JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, D00A02, doi:10.1029/2007JD009596, 2008

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Studying the vertical variation of cloud droplet effective radius using ship and space-borne remote sensing data

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Received 12 November 2007; revised 28 February 2008; accepted 2 May 2008; published 25 July 2008.

[1] The albedo of marine stratocumuli depends upon cloud liquid water content, droplet effective radius (r_e), and how these parameters vary with height. Using satellite data and shipborne data from the East Pacific Investigation of Climate (EPIC) Stratocumulus Study, this study investigates the cloud r_e vertical variation for drizzling and nondrizzling clouds. Visible/near-infrared retrievals from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) are used to estimate the vertical profile of r_e. MODIS r_e observations and collocated shipborne scanning C-band precipitation radar data show that r_e generally increases with height in nondrizzling clouds, consistent with aircraft observations. It is found that in clouds with precipitation rates greater than a few hundredths of a mm h^{-1} the vertical gradient of r_e is significantly less than that in nondrizzling clouds and can become negative when the drizzle is heavier than approximately 0.1 mm h^{-1}. High values of r_e at drizzling cloud base are consistent with estimates of the ratio of liquid water in the drizzle drops to that in the cloud droplets. C-band derived cloud base precipitation rates are found to be better correlated with r_e at cloud base than with r_e at cloud top, suggesting that passive remote sensing may be useful for drizzle detection.

Citation: Chen, R., R. Wood, Z. Li, R. Ferraro, and F.-L. Chang (2008), Studying the vertical variation of cloud droplet effective radius using ship and space-borne remote sensing data, *J. Geophys. Res.*, *113*, D00A02, doi:10.1029/2007JD009596.

1. Introduction

[2] Low-level stratiform liquid water clouds have a significant influence on the Earth's climate due to their strong shortwave radiative forcing [*Greenwald et al.*, 1995]. Such clouds cover large regions of the Earth's oceans [*Klein and Hartmann*, 1993]. The shortwave optical depth of liquid water clouds depends upon both the bulk condensate amount and the size of the cloud drops. Dependence on the latter is conveniently expressed as an effective radius which is the ratio of the third to second moments of the cloud droplet size distribution.

[3] The vertical variation of cloud droplet effective radius (r_e) is an important cloud property which reflects both condensation and coalescence growth. There are different ways to obtain information on the vertical profile of cloud r_e, including in situ aircraft measurements [e.g., *Martin et al.*, 1994; *Wood*, 2000; *Miles et al.*, 2000] and new retrievals from satellite measurements of solar reflectance [*Chang and Li*, 2002]. The aircraft measurements in low clouds show that r_e generally increases with height for nondrizzling clouds [*Martin et al.*, 1994; *Miles et al.*, 2000; *Wood*, 2000] but that drizzle drops start to increase the effective radius significantly if the liquid water content of drizzle drops is above 5–10% of the liquid water content of small cloud droplets [*Wood*, 2000]. These drizzle droplets thus reduce the vertical gradient and even lead to r_e decreasing with height because drizzle drops tend to increase in size toward the base of the cloud [*Wood*, 2005a]. However, only limited work has been carried out to examine the vertical profile of effective radius in drizzling low clouds. Drizzle commonly occurs in marine low clouds and its effects upon cloud optical properties are very poorly understood [*Albrecht*, 1989; *Wood*, 2005a; *Comstock et al.*, 2004; *VanZanten et al.*, 2005].

[4] Satellite observation is the only practical way to infer cloud r_e globally. Solar reflectance measurements from a visible channel and a near infrared (NIR) channel are widely used to estimate cloud optical depth and cloud top r_e [*Nakajima and King*, 1990; *Han et al.*, 1994]. Using radar and a solar/infrared radiometer on board the Tropical Rainfall Measuring Mission (TRMM), *Kobayashi* [2007] found that cloud r_e of precipitating clouds is obviously larger than that for nonprecipitating clouds. In previous studies, cloud r_e retrievals have used three NIR channels, which have wavelengths of $\lambda = 1.6$ μm, 2.1 μm, and 3.7 μm [*King et al.*, 2003]. Because clouds absorption is different at the three wavelengths, the NIR channels have different reflectance weighting functions from cloud top to cloud

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0148-0227/08/2007JD009596$09.00

base. *Platnick* [2000] found the weighting function for λ = 3.7 μm is mainly confined to the cloud top layer (i.e., within optical depth 2) and sharply decrease toward cloud base, while the weighting function at λ = 1.6 μm spreads more evenly into the lower cloud layer (i.e., for a cloud with optical depth equal to 8, the weighting function value at cloud base is around half of its maximum value). Consequently, the λ = 3.7 μm retrieval corresponds to the r_e close to the top of the cloud layer, whereas the λ = 2.1 μm and λ = 1.6 μm retrievals are sensitive to r_e values deeper inside the cloud. Assuming that the r_e has a linear distribution in the vertical direction, *Chang and Li* [2002, 2003, hereinafter referred to as CL] present a method to determine an optimal linear r_e profile by using a combination of NIR measurements at λ = 3.7μm, 2.1 μm, and 1.6μm. The linear r_e assumption is based on many r_e profile measurements worldwide [*Miles et al.*, 2000; *Wood*, 2000; *Brenguier et al.*, 2000].

[5] Applying the CL algorithm to reflectance measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA Aqua satellite, *Chen et al.* [2007] conducted a preliminary study to show that the distributions of r_e profile are different for drizzling and nondrizzling clouds. However, the definition of drizzling used in their study was based on an empirical threshold of liquid water path (LWP), which is retrieved from brightness temperature measurements from the Advanced Microwave Scanning Radiometer (AMSR-E) on Aqua. The threshold-based detection of drizzling suffers from an ambiguity caused by cloud LWP (i.e., it is not clear how to separate the detected LWP into cloud and rain components) and has difficulty detecting light drizzle [*Zuidema et al.*, 2005]. Failure to detect light drizzle could also be caused by the nearly 100 km^2 field of view size of AMSR-E 37 GHZ channel, which is the primary channel used in LWP estimation [*Ashcroft and Wentz*, 2000].

[6] In this study, measurements from the East Pacific Investigation of Climate (EPIC) Stratocumulus Study are used for cloud profile analysis. Coincident radiance measurements from MODIS on the Terra satellite are used to estimate the r_e profile with the CL algorithm. Through a synergistic analysis of radar reflectivity profile measured by a millimeter cloud radar (MMCR), drizzle measurements from a scanning C-band radar, and satellite estimation of the (assumed linear) r_e profile, the vertical variation of cloud r_e is estimated for both drizzling and nondrizzling clouds. Such analysis was not possible in previous studies because of the lack of observation of cloud r_e profile and drizzle. The estimation of vertical r_e variation and how it depends upon the drizzle rate provide useful information for drizzle detection, cloud modeling, and climate studies (i.e., study of aerosol indirect effect).

[7] Section 2 introduces the instruments that are used in this study and the data processing methods. The uncertainties of the data from these instruments are also discussed. In section 3, estimates of the partitioning of liquid water content between drizzle drops and small cloud droplets is carried out using MMCR data in drizzling stratocumulus by incorporating simultaneous LWP estimates from a passive microwave radiometer. Drizzle precipitation rates obtained from the C-band radar and spatiotemporally matched r_e profile estimation from MODIS satellite measurements are combined to evaluate the impact of drizzle on the trend of vertical r_e variation. Section 4 summarizes the result of this study, discusses the potential of profile retrieval on drizzle detection, and presents further research need to be done in the future.

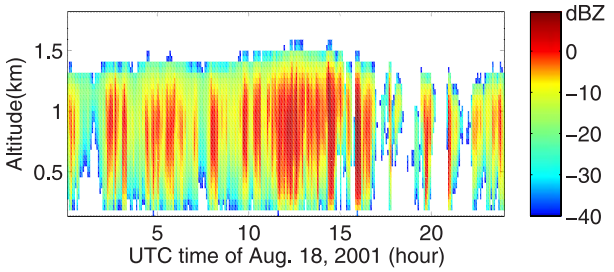

Figure 1. Millimeter cloud radar reflectivity measurements on 18 October 2001.

2. Data and Methods

[8] The EPIC Stratocumulus Study [*Bretherton et al.*, 2004] was conducted in October 2001 within the southeastern Pacific stratocumulus region. From 16 to 22 October, the NOAA research vessel R/V *Ronald Brown* (RHB) was stationary at 20°S, 85°W and observed a relatively well-mixed boundary layer with predominantly overcast skies and few upper level clouds. Comprehensive cloud and precipitation measurements were taken by vertically pointing remote sensing instruments on the RHB. This investigation uses cloud profile and drizzle estimates at 20°S, 85°W from EPIC instruments, as well as r_e profile estimation from spatiotemporally matched data from MODIS on Terra.

2.1. Cloud Measurements From Millimeter Radar, Ceilometer, and Microwave Radiometer

[9] Cloud reflectivity profiles are provided by vertically pointing 8.6mm wavelength radar (MMCR), which has a vertical resolution of 45 m [*Moran et al.*, 1998]. The beam width is 0.5° and the minimum detectable reflectivity is around −60 dBZ. The radar obtains a reflectivity profile every 10 s, but the reflectivity profile measurements are averaged to a 5 min temporal resolution for this study (equivalent to approximately 5 km horizontal spatial resolution). The calibration error of MMCR data are less than 1 dBZ. *Comstock et al.* [2004] showed that the uncertainty of the MMCR radar measurements caused by Mie scattering is less than 10% for stratocumulus clouds given the mean radii of cloud and drizzle drops encountered in EPIC. Cloud top height is determined using a reflectivity threshold of −40 dBZ to define cloud, a value that leads to cloud top heights very close to the height of the inversion base as determined using radiosondes (not shown). The cloud base height is measured using a ceilometer with 15 m vertical resolution. The LWP is estimated from brightness temperature measurements of a microwave radiometer at 22 GHz and 31 GHz [*Zuidema et al.*, 2005]. The uncertainty of the LWP estimation is around 10−25 g^{-2}. Figure 1 shows an example of MMCR reflectivity measurements for a 24 h period (18 October 2001) in which significant drizzle was observed to fall [see *Comstock et al.*, 2004]. In this study,

estimates of the partitioning of liquid water content between drizzle drops and small cloud droplets is carried out using MMCR data in stratocumulus by incorporating simultaneous LWP estimates from a passive microwave radiometer.

2.2. Estimates of Drizzle From Scanning C-Band Radar

[10] The C-band radar on the RHB has a 5 cm wavelength and 0.95° beam width. During EPIC, the C-band completed an 11-elevation angle volumetric scan out to 30 km radius every 5 min [*Comstock et al.*, 2004]. Reflectivity between 0.5 km and 2 km altitude is averaged to produce two-dimensional maps with an estimated calibration error of ±2.5 dBZ. The minimum detectable reflectivity is approximately −12 dBZ at 30 km distance. Because of its sensitivity, C-band measurements in low water clouds are only sensitive to drizzle, as cloud liquid water content cannot produce the reflectivity at sufficient magnitude to be detected. In this study, the cloud base precipitation rate is estimated using $Z = 25R^{1.3}$, where Z is the radar reflectivity in mm^6m^{-3}, and R is the rain rate in mm h^{-1}. This $Z - R$ relationship was derived using vertically pointing MMCR data in drizzling stratocumulus during EPIC [*Comstock et al.*, 2004] and consistent with aircraft in situ measurements in drizzling stratocumulus [*Wood*, 2005b]. The C-band measurements are compared with the r_e profile retrieval from MODIS on Terra described below.

2.3. Cloud Profile Retrieval Using MODIS

[11] MODIS L1B reflectance measurements at $\lambda = 0.86$ μm, 1.6 μm, 2.1 μm, and 3.7 μm from Terra satellite are used to estimate cloud optical depth, the r_e profile, and the LWP using the CL algorithm at a nadir resolution of 1×1 km^2. Only daytime MODIS measurements are used in this study because solar reflectance measurements are needed for retrieving cloud parameters. The Terra overpass time is close to 1600 UTC at 20°S, 85°W, when the solar zenith angle is between 20° and 30° during October. The satellite zenith angle of MODIS ranges between −55° and 55°.

[12] In the CL algorithm, the linear r_e profile is defined as a function of height z, which is defined by

$$r_e(z') = r_{e1} + (r_{e2} - r_{e1})z', \tag{1}$$

where $z' = (z - z_{\text{top}})/(z_{\text{base}} - z_{\text{top}})$ denotes the fractional cloud height with $z' = 0$ for the cloud top and $z' = 1$ for the cloud base. Thus, the linear r_e profile is parameterized by r_{e1} at $z' = 0$ and r_{e2} at $z' = 1$ representing the cloud top and cloud base r_e, respectively. The retrievals of r_{e1} and r_{e2} are determined by matching the MODIS measurements with radiative transfer calculations at 3.7, 2.1, and 1.6 μm. *Chang and Li* [2002] analyzed the potential biases associated with the assumption of a linear r_e profile and those arising from reflectance error. They showed that the linear r_e profile retrieval works best for cloud optical depths ranging between 10 and 28. The retrieval mean biases are on the order of 1 μm for cloud top and slightly larger for cloud base if the r_e profile has a close-to-linear variation. However, if the r_e variation is very nonlinear, large biases may be incurred, in particular for cloud base r_e. Also when clouds have large optical depth (>28), the quality of r_e profile estimation does not change much for cloud top but gets much worse for cloud base because the signal from cloud base is weak for thick clouds. Over all, the uncertainties in r_{e2} are typically 2−3 times larger than the uncertainties in r_{e1}.

[13] Traditionally, with the assumption that r_e is vertically constant, cloud LWP is derived as given by

$$LWP = \frac{4\rho_w}{3Q_e}\tau r_e, \tag{2}$$

Here, τ is the cloud optical depth, ρ_w is the density of liquid water, Q_e (=2) is the extinction efficiency. Previously, r_e retrieved with reflectance measurements using a single NIR channel have been used to calculate LWP with equation (2). As discussed earlier, the r_e retrieved from a single NIR channel like 3.7 μm is more sensitive to the layer near the cloud top, which can cause biases in LWP calculations for cloud with vertical r_e variation. In the CL algorithm, cloud optical depth is retrieved from MODIS 0.86-μm reflectance measurement for clouds over ocean and LWP is calculated with the linear r_e profile estimation. *Chen et al.* [2007] showed that MODIS LWP estimation using CL algorithm is consistent with LWP retrieved from AMSR-E microwave observations (i.e., correlation coefficient is around 0.9 for overcast clouds with warm top) and LWP calculation with r_e profile corrects the biases caused by the assumption of vertically constant r_e.

2.4. Spatial and Temporal Matching of MODIS and C-Band Data

[14] For each RHB location covered by a MODIS scan (a total of five MODIS overpasses during the 6 d during EPIC), the r_e profile retrievals are compared with coincident RHB scanning C-band radar measurements. MODIS provides instantaneous measurements, while the temporal resolution of the C-band radar is 5 min. To alleviate the influence of the small, but nonnegligible, temporal gap between the two instruments, both MODIS data and C-band data are aggregated and averaged within 5×5 km boxes. We aggressively discard aggregated samples that are not fully overcast by insisting that all 25 pixels must contain cloud. There are large uncertainties and ambiguities in retrieval of effective radius if the clouds are very thin (i.e., optical thickness is less than 4) [*Nakajima and King*, 1990]. In this study, to ensure reliable retrieval of cloud parameters, the optical depths for all cloudy pixels are required to be larger than 4. These constraints have been applied to ensure that as many broken, thin, and highly heterogeneous MODIS pixels (i.e., those most likely to violate the plane-parallel retrieval assumption) are not included in the analysis.

[15] The C-band radar measurements are compared with the r_e profile retrieval from MODIS on board Terra satellite. As an example of these data, Figure 2 shows coincident images of C-band radar reflectivity, MODIS r_e profile retrieval (i.e., r_{e1} and r_{e2}) and MODIS LWP estimates at 1555 UTC of 18 October 2001, a period of strong drizzle also shown in the MMCR data (Figure 1). Data in which cloud is not present or broken, as detailed above, are blanked out. There is considerable heterogeneity in the precipitation field but it is clear that regions of strong drizzle (large Z) are generally associated with higher LWP

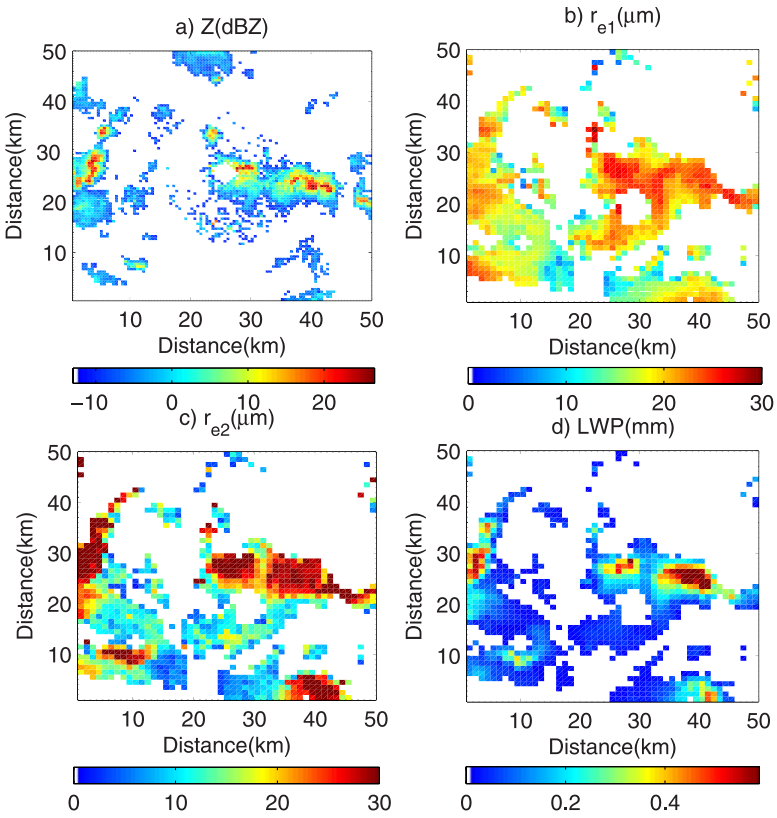

Figure 2. Coincident images of C-band radar reflectivity and MODIS cloud profile at UTC 1555, 18 October 2001. (a) RHB C-band radar reflectivity image. (b) MODIS estimation of droplet effective radius at cloud top (r_{e1}). (c) MODIS estimation of droplet effective radius at cloud base (r_{e2}). (d) MODIS LWP estimation.

and large drops at cloud base (i.e., large r_{e2}). There is also a correlation of Z with the cloud top effective radius r_{e1} but it is not as clear as with r_{e2}. This is consistent with the idea that, for heavy drizzle, the drizzle drops themselves may be directly impacting the drop effective radius close to the cloud base. We return to this issue in section 3.2.

3. Results

3.1. MMCR Reflectivity Profile and Estimates of the Partitioning of Liquid Water Content Between Drizzle Drops and Small Cloud Droplets

[16] Figure 3 shows the scatterplot of mean radar reflectivity Z over the upper third ($0 < z' < 1/3$) and lower third ($2/3 < z' < 1$) of the cloud layer, with z' determined using the cloud top and base heights from the MMCR and ceilometer, respectively. The column maximum reflectivity is shown by the color of the data samples. Radar reflectivity Z depends the sixth moment of the cloud and drizzle size distribution. Radar reflectivity thresholds for drizzle detection generally range between −20 dBZ and −15 dBZ in previous studies [*Sauvageot and Omar*, 1987; *Wang and Geerts*, 2003; *Kogan et al.*, 2005]. For drizzling clouds, the reflectivity due to precipitation drops starts to overwhelm that due to cloud droplets and corresponds to precipitation rates of only a few thousandths of a mm hr^{-1}. Thus even modest amounts of precipitation can overwhelm the radar signal due to cloud droplets [*Fox and Illingworth*, 1997] even when the drizzle has limited effect on the overall liquid water content and effective radius of the cloud. Figure 3 shows that cloud top Z is greater than cloud base Z for nondrizzling clouds (i.e., column maximum reflectivity is

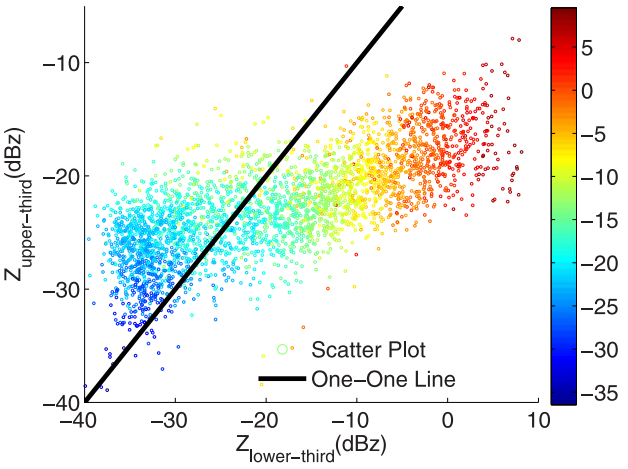

Figure 3. Scatterplot of reflectivities over upper 1/3 portion of cloud layer ($Z_{upper-third}$) and reflectivities over lower 1/3 portion of cloud layer ($Z_{lower-third}$). Color of the scatterplots represents the column maximum radar reflectivity. The data is from MMCR.

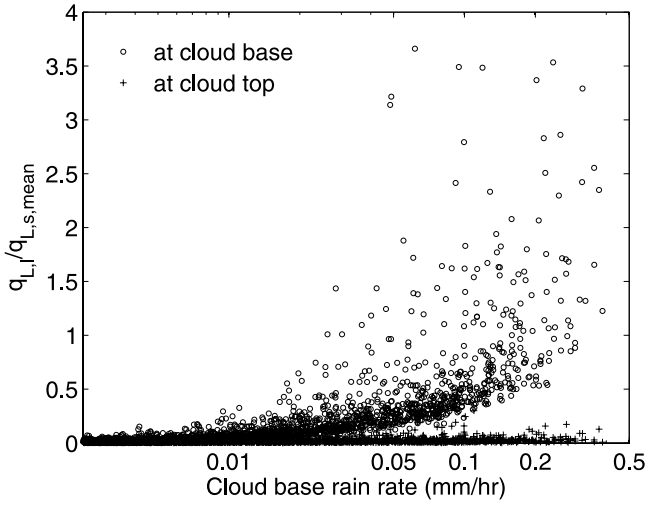

Figure 4. Scatterplot of the ratio between the liquid water content of drizzle drops ($q_{L,l,}$) and the column mean liquid water content of small droplets ($q_{L,s,mean}$) versus rain rate at cloud base. Circles represent $q_{L,l,base}/q_{L,s,mean}$ at cloud base and pluses represent $q_{L,l,top}/q_{L,s,mean}$ at cloud top. The estimates are made with data from shipborne MMCR and microwave radiometer.

−30 dBZ), while the opposite is true for drizzling clouds (i.e., column maximum reflectivity is −10 dBZ) (a result consistent with *Comstock et al.* [2004, Figure 4]). For nondrizzling clouds, cloud droplet size and number concentration determines *Z,* and its increase with height is caused primarily by condensational growth of cloud droplets. Drizzle drops dominate radar reflectivity in drizzling clouds. Aircraft observations [*Wood*, 2005a] show that in drizzling stratocumulus the precipitation rate tends to be roughly constant in the lowest two thirds of the cloud layer before decreasing rapidly above this. For drizzling clouds in Figure 3, the large reflectivity in the lower portion of the cloud layer is caused by drizzle at cloud base, while the small radar reflectivity at upper portion of cloud layer is consistent with there being much less drizzle near cloud top.

[17] *Wood* [2000] found that drizzle drops start to increase effective radius significantly if $\phi = q_{L,l}/q_{L,s}$ is above 0.1, where $q_{L,l}$ is the liquid water content of large drops ($r >$ 20 μm) and $q_{L,s}$ is the liquid water content of small ($r <$ 20 μm) cloud droplets. His study found that it is possible to parameterize the impact of drizzle drops on effective radius as

$$\frac{r_e}{r_{e,s}} \approx \frac{(1+\phi)^{\frac{2}{3}}}{\left\{1+0.2\left(\frac{k_l}{k_s}\right)^{\frac{1}{3}}\phi\right\}} \tag{3}$$

where r_e is the effective radius for all droplets, $r_{e,s}$ is the effective radius for small cloud droplets, k_l is the ratio between the cubes of the volume and effective radius for large drops, and k_s is the ratio between the cubes of the volume and effective radius for small droplets. In his study, k_l is parameterized as 2/9 (the exact value for an exponential distribution to which populations of drizzle drops adhere quite closely [*Wood*, 2005b]) and k_s ranges between approximately 0.6 and 0.9 [e.g., *Martin et al.*, 1994]. On the basis of equation (3), with the assumption of k_s equal to 0.75, the drizzle drops would increase r_e by 40% for $\phi = 1$ and 10% for $\phi = 0.2$. With the MMCR reflectivity profile and the LWP estimation from RHB microwave radiometer, liquid water content of drizzle drops and liquid water content of small cloud droplets can be roughly estimated. The liquid water content of drizzle drops at cloud base is estimated with $q_{L,l} = \rho R/w_T$, where R is cloud base precipitation rate, ρ is the density of water, and w_T is the mass-weighted fall speed of drizzle drops. Using a typical fall speed of 0.4m s^{-1} for drizzle drops (consistent with the aircraft data of *Wood* [2005a] for which w_T is in the range 0.2−0.6 m s^{-1}), the drizzle liquid water content would be $q_{L,l} \approx 0.69R$ in g m^{-3}. The rain rate profile can be estimated from the MMCR reflectivity profile with $Z = 25\ R^{1.3}$ [*Comstock et al.*, 2004]. Thus, the LWP contributed by drizzle drops (LWP_l) is the vertical integral of $0.69R$ over the depth of the precipitating layer, and LWP contributed by small cloud droplets (LWP_s) is estimated by subtracting LWP_l from total LWP estimated with RHB microwave radiometer measurements. The mean liquid water content of small droplets ($q_{L,s,mean}$) can be estimated from the mean LWP_s over the cloud depth. Figure 4 shows estimated $q_{L,l,base}/q_{L,s,mean}$ and $q_{L,l,top}/q_{L,s,mean}$ against R_{cb}, where $q_{L,l,base}$ is the liquid water content of drizzle drops at cloud base, $q_{L,l,top}$ is the liquid water content of drizzle drops at cloud top, and R_{cb} is the rain rate at cloud base. It is shown that the $q_{L,l,base}/q_{L,s,mean}$ grows from <0.1 at $R_{cb} < 0.01$ mm h^{-1} to >1 as R_{cb} reaches a few tenths of a mm h^{-1}, while $q_{L,l,top}$ is always much smaller than $q_{L,s,mean}$. Because the radius of small cloud droplets generally increases with height, $q_{L,s}$ at cloud base is expected to be less than $q_{L,s,mean}$ and $q_{L,l}/q_{L,s}$ at cloud base is expected to be larger than $q_{L,l,base}/q_{L,s,mean}$ and so the ratios of drizzle to cloud liquid water presented in Figure 4 are representative of the cloud as a whole and most likely underestimate the impact of drizzle close to cloud base. In any case, taken together with equation (3), such ratios are consistent with drizzle having an impact on the effective radius when the precipitation rate exceeds a few hundredths of a mm h^{-1}. It is remarkable that for even relatively modest precipitation rates, a significant fraction of the liquid water content in stratocumulus clouds can reside in drizzle-sized drops. The impacts of drizzle upon r_e at cloud base could significantly change the trend of vertical r_e variation because there are not many drizzle drops at cloud top. Using the r_e profile estimated from satellite reflectance measurements, the following section assesses the impact of drizzle drops on vertical r_e variation in detail.

3.2. Satellite Estimates of the r_e Profile for Drizzling and Nondrizzling Clouds

[18] Figure 5 shows the C-band precipitation rate against the MODIS-derived droplet effective radius at cloud top r_{e1} and cloud base r_{e2} for the spatially matched data set from EPIC. A threshold of −12 dBZ (minimum detectable reflectivity of the C-band radar) is used to classify the 5 × 5 km regions into either drizzling or nondrizzling. Statistics of r_{e1} and r_{e2} are shown in Table 1. Both r_{e1} and r_{e2} are larger for drizzling clouds than for nondrizzling clouds, with a threshold for drizzle of approximately 15 μm in r_{e1}

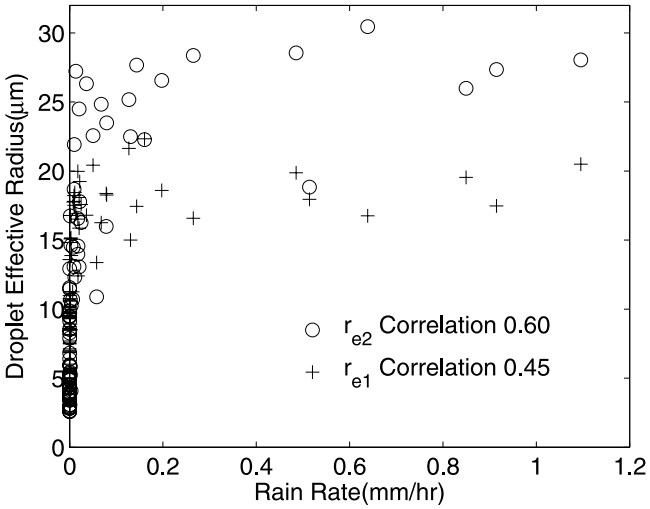

Figure 5. Scatterplot between rain rates and cloud droplet effective radius. Here r_{e1} is droplet effective radius at cloud top and r_{e2} is droplet effective radius at cloud base. The estimates are made with data from MODIS and C-band radar.

consistent with earlier in situ studies [e.g., *Gerber*, 1996]. However, r_{e2} shows a greater contrast between drizzling clouds and nondrizzling clouds. The mean value of r_{e1} is 9.6 μm for nondrizzling cloud and 17.1 μm for drizzling clouds, while the mean value of r_{e2} is 6.3 μm for nondrizzling cloud and 20.8 μm for drizzling clouds. The correlation coefficient with rain rate is 0.45 for r_{e1} and is 0.60 for r_{e2}. The reason that r_{e2} is better correlated with rain rate is that the drizzle drops at cloud base increase the effective radius. On the other hand, drizzle decreases markedly toward the cloud top. The correlation between precipitation rate and cloud top effective radius is therefore expected not because the precipitation itself contributes to r_e but because clouds with large drops near their tops will be more prone to collision-coalescence which ultimately manifests itself as greater precipitations rates lower down in the cloud.

[19] Figure 6 shows the scatterplot between r_{e1}/r_{e2} and coincident rain rate. Values of r_{e1} are generally larger than r_{e2} for nondrizzling clouds and the mean value of r_{e1}/r_{e2} is 1.61 for nondrizzling clouds. The ratio decreases as the clouds start to drizzle and can become less than unity if drizzle is heavy (i.e., larger than 0.2mm h^{-1}). The mean rain rate is 0.04 mm $h^{-1}$for drizzling clouds with $r_{e1}/r_{e2} > 1$ and 0.18 mm h^{-1} for drizzling clouds with $r_{e1}/r_{e2} < 1$. The mean value of r_{e1}/r_{e2} is 0.92 for drizzling cloud. The correlation coefficient between r_{e1}/r_{e2} and rain rate is -0.43.

[20] Using rain rate estimation from the C-band radar and LWP from MODIS, we can make a rough estimate of $q_{L,l}/q_{L,s}$ using the same method as in section 3.1. Figure 7 shows a plot of the precipitation rate against LWP. For drizzling cloud, the mean rain rate is 0.15 mm h^{-1} and the mean cloud LWP is 0.16 mm. As discussed in section 3.1, the drizzle liquid water content would be 0.69R in g m^{-3}. The 0.15 mm h^{-1} mean rain rate in Figure 7 means a drizzle liquid water content of $q_{L,l}$ of $\sim$0.10 g m^{-3}. The average thickness of a drizzling cloud is around 0.6 km for the data used in this study (estimated with MMCR and ceilometer). For an average cloud LWP of 0.16 mm in Figure 7, the average cloud liquid water content ($q_{L,l} + q_{L,s}$) is around 0.25 g m^{-3} and $q_{L,s}$ would be around 0.15 g m^{-3} after the 0.10 g m^{-3} $q_{L,l}$ is subtracted. Considering that $q_{L,s}$ at cloud base is less than $q_{L,s}$ at cloud top because r_{e1}/r_{e2} is larger than 1 without contribution from drizzle drops, $q_{L,s}$ would be in the same order of magnitude as $q_{L,l}$ at cloud base for the average rain rate of 0.15 mm h^{-1}. Certainly, $q_{L,l}$ would be smaller than $q_{L,s}$ when the drizzle is light (i.e., 0.01 mm h^{-1}) and would be larger than $q_{L,s}$ when the drizzle is high (i.e., 0.5 mm h^{-1}).

[21] The above comparison of $q_{L,l}$ with $q_{L,s}$ indicates that, for the drizzling clouds in Figure 6, we expect a significant amount of drizzle liquid water content close to cloud base, especially when the precipitation rate exceeds about 0.1 mm h^{-1}. Given that the drizzle drops start to increase effective radius significantly if $q_{L,l}/q_{L,s}$ is above 0.1, the neutralization and conversion of the trends of r_e vertical variation by drizzle drops in Figure 6 is consistent with theoretical calculations by *Wood* [2000] and with in situ observations [*Martin et al.*, 1994].

[22] *Chen et al.* [2007] also suggested similar impact of drizzle on vertical r_e variation, but in that preliminary study the r_e decreases with height for most precipitating clouds, and could be either increasing or decreasing for nonprecipitating clouds. As previously stated, this investigation found that most nondrizzling clouds have a r_e profile that increases with height and drizzling clouds have r_e profiles that either increase or decrease with height. The differences between the results of the two studies are caused by utilizing different drizzle detection techniques. As stated in section 1, AMSR-E rain detection used in the work of *Chen et al.* [2007] misses light drizzle and possibly some heavy drizzle if the cloud LWP is low. As a result, the drizzle defined by AMSR-E is necessarily heavy drizzle, while the nondrizzling clouds defined by AMSR-E contain both drizzling and nondrizzling clouds.

4. Summary and Future Studies

[23] Using data from the EPIC 2001 Stratocumulus Study, this study investigates the cloud r_e vertical variation for drizzling and nondrizzling clouds. Estimates of the partitioning of liquid water content between drizzle drops and small cloud droplets is carried out using MMCR data in drizzling stratocumulus by incorporating simultaneous LWP

Table 1. Comparison of Cloud Parameters for Raining Clouds and Nonraining Clouds

	r_{e1}(μm)	r_{e2}(μm)	r_{e1}/r_{e2}	Cloud LWP (mm)	Rain Rate (mm h^{-1})
Correlation with rain rate	0.45	0.60	−0.44	0.76	N/A
Mean for nonraining clouds	9.6	6.3	1.61	0.034	0
Mean for raining clouds	17.1	20.8	0.92	0.155	0.149

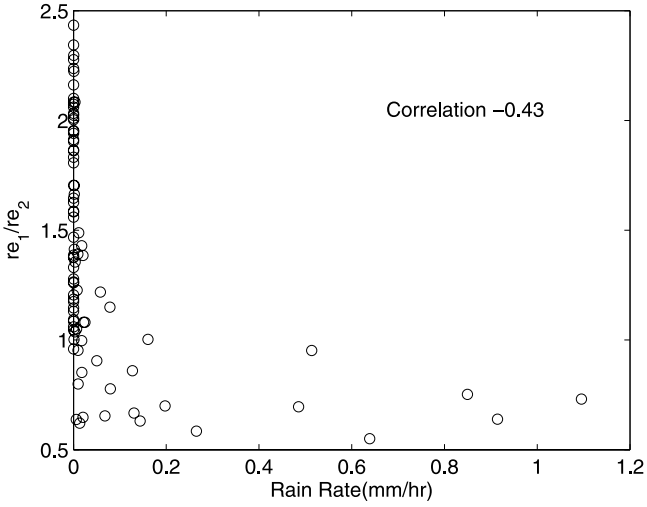

Figure 6. Scatterplot between rain rates and ratio between droplet effective radius at cloud top (r_{e1}) and droplet effective radius at cloud base (r_2). The estimates are made with data from MODIS and C-band radar.

estimates from a passive microwave radiometer. Satellite reflectance measurements from MODIS on the Terra satellite are used to estimate the trend of vertical r_e variation. Using drizzle rates estimated with a scanning C-band radar we show that the cloud r_e can decrease with height in clouds with sufficiently strong drizzle. For nondrizzling clouds, the r_e generally increases with height in accordance with the growth of cloud droplets by condensation. For drizzling clouds, at cloud base, liquid water content of drizzle drops is found to be of comparable magnitude to liquid water content of small cloud droplets when rain rate at cloud base is above a few hundredths of a mm h^{-1}. Both previous theoretical analyses [*Wood*, 2000] and the synergetic observations in this study suggest that drizzle drops can increase r_e significantly at drizzle rates found in low liquid water clouds. Because drizzle is typically found toward the bottom of these clouds, the r_e increase by drizzle drops at cloud base can change the trend of vertical r_e variation and r_e can decrease with height if drizzle is heavy. On the basis of the radar precipitation observations and satellite cloud r_e profile estimation, r_e generally decreases with height when rain rate is above 0.1 mm h^{-1}.

[24] Both r_e at cloud base and r_e at cloud top are shown to have certain distinction between drizzling and nondrizzling clouds: larger for drizzling clouds than for nondrizzling clouds. The distinction is more striking for r_e at cloud base than r_e at cloud top. The r_e at cloud base is also found to be better correlated with rain rate. The finding of this study suggests that the profile of r_e or r_e at cloud base has the potential for drizzle detection in marine low clouds. Drizzle detection is very important in climate studies because drizzle can affect the optical properties of low clouds by changing their macrophysical and microphysical structure [e.g., *Albrecht*, 1989; *Stevens et al.*, 2005; *Wood*, 2007]. It is important to develop methodologies for the detection and quantification of drizzle and other light precipitation in low clouds.

[25] Both space-borne passive microwave observations and solar observations have been used for detection of drizzle. Drizzle detection with passive microwave observation uses the estimation of column LWP, which contains both cloud liquid water and drizzle liquid water. The threshold of LWP for drizzle detection is about 0.2 mm [*Ferraro et al.*, 1996; *Wentz and Spencer*, 1998]. Microwave observation has the advantage of being sensitive to drizzle directly, but the ambiguity caused by cloud liquid water may degrade its performance in detection of light drizzle. *Zuidema et al.* [2005] found that light drizzle is common even at low LWP. Depending upon the microphysical cloud properties such as cloud droplet concentration the column LWP can be very small (i.e., 0.05 mm) for light drizzle with small rain rate (e.g., 0.02 mm h^{-1} [*Wood*, 2005a]). On the other hand, the cloud LWP can be as large as 0.2–0.4 mm even for nondrizzling clouds [*Wood*, 2005a; *Berg et al.*, 2006]. If a 0.2 mm threshold of column LWP is applied for drizzle detection, most light drizzle with rain rate less than 0.1 mm h^{-1} would be missed. Given that typical precipitation rates in marine low clouds range from 0.01 to 0.1 mm h^{-1} [e.g., *Yum and Hudson*, 2002; *Wood*, 2005a], this detection threshold will miss a significant fraction of drizzling clouds over the oceans. Indeed, results from EPIC show that for these clouds approximately 80% of the drizzling area consists of precipitation rates smaller than 0.1 mm h^{-1} and that these weakly drizzling clouds contribute around 25% of the accumulated precipitation at cloud base [*Comstock et al.*, 2004, Figure 9].

[26] Drizzle detection with solar reflectance observations has used cloud r_e retrieved from single NIR channels. The r_e threshold for drizzle detection is about 14 μm in previous studies [*Rosenfeld and Gutman*, 1994; *Han et al.*, 1995]. However, the r_e retrieved from a single NIR channel is biased toward cloud top, whereas most drizzle is found lower down in the cloud. For example, r_e retrieval from 3.7 μm represent most top of the cloud layer, while r_e retrieved from 2.1 μm may represent upper 20% ~40% optical depth of cloud layer with optical depth equal 8 [*Nakajima and King*, 1990]. As previously stated, between drizzling clouds and nondrizzling clouds, there is a

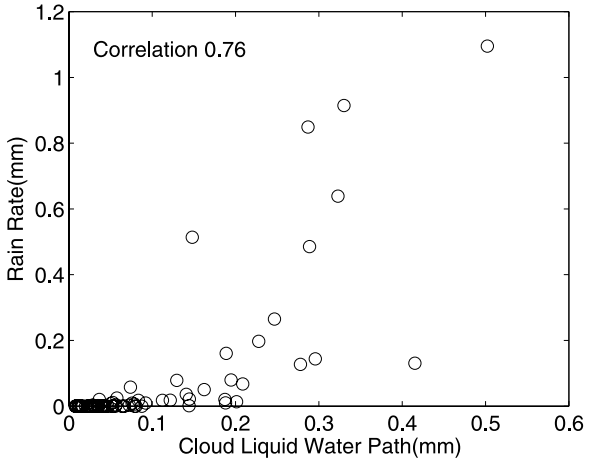

Figure 7. Scatterplot between rain rates and liquid water paths. The estimates are made with data from MODIS and C-band radar.

difference in r_e at cloud top, but a greater contrast in r_e at cloud base due to the drizzle drops at cloud base for drizzling clouds.

[27] Results of this study shows that satellite r_e profile estimation (r_{e2} at cloud base or ratio r_{e1}/r_{e2}) could be used as another method for drizzle detection in marine low clouds. The technique details and the quality of the methods beyond the scope of this study because limited data has been available. Future study on this topic could be done when CloudSat data and more campaign data are available.

[28] **Acknowledgments.** EPIC 2001 was a cooperative effort among many scientists, students, staff, and the crew and officers of the R/V *Ronald H Brown*. The authors appreciate their work of acquiring the EPIC 2001 data used in this study. The authors are grateful to the Goddard DAAC for providing MODIS L1B data. This study is supported by the NOAA's GOES-R risk reduction program, the GOES-R algorithm development program, and a grant from the National Basic Research Program of China (2006CB403702). We are grateful to Sandra Yuter (North Carolina State University) and to Kimberly Comstock for their efforts in producing the C-band radar data set.

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