 does not generally convey the presence of drizzle. R37 increases with hydrometeor droplet growth when R21 < 14 \textmu m but can actually decrease because of the evaporation of droplets at the cloud top even when R21 > 14 \textmu m. Since the Aqua/MODIS 1.6-\textmu m channel has proved problematic for a number of detectors, and given the similar nature of the behavior of R16 and R21, we hereafter use R21 as an indicator of hydrometeor droplet growth processes.

4. Synergistic analysis of Aqua/MODIS and CloudSat/CPR

We have stressed that the MODIS R21 is apparently a reasonable indicator of the transition between cloud droplets and drizzle. If R21 actually indicates transitions between different cloud droplet growth modes, we expect to be able to identify these continuous transitions in radar reflectivity profiles that are classified in terms of different R21 domains. Radar reflectivity data are often expressed as a contoured frequency of altitude diagram (CFAD) to statistically characterize the vertical structure of radar signals. Here we modify this approach introducing a contoured frequency diagram of the radar reflectivities using cloud optical depth as a vertical axis.
instead of altitude. The vertical slicing of optical depth used for this axis is that obtained from the 2B-Tau optical depth profile. We refer to this as the contoured frequency by optical depth diagram (CFODD). The use of optical depth as the vertical axis has some advantages in that it provides a normalization of the vertical scale, reducing the tendency inherent in CFADs to smear the vertical structure, especially when compositing clouds of different geometrical thicknesses.

Figures 2 and 3 present a series of CFODDs classified by R21 with thresholds of 6, 8, 10, 12, 14, 16, 18, 20, 25, and 30 μm for the oceanic clouds (Fig. 2) and clouds over land (Fig. 3). Radar reflectivities with column cloud optical depth larger than one were used for generating these CFODDs. Striking in these diagrams are three modes of CPR reflectivities Ze: roughly less than −20, −15 to 0, and 0 to −15 dBZe, which we interpret as cloud droplets, drizzle, and rain, respectively. The drizzle mode slowly evolves from Fig. 2d to 2f from approximately −10 to −5 dBZe in Fig. 2d to −5 dBZe in Fig. 2f. Also striking is the evolution from mode to mode as R21 increases. We interpret this as a continuous transition from clouds
(Ze < −20 dBZe) to drizzle (−15 < Ze < 0) to rain (Ze > 0) with increasing R21. This is consistent with our previous interpretation that increasing R21 reflects the transition in particle growth from cloud to rain. Figures 2a and 2b are somewhat noisy because of a smaller population of samples in these size ranges. The cloud droplet mode gradually becomes obvious with increasing R21 toward R21 ≈ 14 μm; then the drizzle mode becomes apparent as R21 exceeds 14 μm. The rain mode appears when R21 exceeds ~20 μm and the drizzle mode has slowly transitioned into a rain mode.

The contrast of CFODD between ocean and land area is also noteworthy. Figure 3 shows a similar transition from cloud to drizzle and then drizzle to rain. The transition from cloud to drizzle, however, is much more ambiguous than for oceanic clouds, suggesting a reduced frequency of drizzle in these clouds. Optical depths where the transitions occur are also smaller in land clouds than in than oceanic clouds. For example, drizzle and rain modes appear to start at optical depths typically nearer cloud top over land, whereas these modes appear to develop at depths more characteristic of optical depths.
around 20 and 30 over oceans. These differences require further study.

The behavior of $R_{21}$ revealed in Figs. 2 and 3 in relation to radar Ze profiles is also consistent with the behavior of $R_{37}/R_{21}$ with changing $R_{21}$ noted in Fig. 1. Figure 4 is the frequency of $R_{37}/R_{21}$ for several of the $R_{21}$ categories used in Figs. 2 and 3. When $R_{21} < 14 \mu m$, $R_{37}/R_{21}$ gradually increases in oceanic clouds with increasing $R_{21}$ (Fig. 4a). Again, this indicates that these conditions are consistent with these clouds being in a mode of condensation growth. By contrast, $R_{37}/R_{21}$ decreases with increasing $R_{21}$ for $R_{21} > 14 \mu m$. Under these conditions, cloud particles are growing by coalescence, and the resultant formation of drizzle particles reduces $R_{37}/R_{21}$. The variations of $R_{37}/R_{21}$ over land are basically similar to those over ocean, especially in the $R_{21} < 14 \mu m$ region. However, comparing Figs. 4b and 4d, we observe that $R_{37}/R_{21}$ decreases more quickly in ocean clouds than in land-based clouds when $R_{21} > 14 \mu m$. This is due to the combined effect of the vertical inhomogeneity of cloud droplet sizes (drizzle existing lower down in clouds as shown in CFODD) and the existence of the small cloud droplets at the cloud top that we propose occur by evaporation at the cloud top.

The information presented in the CFODD diagrams is consistent with the previous interpretation of the difference between $R_{37}$ and $R_{21}$ for $R_{21} > 14 \mu m$ resulting from the effects of drizzle droplets. We also hypothesized in Part I that influences of small cloud droplet (radii ~4 $\mu m$) and the vertical inhomogeneity of cloud droplets...
within the cloud mode (radii ~ 10 μm) are another factor. In Part I, we suggested that R37/R21 is less than unity because of the existence of small cloud droplets at cloud top even though R21 < 14 μm. We also suggested that R16/R21 is less than unity when R21 < 14 μm because of the general increase in droplet size with height typical of adiabatic conditions during the condensation phase. However, these effects cannot be clearly identified in CFODD alone. The signal of Ze by small cloud droplets may fall below the CPR detection limits. The adiabatic droplet condition, on the other hand, does appear in the JPDF of optical depth versus CPR reflectivities. Figure 5 is same as Fig. 2 except that the data are composited into finer-resolution bins defined by R21 thresholds of 8, 10, 12, 14, 16, 18, and 20 μm. To focus on cloud particles mode, the horizontal axis Ze is expanded from −30 to −10 dBZeo. The general tendency is that the radar reflectivities increase with decreasing optical depth when R21 < 14 μm, which is consistent with relatively large and small cloud droplets in the upper and lower layers, respectively.

5. Discussion and summary

The findings of this paper are summarized by revisiting the three basic questions posed in Part I and summing up our findings in relation to these questions.

a. Question 1: What do R16, R21, and R37 represent in terms of cloud microphysical properties?

Although R16, R21, and R37 are referred to as the effective radii of clouds, they represent vertically averaged particle sizes over different layers of cloud. Radiative transfer simulations reported in Part I demonstrated that R16, R21, and R37 have information on the cloud droplet sizes over optical depth regions of 0–28, 0–15, and 0–8 from the cloud top, respectively. Thus, it is expected that the ratio R37/R21 is influenced by droplet sizes in the upper layers of clouds and within moderately optically thick portions of clouds. It is also shown that the sensitivities to drizzle droplets are markedly different between 2.1 and 3.7 μm. Since 2.1 μm is more sensitive to the drizzle droplets, because R21 results in a deeper layer average, R21 tends to be larger than R37 when drizzle droplets exist in the clouds. Since the sensitivity of R16 and R21 with respect to drizzle droplets is similar, the contrast between R16 and R21 reflects vertical inhomogeneity of hydrometeor particle sizes. The JPDF of R37/R21 versus R21 (Fig. 1) suggests that R21 is a reasonable indicator of different cloud droplet growth modes, whereas the ratio itself has a complex structure. The CFODDs introduced in section 4 support this interpretation, and it was shown how the transition from
cloud to drizzle to rain evident in the radar data is also reflected in R21. This suggests important new uses of R21 (a standard product of the MODIS) and/or R37 (e.g., a standard product of the JAXA/GLI mission) for several cloud physics and related applications.

b. Question 2: Why are most R37/R21 values less than unity and why is the R16/R21 mode near unity?

The radiative transfer simulations of Part I suggested that the existence of small cloud droplets near the cloud top in part explains why R37/R21 < 1. At the same time, R37 increases faster than does R21 when R21 < 14 μm; thus, the ratio R37/R21 increases with increasing R21, as observed. When R21 > 14 μm, R37 is still smaller than R21. Two factors contribute to the decreasing ratio for R21 > 14 μm. One is the vertical inhomogeneity of the hydrometeor droplet sizes; the other is bimodal particle size distribution as suggested by the radiative transfer simulations. Both possibilities produce R37/R21 < 1. The CFODD suggested that the vertical inhomogeneity is dominant over ocean because the drizzle mode separately exists from the cloud mode; drizzle appears to take place in the middle and low layers of the cloud. The bimodal size distribution is dominant over land because both the cloud and drizzle/rain droplets appear to coexist at cloud top. These results are independent of the problems with sensor calibration and/or retrieval algorithms. The characteristics of R37/R21 were obtained not only from MODIS data but also from GLI data, each using different algorithms applied to different sensor data.

c. Question 3: Does the vertical inhomogeneity of cloud droplet sizes explain the ratio values R37/R21 and R16/R21?

Small droplets at cloud top tend to be undetected by the CPR. The CFODD generated from CPR reflectivity, however, appears to be a useful way of revealing the vertical inhomogeneity of hydrometeor droplet sizes. The CFODD shows that the drizzle droplets gradually appear as R21 increases above ~14 μm. This is consistent with the results obtained from Aqua/MODIS individual results shown in section 3. When R21 < 14 μm, the fact that R37/R21 < 1 is due in part to small droplets, but this cannot be confirmed in the CFODD diagrams. Such droplets are too small to be detected by CPR and the layers of these droplets are below the vertical resolution of the CPR. This topic requires further research.

Figure 6 further summarizes the results of our study. The diagram attempts to illustrate the transitions apparent in the CFODD analysis. The cloud mode has CPR reflectivities of approximately Ze < −20 dBZe and cloud droplets grow by condensation, growing to R21 ~ 14 μm size. When R21 ~ 14 μm, the collision process is more prevalent and drizzle droplets appear. Rain in turn develops when R21 > 20 μm. Drizzle and rain occur over depths of cloud layers that are different between ocean and land areas. For clouds over land, we speculate that stronger updrafts maintain large droplets higher in clouds so that the drizzle and rain coexist in the upper layers of clouds. By contrast, drizzle and rain appear to form lower down in oceanic cloud layers, which we speculate is a result of weaker updrafts in clouds over oceans. Figure 7 graphically explains how the values of R21, R37, and R37/R21 associated with these processes also change. In the condensation phase (R21 < 14 μm domain; Fig. 7a), R37 is smaller than R21 in large part because of evaporation near cloud top. As particles grow by condensation, R37 increases faster than does R21, and R37/R21 increases with R21 increasing as is observed [process (i) to (ii) in Fig. 1a]. Figures 7b and 7c illustrate the case for R21 > 14 μm over ocean and land, respectively. In these circumstances, R37/R21 is less than 1 because of the existence of the drizzle mode. The tops of clouds over ocean primarily contain cloud droplets with drizzle and rain coexisting deeper down in clouds (Fig. 7b), whereas cloud and drizzle droplets appear to coexist near the tops of clouds over land (Fig. 7c).

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