Identifying Particle Growth Processes in Marine Low Clouds Using Spatial Variances of Imager-Derived Cloud Parameters

Takashi M. Nagao and Kentaroh Suzuki

Abstract This study proposes a new approach that probes particle growth processes of liquid clouds with satellite observables from passive imagers. Based on the notion that the condensation growth and the coalescence process are characterized by constant cloud droplet number concentration (CDNC) and liquid water path (LWP), respectively, the method adopted used spatial variances of imager-derived cloud properties to estimate relative contributions from these processes embedded in the cloud system. The relative standard deviations (RSDs) of CDNC and LWP associated with their horizontal variances were compared in the form of their ratio. This approach was applied to the GCOM-C/SGLI cloud product, and spatial variability in this RSD ratio was consistent with cloud horizontal morphology such as open- and closed-cell structures. The results suggest that spatial variances of imager-derived cloud properties depict signatures of cloud microphysical processes in the way mappable on the horizontal extent of the cloud system.

Plain Language Summary In low-level clouds consisting of liquid water droplets, called warm clouds, droplets grow via the condensation and coalescence processes. The condensation process involves the growth of particles by absorption of water vapor and typically occurs in the early stages of cloud development. The coalescence process involves collision and coalescence with other particles and typically occurs when droplets grow to a size large enough for them to collide with each other. This study proposes a new approach that employs satellite observations to quantitatively estimate how these two processes occur in a given cloud system and to display it in the form of a geographical map of a quantity representing relative contributions of the two processes. The quantity was computed using spatial variances of satellite-observed cloud properties such as cloud droplet number concentration and liquid water path to diagnose the two processes characterized by conservation of each property. The results highlight that spatial variability in relative contributions of the two processes was consistent with cloud horizontal morphology such as open- and closed-cell structures that are identified as honeycomb-like patterns of cloudiness. The proposed approach may serve as a satellite-based way of “geographical process mapping” of warm clouds in the spatial context.

1. Introduction

Various techniques to retrieve cloud properties such as cloud optical thickness (COT) and cloud effective radius (CER) from remotely sensed measurements in the visible-to-infrared region have been established (e.g., Nakajima & King, 1990; Nakajima & Nakajma, 1995; Twomey & Cocks, 1982; Twomey & Seton, 1980). These techniques have been applied to satellite-borne imaging spectroradiometers such as Moderate Resolution Imaging Spectroradiometer (MODIS) (e.g., Kawamoto et al., 2001; Nakajima et al., 2009; Platnick et al., 2003, 2017; Roebeling et al., 2006). The imager-derived cloud properties have provided information critical to our understanding of cloud impact on the Earth’s radiation and water budget in the form of the global geographical distribution of cloud properties and their diurnal, seasonal, and internal variabilities (e.g., King et al., 2013; Rossow & Schiffer, 1991) and of global statistics of the aerosol effects on clouds (e.g., Grysspeerdt et al., 2016; Grysspeerdt et al., 2019; Kaufman et al., 2005; Matsui et al., 2006; Nakajima et al., 2001; Quaas et al., 2006; Rosenfeld et al., 2019; Sekiguchi et al., 2003; Toll et al., 2019).

These satellite-derived cloud properties, particularly when combined with each other, also provide information on particle growth processes working within cloud systems. Previous studies have used three approaches to examine what information about the particle growth process can be inferred from imager-derived liquid water cloud properties.
First, imager-derived CER itself can be interpreted as a proxy for drizzle existence and the in-cloud vertical microphysical structure. The CER of 12 to 14 μm has been suggested as an approximate indication of drizzle formation (Gerber, 1996; Rosenfeld, 2000; Rosenfeld & Gutman, 1994). The relevance of CER to the in-cloud vertical microphysical structure was demonstrated by a combined analysis of MODIS and CloudSat, revealing how the particle growth process in vertical dimension from cloud to rain occurs fairly monotonically with increasing CER (Nakajima et al., 2010b; Suzuki et al., 2010). Three CERs obtained from 1.6, 2.1, and 3.7 μm bands penetrating different optical depths have also been suggested to possess information on the in-cloud vertical particle size distribution and the existence of drizzle (Nagao et al., 2013; Nakajima et al., 2010a; Platnick, 2000). These findings also motivated the algorithms for retrieving the CER vertical profile from the shortwave-infrared bands to be proposed (Chang & Li, 2002, 2003; Kokhanovsky & Rozanov, 2012).

Second, the correlation statistics between imager-derived COT and CER were interpreted to be indicative of the particle growth process. The positive and negative correlation patterns between COT and CER have been suggested to indicate nondrizzling and drizzling clouds, respectively (Nakajima et al., 1991). This interpretation was aided with numerical modeling based on a detailed microphysical process representation, simulating the distinctively different correlation patterns—shaped by different particle growth processes (i.e., condensation and coalescence) (Suzuki et al., 2010), in the manner influenced by aerosol and stability conditions (Suzuki et al., 2010).

Third, the spatial characteristics of clouds have been investigated in relation to cloud microphysics. For example, cloud horizontal morphology (e.g., open- and closed-cell structures) has been related to drizzle existence (Stevens et al., 2005), and mesoscale cloud organization patterns in the Tradewinds have been classified using visible images from MODIS (Stevens et al., 2019). As a key signature of aerosol-cloud interaction, ship tracks are also identified by spatial differences of CER and visible reflectance (e.g., Coakley et al., 1987; Conover, 1966; Radke et al., 1989; Yuan et al., 2019).

This study builds upon and combines some of these approaches to develop a method for quantitatively probing the particle growth processes in terms of spatial (horizontal) characteristics of cloud properties. We propose a new approach that exploits spatial variances of imager-derived cloud properties as a means to quantify relative contributions from different particle growth processes (i.e., condensation and coalescence) and to place them in the context of horizontal cloud structures (morphology). Specifically, the relative standard deviations (RSDs) of cloud droplet number concentration (CDNC) and liquid water path (LWP) were estimated based on their horizontal variabilities and compared in the form of their ratio as a measure of whether the condensation or coalescence process dominates over different locations in a given cloud system scene.

This approach was applied to a multispectral imager, Second Generation Global Imager (SGLI), on board a polar orbit satellite, Global Change Observation Mission-Climate (GCOM-C). In doing so, this study shows how the spatial variability of the RSD ratio manifests differing contributions of the condensation and coalescence processes to spatial cloud structures. In particular, the spatial variability of the RSD ratios was found to be consistent with cloud morphology, such as open- and closed-cell structures.

2. Data and Methods

2.1. Data

The SGLI used in this study is a visible-to-infrared multispectral imager on board Japan Aerospace Exploration Agency’s (JAXA’s) polar orbit satellite GCOM-C launched at the end of 2017 (Tanaka et al., 2018). SGLI has characteristics similar to MODIS in terms of the spectral channels (19 channels; 380 nm to 12 μm), the swath (>1,000 km), and the spatial resolution (250 m to 1 km). SGLI also has unique aspects such as polarimetry observation functions for land aerosol retrievals and 763 nm channels for cloud geometric thickness retrievals.

The SGLI cloud product (hereafter SGLI-CLPR) provides COT, CER, and cloud top temperature (CTT) for both liquid water and ice clouds at a 1 km spatial resolution, retrieved from the measurements at the SGLI SW1 (1.05 μm), SW3 (2.21 μm), and T1 (10.8 μm) channels using a previously developed algorithm (Kawamoto et al., 2001; Nakajima & King, 1990; Nakajima & Nakajima, 1995). It has been confirmed that the SGLI-CLPR COT, CER, and CTT for liquid water clouds used in this study are quantitatively consistent with the MODIS collection 6.1 cloud property product (Nakajima et al., 2019).
The SGLI-CLPR COT ($\tau$) and CER ($r_e$) were then used to estimate CDNC ($N_c$) and LWP ($W$) by using the following equations based on an adiabatic cloud model (e.g., Bennartz, 2007; Bennartz & Rausch, 2017; Grosvenor, 2018):

$$W = \frac{5}{5} \rho_w \tau r_e$$  (1)

$$N_c = \frac{\sqrt{10}}{4\pi k} \left[ \frac{f_{ad} \Gamma_{ad}}{\rho_w} \right]^{\frac{1}{2}} r_e^{-\frac{5}{2}}$$  (2)

where $\rho_w$ is the density of liquid water, $k$ is a factor relating the volume droplet radius to $r_e$, $f_{ad} (< 1)$ is the factor representing the adiabaticity of the cloud, and $\Gamma_{ad}$ is the condensation rate that depends on temperature and pressure. Following previous studies (Bennartz & Rausch, 2017), we assumed $k = 0.8$ and $f_{ad} = 0.8$ to be constant and computed $\Gamma_{ad}$ from the SGLI-CLPR CTT and an assumed pressure of 850 hPa.

It is known that cloud horizontal inhomogeneity at the subpixel scale (mainly by clear-sky contamination) induces a large positive bias in the CER retrievals (Zhang et al., 2012; Zhang & Platnick, 2011). To avoid this bias, only data with COT > 4 were used in this study (the threshold was determined empirically) to restrict the analysis to clouds that are likely to suffer from minimum influences of clear-sky contamination.

An example of the GCOM-C/SGLI scene and its analysis is shown in Figures 1a–1e. Figure 1a shows the image of the color composite of the GCOM-C/SGLI VN8, VN5, and VN3 channels centered at 673.5, 530, and 443 nm, respectively. The image covers the area from 90°W to 80°W and 10°S to 20°S over the ocean offshore of Peru on 17 June 2019. Figures 1b and 1c show the COT and CER retrievals, respectively, for the scene of Figure 1a. Figures 1d and 1e show LWP and CDNC estimated by equations (1) and (2), respectively, for the scene of Figure 1a.

2.2. Methods

This study builds upon findings by previous studies (Nakajima et al., 1991; Suzuki, Nakajima, Nakajima, & Khain, 2010; Suzuki, Nakajima, & Stephens, 2010) where different (positive/negative) correlation patterns between COT and CER are indicative of different particle growth processes (i.e., condensation/coalescence). The correlation statistics are shown in Figure 2a in the form of the joint probability density function (PDF) of COT and CER obtained from the SGLI-CLPR. Each panel in Figure 2a corresponds to each grid box at 2.5° intervals that divide the whole scene of Figure 1. The blue and red lines superimposed in Figure 2a represents theoretical relationships for various constant values of CDNC and LWP given by equations (1) and (2), respectively. These relationships aid the interpretation of the COT-CER correlations as schematically illustrated in Figure 2b. This represents how tendencies of COT and CER and their resultant correlations differ among nondrizzling, drizzling, and decaying stages of single warm cloud development, as hypothesized by Suzuki et al. (Suzuki, Nakajima, Nakajima, & Khain, 2010). Specifically, both COT and CER increase when the CDNC remains constant under the dominance of the condensation process, as is typically the case in the nondrizzling stage. In contrast, the coalescence process with a constant LWP induces a decrease of COT with increasing CER, as is typical of the drizzling stage. These theoretical relationships embedded in the COT-CER correlation statistics provide a quantitative reference for condensation and coalescence processes in terms of the conserved properties (i.e., mass and number) for these processes.

The correlation characteristics for different subdomains (Figure 2a) can be regarded as dominated by different growth processes to varying extents. The joint PDFs in the lower right panels of Figure 2a are well represented by a constant CDNC of approximately 90 cm$^{-3}$ indicative of condensation growth. Conversely, the joint PDFs in the upper left panels are more like distributed along the line corresponding to a constant LWP that is indicative of the coalescence process. The other panels of Figure 2a were found to depict the COT-CER correlation statistics that vary continuously between the two cases. This may be the transition from condensation growth to the coalescence process.

This study proposes to investigate spatial variances of CDNC and LWP derived from horizontally sampled CER and COT as a way of quantifying the behavior of the correlation statistics between CER and COT obtained from spatial sampling. Specifically, the relative standard deviations (RSDs) of CDNC and LWP were computed, and their ratio was analyzed to quantify relative contributions from the two processes.
For this purpose, we assume that the CDNC and LWP follow the lognormal distribution based on previous studies (Lebsock et al., 2013; Zhang et al., 2019). If the random variable $X$ is lognormally distributed, the RSD is given by

$$RSD_X = \sqrt{\frac{SD_X}{E_X}} = \sqrt{e^{\sigma_{ln}^2} - 1},$$

(3)

where $E[X]$ and $SD[X]$ are the expected value and the standard deviation of a random variable $X$, respectively. $\sigma_{ln}$ is the sample standard deviation of the variable’s natural logarithm and is distinct from $SD[X]$. To compare the RSDs of CDNC and LWP, the ratio of $RSD[CDNC]$ to $RSD[LWP]$ is defined as

$$RSD \text{ ratio} = \frac{RSD[CDNC]}{RSD[LWP]}.$$  

(4)

This quantity characterizes the COT-CER correlation in terms of the dominant microphysical processes as follows. The smaller the RSD ratio, the smaller the variance of the CDNC, and thus the closer the correlation to a constant CDNC, indicative of condensation growth. In contrast, the larger the RSD ratio, the larger the
variance of the CDNC, and thus the closer the correlation to a constant LWP. Thus, the larger (smaller) RSD ratio suggests that the coalescence (condensation) process tends to be dominant.

The RSD ratio computed using (4) at each grid of Figure 2a is shown in Figure 2c in the form of its geographical distribution over the scene of Figure 1. The RSD ratio was found to increase from the lower right to the upper left regions in the scene. This trend is consistent with the variability in the COT‐CER correlation statistics are shown in Figure 2a. Here the correlation varies in the manner that increases the CDNC variance rather than the LWP variance from the lower right to upper left panels. This demonstrates that the RSD ratio reasonably quantifies the change in the shape of the COT-CER correlation statistics in terms of the constancy of CDNC and LWP.

3. Results and Discussion
3.1. The Relevance of RSD Ratio to the Particle Growth Process

To better understand how the RSD ratio relates to the COT-CER correlation characteristics, Figures 3a–3c show the joint PDF of COT and CER from the same data as Figures 1b and 1c but separately for different ranges of the RSD ratio. When the RSD ratio was small (Figure 3a), the correlation was well aligned along the line of constant CDNC (~90 cm$^{-3}$) with the variance of CDNC much smaller than that of LWP. This tendency may indicate the dominance of the condensation growth. For intermediate RSD ratios (Figure 3b), the variation of CDNC was larger compared to Figure 3a, where there was a decrease in the CDNC while the
variation of LWP was not much different from Figure 3a. This difference between Figures 3a and 3b may be attributed to increased contributions of the coalescence process relative to condensation growth. This tendency was further pronounced for the largest values of the RSD ratio (Figure 3c), where the variation of CDNC was even larger compared to Figure 3b, further decreasing CDNC. These characteristics appear to indicate that clouds dominated by coalescence growth are more abundant in Figure 3c compared to Figure 3b. It is also worth noting that the joint PDF in Figure 3c does not spread toward CDNC beyond 90 cm$^{-3}$. This implies that processes increasing CDNC with constant LWP tend not to exist. This gives credence to the hypothesis that the CDNC spread occurs due to coalescence that decreases CDNC.

Figure 3d shows how the RSD ratio tends to vary with CER in the form of the conditional probability density function of the RSD ratio at various given CERs. The RSD ratio was found to drastically change around CER = 13 $\mu$m, which is close to a known “threshold” of drizzle formation (Rosenfeld, 2000; Rosenfeld & Gutman, 1994). When CER < 13 $\mu$m, the RSD ratio takes the lowest value with little variations, while for CER > 13 $\mu$m, the RSD ratio tends to increase with increasing CER. This tendency was also found in geographical distributions of the RSD ratio (Figure 2c) and CER (Figure 1c) which show that the RSD ratio systematically increases from the southeast to northwest regions in the scene (Figure 2c), corresponding to the CER variation (Figure 1c). These results suggest that the RSD ratio and its close relationship with CER manifest microphysical process characteristics in terms of the spatial (horizontal) extent of a given cloud system. This is also relevant to the cloud horizontal structure as discussed in section 3.2.

### 3.2. Correspondence of the RSD Ratio to Cloud Morphology

The RSD ratio characteristics described above were further investigated in terms of the spatial (horizontal) structure of clouds. Figure 4 compares the visible image (left panels), the RSD ratio (middle panels), and the
Figure 4. Images of (a) the SGLI visible color composite similar to Figure 1a, (b) the RSD ratio similar to Figure 2c, and (c) the CER retrievals similar to Figure 1c. The images cover the same area as Figure 1 but are composed of the observations on 21 June 2019. (d, e, and f) The same as (a), (b), and (c), respectively, but for 2 June 2019. (g, h, and i) Also the same as (a), (b), and (c), respectively, but for 2 July 2019.
CER retrieval (right panels) for three different scenes (top to bottom) measured by GCOM-C/SGLI. These include the closed- and/or open-cell clouds over the same area observed at different dates.

The top row panels (Figures 4a–4c) illustrate examples of closed-cell clouds. The CER was around 12 μm (Figure 4c), while the RSD ratio was smaller than 0.5 almost everywhere (Figure 4b). This suggests that condensation growth was dominant over the whole domain. In the middle row panels (Figures 4d–4f), open-cell clouds were embedded around the center of the scene bounded by closed-cell clouds. The RSD ratio in the open-cell region was found to be substantially greater than that in the closed-cell region. This suggests that the coalescence process has a larger contribution than condensation growth in the open-cell clouds, whereas the opposite was true in the closed-cell cloud regions. This is also supported by the fact that the CER was much larger than 13 μm in the open-cell cloud region. As an example, consisting of more open-cell clouds, the bottom row panels (Figures 4g–4i) show cloud morphology that is different from the top and middle rows. In this scene, both the RSD ratio and CER were even larger than in the middle row. This suggests that the coalescence process is more dominant over the region in the manner consistent with cloud morphology dominated by open-cell clouds.

Figure 4 demonstrates that the spatial characteristics of the RSD ratio overall correspond to the cloud horizontal morphology (open/closed cells) as well as to the CER value hinting the drizzle existence. This suggests that the shift of the dominant cloud process indicated by the RSD ratio occurs in a way coherent with cloud morphology identified by visible images. It is worth noting that these results were demonstrated from passive remote sensing alone based on its horizontal sampling.

### 3.3. Discussion

This study proposed an approach to combine COT and CER obtained from a passive sensor in the form of the RSD ratio that quantifies how the COT-CER correlation statistics are close to constant CDNC or LWP. This provides a quantitative way to probe the cloud particle growth processes characterized by the constancy of these quantities (i.e., conserved properties). The RSD ratio is thus deemed a process-oriented parameter that characterizes dominant particle growth processes based on the spatial (horizontal) variability of cloud properties. While CER is often used as a proxy that indicates the onset of the coalescence process, the RSD ratio is an index that describes cloud particle growth processes more directly through examining conservations of CDNC and LWP. The RSD ratio introduced has an advantage that it allows to quantify microphysical processes in the way that can also be compared to other physical quantities. Figure 3d compares the RSD ratio with CER to provide better identifications of the CER value where the coalescence process starts. Another advantage is that it may serve as a satellite-based way of geographical process mapping of warm clouds as shown in Figure 4.

The proposed approach with the RSD ratio interprets the COT-CER correlation statistics in the context of only condensation and coalescence processes. This interpretation should be used cautiously when other factors, such as the cloud horizontal inhomogeneity at the subpixel scale, distort the correlation statistics. For instance, clear-sky contamination causes a large positive bias in the imager-derived CER retrieval (Zhang et al., 2012; Zhang & Platnick, 2011) and thus induces a negative bias in CDNC estimated by equation (2). This results in an apparent increase in the CDNC variance that can be misinterpreted as the coalescence process is dominant. To minimize this effect in a simple way, this study restricted the analysis to data with COT > 4 to exclude inhomogeneous broken clouds.

Another uncertainty in the proposed method is a possible dependency of the window length selected for computing the RSD ratio on the horizontal scale of clouds. This is particularly given the assumption that the clouds within the window are dominated by the same growth processes. Dynamically adjusting window length to match the horizontal cloud scale would increase the robustness of this method and enable investigation on scale dependency of dominant microphysical processes in future studies.

It should be recognized that it is not reasonable to assume that \( f_{\text{adv}} \) and \( k \) in equation (2) are constants in open-cell and closed-cell regions where entrainment rate on which \( f_{\text{adv}} \) depends may be quite different. Merk et al. (2016) reported \( f_{\text{adv}} = 0.63 \pm 0.22 \) based on the combination of ground-based cloud radar, ceilometer, and microwave radiometer, which means that neither the assumption of a completely adiabatic cloud nor the assumption of a constant subadiabatic factor is fulfilled. Also, \( k \) is related to relative dispersion of cloud droplet size distribution, which is further affected by aerosol and vertical velocity (e.g., Chandrakar...
et al., 2016; Lu et al., 2012). These uncertainties should induce uncertainties in CDNC estimates. Note, however, that RSD ratio was defined as a function of $\sigma_n$ which is the sample standard deviation of the natural logarithm of the quantity $n$. Since the standard deviation of the natural logarithm does not depend on any factors multiplied to $X$, the RSD ratio also does not directly depend on either $f_a$ or $k$. This is another advantage of the RSD ratio introduced in this study.

While the RSD ratio was introduced in this study for convenience of using a single parameter to characterize microphysical processes, a more complete characterization of particle growth processes would be possible using two RSDs of CDNC and LWP. The variances for each of them rather than their ratio is likely to link more directly to satellite-observed cloud microphysics parameters themselves. Furthermore, when the variances of either CDNC and LWP are small, such as in the infant stages of the cloud lifecycle, the RSD ratio would be unstable, and it would be more suitable to investigate the variances themselves (not their ratio).

4. Conclusions

This study proposed an approach of exploiting variances of imager-derived cloud properties to quantify relative contributions from the condensation and coalescence processes at work within cloud systems. Specifically, the RSDs of CDNC and LWP were introduced and compared in the form of their ratio on the premise that condensation growth and coalescence process are characterized by constant CDNC or LWP, respectively. This approach was applied to the GCOM-C/SGLI measurements to show how the correlation statistics of the SGLI-derived CER and COT within a relatively small scene follow the theoretical curves dictating a constancy of CDNC and LWP, indicative of condensation and coalescence processes, respectively. We also demonstrated that the spatial variability of the RSD ratio was consistent with cloud horizontal morphology, such as open- and closed-cell spatial structures. This suggests that statistical parameters such as derived variances of imager-based CDNC and LWP may serve as a clue to characterize cloud growth processes. This was achieved in a manner that is mappable as the geographical distributions and thus linked to the spatial structure of cloud systems.

References

Bennartz, R. (2007). Global assessment of marine boundary layer cloud droplet number concentration from satellite. *Journal of Geophysical Research: Atmospheres*, 112(D2), 32141. https://doi.org/10.1029/2006JD007547

Bennartz, R., & Rausch, J. (2017). Global and regional estimates of warm cloud droplet number concentration based on 13 years of AQUA-MODIS observations. *Atmospheric Chemistry and Physics*, 17(16), 9815–9836. https://doi.org/10.5194/acp-17-9815-2017

Chandrakar, K. K., Cantrell, W., Chang, K., Ciochetto, D., Niedermeier, M., Ovchinnikov, M., et al. (2016). Aerosol indirect effect from turbulence-induced broadening of cloud-droplet size distributions. *Proceedings of the National Academy of Sciences of the United States of America*, 113(50), 14,243–14,248. https://doi.org/10.1073/pnas.1612686113

Chang, F.-L., & Li, Z. (2002). Estimating the vertical variation of cloud droplet effective radius using multispectral near-infrared satellite measurements. *Journal of Geophysical Research: Atmospheres*, 107(D), 4257. https://doi.org/10.1029/2001JD000766

Chang, F.-L., & Li, Z. (2003). Retrieving vertical profiles of water-cloud droplet effective radius: Algorithm modification and preliminary application. *Journal of Geophysical Research*, 108(D), 4763. https://doi.org/10.1029/2003JD003906

Cookley, J. A., Bernstein, R. L., & Durkee, P. A. (1987). Effect of ship-stack effluents on cloud reflectivity. *Science*, 237(4818), 1020–1022. https://doi.org/10.1126/science.237.4818.1020

Conover, J. H. (1966). Anomalous cloud lines. *Journal of the Atmospheric Sciences*, 23(6), 778–785. https://doi.org/10.1175/1520-0469(1966)023<0778:ACL>2.0.CO;2

Gerber, H. (1996). Microphysics of marine stratocumulus clouds with two drizzle modes. *Journal of the Atmospheric Sciences*, 53(12), 1649–1662. https://doi.org/10.1175/1520-0469(1996)053<1649:MOMSCW>2.0.CO;2

Grosvenor, D. P., Sourdeval, O., Zuidema, P., Ackerman, A., Alexandrov, M. D., Bennartz, R., et al. (2018). Remote sensing of droplet number concentration in warm clouds: A review of the current state of knowledge and perspectives. *Reviews of Geophysics*, 56, 409–453. https://doi.org/10.1029/2017RG000593

Gryspeerdt, E., Goren, T., Sourdeval, O., Quaas, J., Mölmenstädt, J., Dippu, S., et al. (2019). Constraining the aerosol influence on cloud liquid water path. *Atmospheric Chemistry and Physics*, 19(8), 5331–5347. https://doi.org/10.5194/acp-19-5331-2019

Gryspeerdt, E., Quaas, J., & Bellouin, N. (2016). Constraining the aerosol influence on cloud fraction. *Journal of Geophysical Research: Atmospheres*, 121(7), 3566–3583. https://doi.org/10.1002/2015JD023744

Kauffman, Y. J., Koren, I., Remer, L. A., Rosenfeld, D., & Rudich, Y. (2005). The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean. *PNAS*, 102(32), 11,207–11,212. https://doi.org/10.1073/pnas.0505191102

Kawamoto, K., Nakajima, T., & Nakajima, T. Y. (2001). A global determination of cloud microphysics with AVHRR remote sensing. *Journal of Climate*, 14(9), 2054–2068. https://doi.org/10.1175/1520-0442(2001)014<2054:GDOMC>2.0.CO;2

King, M. D., Platnick, S., Menzel, W. P., Ackerman, S. A., & Huibanks, P. A. (2013). Spatial and temporal distribution of clouds observed by MODIS onboard the Terra and Aqua satellites. *IEEE Transactions on Geoscience and Remote Sensing*, 51(7), 3826–3852. https://doi.org/10.1109/TGRS.2012.2277333

Kokhanovsky, A., & Rozanov, V. V. (2012). Droplet vertical sizing in warm clouds using passive optical measurements from a satellite. *Atmospheric Measurement Techniques*, 5(3), 517–528. https://doi.org/10.5194/amt-5-517-2012
Lebock, M., Morrison, H., & Gettelman, A. (2013). Microphysical implications of cloud-precipitation covariance derived from satellite remote sensing. *Journal of Geophysical Research: Atmospheres*, 118(1), 6521–6533. https://doi.org/10.1002/jgrd.50347

Lu, C., Liu, Y., Niu, S., & Vogelmann, A. M. (2012). Observed impacts of vertical velocity on cloud microphysics and implications for aerosol indirect effects. *Geophysical Research Letters*, 39(21), L21808. https://doi.org/10.1029/2012GL053599

Matsui, T., Masunaga, H., Kreidenweis, S. M., Pielke, R. A., Tao, W.-K., Chin, M., & Kaufman, Y. J. (2006). Satellite-based assessment of marine low cloud variability associated with aerosol, atmospheric stability, and the diurnal cycle. *Journal of Geophysical Research: Atmospheres*, 11(1D1), 1042. https://doi.org/10.1029/2005JD006097

Nagao, T. M., Suzuki, K., & Nakajima, T. Y. (2013). Interpretation of multiwavelength-retrieved droplet effective radii for warm water clouds in terms of in-cloud vertical inhomogeneity by using a spectral bin microphysics cloud model. *Journal of the Atmospheric Sciences*, 70, 2376–2392. https://doi.org/10.1175/JAS-D-12-0225.1

Nakajima, T., Higurashi, A., Kawamoto, K., & Penner, J. E. (2001). A possible correlation between satellite-derived cloud and aerosol microphysical parameters. *Geophysical Research Letters*, 28(7), 1171–1174. https://doi.org/10.1029/2000GL001218

Nakajima, T., & King, M. D. (1990). Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements. Part I: Theory. *Journal of the Atmospheric Sciences*, 47(15), 1878–1893. https://doi.org/10.1175/1520-0469(1990)047<1878:DOTOTA>2.0.CO;2

Nakajima, T., Suzuki, K., Nakajima, T. Y., & Stephens, G. L. (2010). A study of microphysical mechanisms for correlation patterns between droplet radius and optical thickness of warm clouds with a spectral bin microphysics cloud model. *Journal of the Atmospheric Sciences*, 67(4), 1126–1141. https://doi.org/10.1175/2009JAS3283.1

Tanaka, K., Okamura, Y., Mokuno, M., Amano, T., & Yoshida, J. (2018). First year on-orbit calibration activities of SGCL on GCOM-C satellite, *Proc. SPIE 10761, Earth Observing Missions and Sensors: Development, Implementation, and Characterization V*, 10761, p. 107610Q (23 October 2018). https://doi.org/10.1117/12.2324703
Toll, V., Christensen, M., Quaas, J., & Bellouin, N. (2019). Weak average liquid-cloud-water response to anthropogenic aerosols. Nature, 572(7767), 51–55. https://doi.org/10.1038/s41586-019-1423-9

Twomey, S., & Cocks, T. (1982). Spectral reflectance of clouds in the near-infrared: Comparison of measurements and calculations. Journal of the Meteorological Society of Japan. Ser. II, 60(1), 583–592. https://doi.org/10.2151/jmsj1965.60.1_583

Twomey, S., & Seton, K. J. (1980). Inferences of gross microphysical properties of clouds from spectral reflectance measurements. Journal of the Atmospheric Sciences, 37(5), 1065–1069. https://doi.org/10.1175/1520-0469(1980)037<1065:IOGMPO>2.0.CO;2

Yuan, T., Wang, C., Song, H., Platnick, S., Meyer, K., & Oreopoulos, L. (2019). Automatically finding ship tracks to enable large-scale analysis of aerosol-cloud interactions. Geophysical Research Letters, 46(13), 7726–7733. https://doi.org/10.1029/2019GL083441

Zhang, Z., Ackerman, A. S., Feingold, G., Platnick, S., Pincus, R., & Xue, H. (2012). Effects of cloud horizontal inhomogeneity and drizzle on remote sensing of cloud droplet effective radius: Case studies based on large-eddy simulations. Journal of Geophysical Research: Atmospheres, 117(19). D19208. https://doi.org/10.1029/2012JD017655

Zhang, Z., & Platnick, S. (2011). An assessment of differences between cloud effective particle radius retrievals for marine water clouds from three MODIS spectral bands. Journal of Geophysical Research: Atmospheres, 116(20), D20215. https://doi.org/10.1029/2011JD016216

Zhang, Z., Song, H., Ma, P.-L., Larson, V. E., Wang, M., Dong, X., & Wang, J. (2019). Subgrid variations of the cloud water and droplet number concentration over the tropical ocean: Satellite observations and implications for warm rain simulations in climate models. Atmospheric Chemistry and Physics, 19(2), 1077–1096. https://doi.org/10.5194/acp-19-1077-2019