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Comparison of MODIS cloud microphysical properties with in-situ measurements over the Southeast Pacific

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Abstract. Utilizing the unique characteristics of the cloud over the Southeast Pacific (SEP) off the coast of Chile during the VOCALS field campaign, we compared satellite remote sensing of cloud microphysical properties against in-situ data from multi-aircraft observations, and studied the extent to which these retrieved properties are sufficiently constrained and consistent to reliably quantify the influence of aerosol loading on cloud droplet sizes. After constraining the spatial-temporal coincidence between satellite retrievals and in-situ measurements, we selected 17 non-drizzle comparison pairs. For these cases the mean aircraft profiling times were within one hour of Terra overpasses at both projected and un-projected (actual) aircraft positions for two different averaging domains of 5 km and 25 km. Retrieved quantities that were averaged over a larger domain of 25 km compared better statistically with in-situ observations than averages over a smaller domain of 5 km. Comparison at projected aircraft positions was slightly better than un-projected aircraft positions for some parameters. Overall, both MODIS-retrieved effective radius and LWP were larger but highly correlated with the in-situ measured effective radius and LWP, e.g., for averaging domains of 5 km, the biases are up to 1.75 µm and 0.02 mm whilst the correlation coefficients are about 0.87 and 0.85, respectively. The observed effective radius difference between the two decreased with increasing cloud drop number concentration (CDNC), and increased with increasing cloud geometrical thickness. Compared to the absolute effective radius difference, the correlations between the relative effective radius difference and CDNC or cloud geometric thickness are weaker. For averaging domains of 5 km and 25 km, the correlation coefficients between MODIS-retrieved and in-situ measured CDNC are 0.91 and 0.93 with fitting slopes of 1.23 and 1.27, respectively. If the cloud adiabaticity is taken into account, better agreements are achieved for both averaging domains (the fitting slopes are 1.04 and 1.07, respectively). Our comparison and sensitivity analysis of simulated retrievals demonstrate that both cloud geometrical thickness and cloud adiabaticity are important factors in satellite retrievals of effective radius and cloud drop number concentration. The large variabilities in cloud geometrical thickness and adiabaticity, the dependencies of cloud microphysical properties on both quantities (as demonstrated in our sensitivity study of simulated retrievals), and the inability to accurately account for either of them in retrievals lead to some uncertainties and biases in satellite retrieved cloud effective radius, cloud liquid water path, and cloud drop number concentration. However, strong correlations between satellite retrievals and in-situ measurements suggest that satellite retrievals of cloud effective radius, cloud liquid water path, and cloud drop number concentration can be used to investigate aerosol indirect effects qualitatively.

1 Introduction

The most challenging issues in research to understand the role of aerosols in regional and global climate change are (1) how to assess and quantify the temporal and spatial variability of aerosol direct and indirect effects; and (2) how to scale-up observed microphysical and chemical processes of aerosols and clouds from laboratory or ambient scale to the model scale. The integration of cloud and aerosol processes derived from in-situ measurements with measurements obtained from satellite sensors is an under exploited opportunity to address these issues. Satellites, such as Terra, Aqua, CloudSat, CALIPSO, and TRMM, collectively, provide a comprehensive set of observations on large spatial scales of atmospheric moisture and temperature profiles, cloud and aerosol optical properties, precipitation structure, and radiation fields. This type of integrated data set allows: (1) direct assessment of aerosol and cloud radiative forcing at the top of the atmosphere (TOA); (2) investigation of aerosol-cloud processes in the entire atmospheric column when complemented with in situ observations; (3) evaluation of the influence of large or regional scale environmental conditions, such as aerosol transport, moisture supply, dynamics and thermodynamics on locally observed aerosol-cloud interaction; (4) scale-up of microphysics and chemical measurements of aerosols and clouds (in laboratory or ambient air) to the scales for model evaluation and validation.

Along with in-situ data to study aerosol-cloud interaction, an important prerequisite exercise in the effort to utilize satellite observations is a validation and evaluation of the satellite data itself. A particular focus of this evaluation is to characterize the uncertainties of key retrieved intermediate variables that are encompassed in the aerosol-cloud interaction processes, which are linked to cloud radiative properties. These include aerosol number concentration, cloud condensation nuclei (CCN), cloud drop number concentration (CDNC), cloud effective radius, and optical and geometrical thickness. Accurate measurement of these microphysical/macrophysical variables is a critical first step for any rigorous investigation of aerosol-cloud interaction.

Retrieval algorithms for satellite remote sensing are based on certain assumptions, so investigating the validity of these assumptions with respect to realistic conditions in the atmosphere is an important element of a validation study. Given that the ultimate goal is to apply satellite observations of aerosol-cloud interaction to climate models it is also important to study the consistency of assumptions in retrieval algorithms along with the assumptions in climate model parameterizations as a part of the analysis. For example, both MODIS retrieval algorithms and GCM microphysics-radiation parameterizations assume vertically uniform plane-parallel clouds, but observations show that realistic clouds are vertically stratified and horizontally inhomogeneous. Brenguier et al. (2000) have examined this inconsistency in terms of vertical stratification and found that the equivalent effective radius of a vertically uniform model is between 80 % and 100 % of the effective radius at the top of an adiabatic stratified model. The difference between the two depends upon the cloud geometrical thickness and droplet concentration. Brenguier et al. (2000) further put forward a set of two decoupled physical parameters of crucial importance for studies of the indirect effect and cloud feedback: cloud drop number concentration and cloud geometrical thickness.

For satellite remote sensing, inferring the cloud drop number concentration requires information about the physical thickness of the cloud. Both CDNC and cloud thickness are not directly retrievable from MODIS. Cloud droplet number concentration is derived from cloud liquid water path (LWP) which is the cloud liquid water content (LWC) integrated over the cloud geometrical vertical thickness. Currently, most derivations of CDNC assume that the clouds in question are adiabatic; CDNC is constant, and cloud liquid water content varies with altitude adiabatically, i.e., increasing linearly with increasing altitude. As done by Boers et al. (2006) and Bennartz (2007), we have:

$$\mathrm{CDNC} = \frac{C_\mathrm{w}^{1/2}}{k}\frac{10^{1/2}}{4\pi\rho_\mathrm{w}^{1/2}}\frac{\tau^{1/2}}{R_\mathrm{e}^{5/2}} \tag{1}$$

Where C_w is the moist adiabatic condensate coefficient, and is constant over a short altitude range (Brenguier, 1991). Its value depends slightly on the temperature of the cloud layer, ranging from 1 to $2.5\times10^{-3}\,\mathrm{g\,m^{-4}}$ for a temperature between 0°C and 40 °C. The coefficient k, is the ratio between the volume mean radius and the effective radius, and varies between 0.5 and 1 (Brenguier et al., 2000). ρ_w is cloud water density. τ and R_e are retrieved cloud optical depth and cloud effective radius, respectively.

The cloud geometrical thickness can be estimated from satellite inferred cloud top temperature and re-analysis near-surface air temperature and relative humidity, or directly measured from active cloud radar and lidar sensors (such as CloudSat and CALIPSO). Bennartz (2007) outlined an approach to derive the cloud geometrical thickness, H, from observed cloud liquid water path, also within the framework of an adiabatic cloud model, i.e.,

$$H = \left[2\frac{\mathrm{LWP}}{C_\mathrm{w}}\right]^{1/2} \tag{2}$$

However, the vertical variation assumed in deriving CDNC and H, i.e., an adiabatic cloud model, is inconsistent with the assumption of vertical uniformity for inferring these two key parameters. Furthermore, not all clouds are adiabatic, which can introduce substantial uncertainties.

Numerous efforts have been made to validate satellite-retrieved cloud properties with ground based and in-situ measurements (Platnick and Valero, 1995; Min and Harrison, 1996; Min et al., 2004; Dong et al., 2008; Mace et al., 2011; Painemal and Zuidema, 2011; Zheng et al., 2011; and many others). The VAMOS Ocean-Cloud-Atmospheric-Land Study (VOCALS) was conducted in the Southeast Pacific (SEP) off the coast of Chile in 2008. VOCALS was a multi-platform field campaign designed to understand the chemical and microphysical properties of aerosols found in pristine and polluted air-masses, and their impacts on cloud microphysical properties. What makes the SEP a particularly unique laboratory for studying aerosol indirect effects is that these marine stratocumulus clouds span a region that experiences a sharp gradient or partition between anthropogenic and natural aerosol loading (Wood et al., 2011). Aerosols near the Chilean coast are dominated by SO_2 emissions from copper smelters. Away from the coast towards the open-ocean the aerosol loading quickly transitions to natural aerosols. Satellite data of cloud fields over the SEP exhibits a gradient in cloud droplet radius and drizzle away from the coast in ways that are consistent with the first and second indirect effects. Hence the VOCALS field campaign with multiple aircraft in-situ measurements provided a unique data set to validate satellite retrievals of cloud microphysical properties. In this study, we will evaluate and compare satellite retrievals of cloud microphysical properties with in-situ measurements, focusing on issues related to aerosol-cloud interactions described above. It is important to note that numerous studies on MODIS validation have been reported in the literature (Platnick and Valero, 1995; Min and Harrison, 1996; Min et al., 2004; Dong et al., 2008; Mace et al., 2011; Painemal and Zuidema, 2011; Zheng et al., 2011). Moreover, Painemal and Zuidema (2011) have used data from the C-130 flight during VOCALS for MODIS validation. This study is distinguished from these previous studies in that a central purpose is to provide guidance on the applicability of satellite data to investigate cloud-aerosol interaction. As such this study focuses on relevant cloud and aerosol properties.

2 VOCALS in-situ measurements and MODIS retrievals

Wood et al. (2011) provided an overview of the VOCALS field campaign. Other publications provide a comprehensive synthesis of meteorological conditions; the chemical composition of the boundary layer and free troposphere; clouds; and precipitation during VOCALS, derived from aircraft measurements of the United Kingdom BAe 146, NSF C-130, CIRPAS Twin Otter, and DOE G-1, and supplemented by surface observations from the research vessel Ronald H. Brown (Allen et al., 2011; Bretherton et al., 2010; Rahn and Garreaud, 2010; Chand et al., 2010; and Kleinman et al., 2012). Painemal and Zuidema (2011) have used C-130 measurements to validate the MODIS cloud effective radius and optical thickness over the SEP during VOCALS. Zheng et al. (2011) also compared the MODIS and GOES retrieved cloud properties with the Twin Otter in-situ measurements. Our study extends to multiple-aircraft in-situ measurements of the G-1 and the C-130, with a focus on both the microphysical/macrophysical properties and the underlying retrieval assumptions pertaining to aerosol-cloud interactions.

As discussed above cloud optical depth and cloud effective radius are key microphysical parameters that are directly retrieved from MODIS sensors onboard Terra and Aqua satellites. Based on Mie theory, cloud liquid water path can be readily derived from these two parameters. Cloud drop number concentration, which is more fundamentally related to the underlying aerosol concentration than the effective radius, can be derived from Eq. (1) with the retrieved cloud optical depth and effective radius. Cloud top temperature, which is inferred from satellite infrared measurements, is an important cloud macrophysical property because it can be used to derive cloud top height. Cloud geometrical thickness is another key parameter for aerosol indirect effect and cloud feedback process. Therefore, it is important to validate MODIS inferred cloud top temperature against in-situ measured cloud top temperature and inferred cloud geometrical thickness. Hence, this study will focus not only on the comparison of MODIS retrieved cloud optical depth and effective radius, but also on the cloud drop number concentration, cloud geometrical thickness, and cloud top temperature for the reasons discussed above. These data are from the level 2 cloud retrieval products of MOD06 and MYD06, and the uncertainties and errors of MODIS retrievals, associated with both model and physical uncertainties, have been discussed in details by King et al. (1997).

Table 1. Airborne instruments and measurements.

Aircraft	Instruments	Measurements	Droplet size range
NSF/NCAR C-130	PVM	LWC	3–50 µm
	CDP	R_e, CDNC	2–52 µm, 30 bins
	2D-C	Drizzle	25–1560 µm, 64 bins
	PCASP	Aerosol	0.1–3 µm
DOE G-1	PVM	LWC	3–50 µm
	CAS	R_e, CDNC	2.5–50 µm
	CIP	Drizzle	8–940 µm
	PCASP	Aerosol	0.1–3 µm

The key airborne instruments of the G-1 and C-130 are listed in Table 1. Details of the G-1 aerosol and cloud microphysical instruments and measurement procedures and uncertainties are described in Kleinman et al. (2012). For each ascent or descent profile, cloud droplet number concentrations, cloud effective radii (R_e), cloud liquid water paths (vertically integrated LWC measured by a Particle Volume Monitor (PVM); Gerber et al., 1994), and cloud top temperatures are analyzed. Specifically, as shown in Fig. 1, the accumulation mode aerosol number concentrations (ACN) at different levels (below cloud, in-cloud, and above cloud) were measured by a Passive Cavity Aerosol Spectrometer Probe (PCASP) for diameters between 0.1 and 3 µm. R_e and CDNC were determined using a Cloud and Aerosol Spectrometer (CAS) probe integrated over a diameter range between 2.5 and 50 µm. The cloud boundaries (base and top heights) were determined by requiring three continuous altitude bins have values greater than $0.02\,g\,m^{-3}$ and $5\,cm^{-3}$ for cloud water content from PMV and cloud drop number concentration from CDP or CAS measurements, respectively. The drizzle has substantial impacts on cloud retrievals, and itself is also important for the research about cloud microphysics and precipitation. For G-1, the drizzle was determined from a DMT

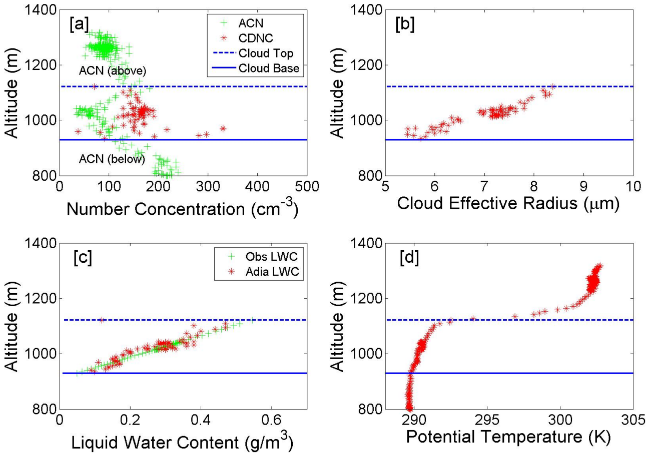

Fig. 1. Vertical distribution of aerosol concentration number (ACN), cloud drop number concentration (CDNC), cloud effective radius (R_e), cloud liquid water content (LWC), and atmospheric temperature measured by G-1 on 6 November 2008.

Cloud Imaging Probe (CIP), which is packaged together with the CAS and hot wire detector as a Cloud, Aerosol, and Precipitation Spectrometer (CAPS). The preprocessing procedures and some in-situ measurements used from the C-130 are identical to those from the G-1. For C-130, the cloud properties, such as cloud effective radius (R_e) and CDNC, were constructed from the drop size distributions measured by the Cloud Droplet Probe (CDP), which can measure droplets within the diameter range from 2 to 52 µm. The drizzle concentration was measured by a Two-Dimensional Cloud (2-D C) probe (diameters upto 1560 µm).

The cloud drop effective radius derived from CAS or CDP measurements exhibits a quasi-linear growth with altitude. Due to the limit of photon penetration depth into optically thick clouds, particularly at a water (or ice) absorbing band in the near-infrared, satellite measured reflectance is only sensitive to the uppermost portion of a cloud. Thus, the retrieved cloud effective radius only represents the droplet population in the uppermost portion of a cloud. To minimize the uncertainty associated with how the cloud top effective radius was defined, we use the averaged R_e over the top 30 % of the cloud in our comparison, which represents what satellite likely samples (Platnick, 2000; Brenguier et al., 2000).

Cloud dynamical processes such as entrainment may be the primary modulator of cloud microphysical properties in certain situations potentially leading to clouds that are non-adiabatic. As discussed previously, the current retrievals of CDNC are based on the adiabatic assumption. It is important to understand the impact of cloud adiabaticity on satellite retrievals. For each cloud profile, the cloud adiabaticity is defined to be the ratio of the measured LWP to the calculated adiabatic LWP from the measured temperature and pressure at the cloud base. The aircrafts had their usual navigational and meteorological package for measuring position, winds, temperature, and dew point. Both temperature and pressure were measured by these navigational and meteorological packages, and consequently are used to define the adiabatic LWP. For some profiling flights, the aircraft maintained a relatively long constant altitude transect to study cloud internal variability. Those long transects may induce some uncertainties. Thus for our analysis we exclude those profiles with long transects.

The clouds we studied are the largest and most persistent deck of subtropical marine stratocumulus clouds over the Southeast Pacific off the coast of Chile. Although they concurrently experience a gradient of aerosol loading from coast to the remote ocean, the local variability in the closed cell region is relatively small. Those clouds are the best for the intercomparison of satellite remote sensing and in-situ measurements, as cloud 3-D effects and sub-pixel variability is minimal, particularly for the cases we selected with cloud fractional cover larger than 0.95 within 5 km. However, various instruments have different sampling rates and observational geometries. While MODIS retrievals yield a spatial distribution of cloud optical/microphysical properties at a given instant, the in-situ measurements sample the cloud field along the flight track at different times. Hence it is critical to understand the effects of spatial-temporal variability of each parameter observed from multiple instruments. Figure 2 shows the longitude-altitude cross section of the G-1 flight track and measured LWC along the track on 28 October 2008; and MODIS images of LWP from both Terra and Aqua satellites. The blue line in the image indicates the G-1 flight track. This data provides a perspective of the surrounding environment on a large scale, and given that the Terra satellite is 3 h ahead of Aqua some temporal variations are also illustrated. Comparing the difference between LWP from Terra-MODIS and Aqua-MODIS (Fig. 2) indicates that the cloud advected to north-west while LWP decreased during the three hours between overpass of the two satellites. Considering the strong diurnal cycle of cloud cover and LWP, the time interval between an aircraft profile and satellite overpass is constrained to a maximum of one hour for the purposes of this comparison. Horizontal advection of the cloud field is an important issue for understanding the spatial and temporal effects. The pink stars and circles in Fig. 2b and c represent the projection of the position of the G-1 at the time of the Terra and Aqua overpasses, respectively as calculated from back trajectories. As the re-analysis has a coarse resolution with some uncertainty in the wind field, the back trajectory calculation is based on the aircraft measured wind speed and direction. Most of the G-1 measurements took place in the late morning; thus our comparison focuses on Terra-MODIS for both the projected and un-projected aircraft positions. Furthermore, to investigate the radiative impacts of aerosol-cloud interaction requires combining MODIS measurements with **C**louds and **E**arth's **R**adiant **E**nergy **S**ystem (CERES) and other satellite sensors. All of those sensors have different footprints. Considering aircraft sampling distances and

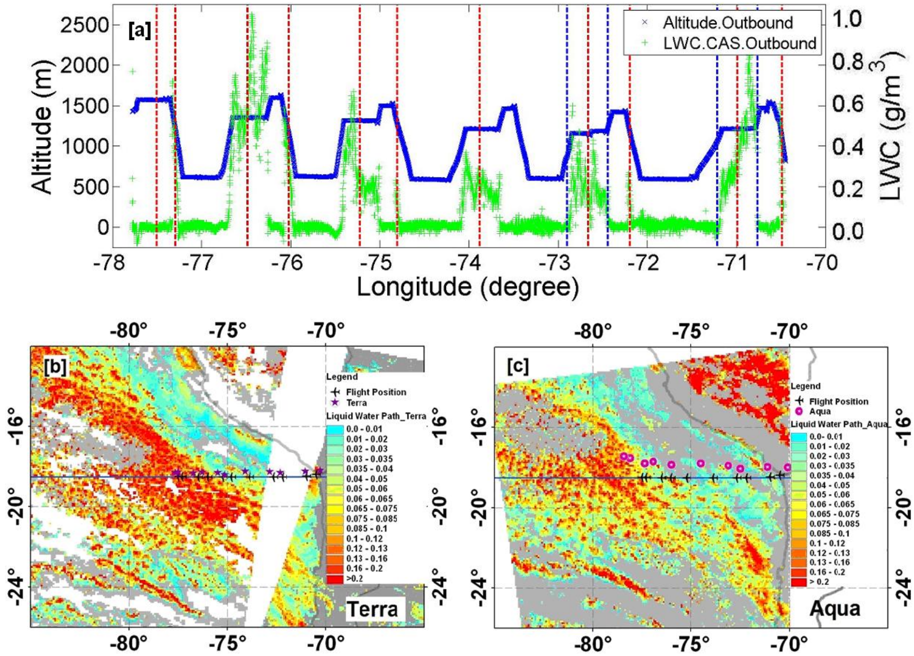

Fig. 2. Longitude-altitude cross section of G-1 flight track for 20081028 and measured LWC along the track; and LWP images from Terra-MODIS and Aqua-MODIS. The blue line in the image indicates the G-1 flight track and the pink stars represent the projection of G-1 position at the time of the satellite overpass through back trajectory calculation.

Table 2. Summary of the 17 profiles used in this study. Aircraft time is the mean time of plane pass through the cloud. The altitude is the mean altitude of plane pass through the cloud.

Date	Research Aircraft				
(2008)	Time (UTC)	Profile #	Lon	Lat	Alt (m)
10/17	14:41	1	−73.55	−18.89	886
10/18	15:60	6	−80.05	−20.00	857
10/18	16:19	8	−82.39	−19.99	927
10/25	14:91	20	−70.88	−19.01	1120
10/28	14:95	10	−77.39	−18.43	1232
11/02	14:83	25	−71.57	−18.96	1071
11/09	13:94	2	−73.00	−20.22	1150
11/09	14:28	3	−73.00	−21.48	1153
11/09	14:69	4	−73.00	−22.80	1062
11/09	15:64	6	−73.00	−26.11	906
11/10	15:79	2	−73.69	−19.57	1112
11/11	13:86	2	−73.00	−20.36	1020
11/11	14:57	4	−73.00	−22.62	986
11/11	15:44	6	−73.00	−25.77	813
11/13	15:37	5	−78.94	−20.01	1016
11/13	16:57	7	−77.27	−18.94	1230
11/15	15:76	6	−80.09	−20.24	1220

different footprints of satellite sensors, we compare in-situ measurements with two different averaging domains: 5 km and 25 km.

3 Results

The cloud geometrical thickness and droplet concentration are two key parameters in determining microphysical properties of an adiabatic cloud (Brenguier et al., 2000). Some clouds are evidently subjected to entrainment, which reduces LWC by either dilution or evaporation. It is important, therefore, to evaluate the role of the sub-adiabaticity on cloud optical properties. There were 111 cloud profiles taken by both G-1 (26) and C-130 (85) during VOCALS without long cloud transects, in which 17 of them had the mean aircraft profiling time within one hour of Terra overpass and without measurable drizzle. A summary of those 17 profiles is provided in the Table 2.

As shown in Fig. 3, about half of those 111 clouds had adiabaticities less than 0.7, indicating that most stratocumulus clouds in SEP were sub-adiabatic clouds. The cloud geometrical thickness varied from 100 m to 500 m. The measured CDNC varied from 25 to 300 cm^{-3}. Interestingly, the cloud adiabaticity decreases with increasing cloud thickness, as shown in Fig. 4.

The characterization above of the vertical and horizontal distribution of cloud and aerosol microphysical properties as observed from aircraft measurements, and the variation of the cloud adiabaticity over the SEP provide an important context and foundation for the subsequent comparison of satellite derived parameters. Cloud effective radii derived from MODIS-Terra are compared against R_e obtained from G-1 and C-130 measurements in Fig. 5. The vertical error bars indicate the

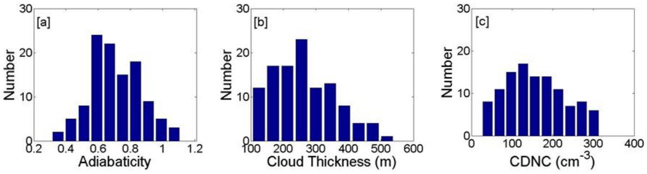

Fig. 3. Distribution of the **(a)** adiabaticity, **(b)** geometric vertical thickness and **(c)** cloud droplet number concentration among 116 clouds profiled by the G-1 and C-130 during VOCALS.

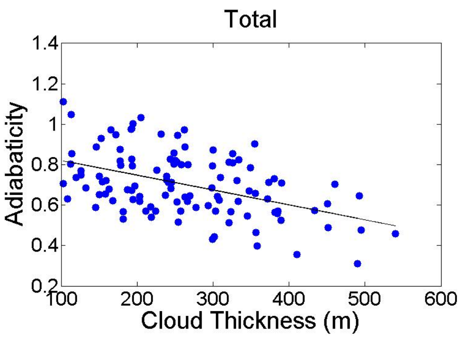

Fig. 4. The adiabaticity of the clouds profiled by the G-1 and C-130 aircrafts as a function of geometric thickness for all cases.

MODIS retrieval error, whereas the horizontal error bars denote the standard deviation of cloud R_e from CDP or CVS. Several factors that may have influences on the comparisons are also evaluated, including the resolution of the satellite data, and lack of coincident sampling as a result of spatial and temporal differences between the satellite and aircraft sampling. To test the latter, satellite observations associated with both projected and un-projected airmasses were used, as noted above. In the case of projected airmasses trajectory analysis was used to find advecting airmasses that were sampled by both the satellites and the aircrafts. Figure 5 shows a comparison between MODIS R_e and the in-situ measured R_e for the top 30 % of the cloud. The correlation coefficient between MODIS 5 km averaged and the in-situ observations is 0.78 with a slope of 1.17 and a bias of 1.86 µm in the un-projected case. On the other hand, for the projected position comparison, the correlation coefficient is 0.80 with a slope of 1.24 and a bias of 1.79 µm. These results are statistically equivalent, indicating that in this dataset it is reasonable to only use the un-projected positions for comparing satellite data with that from the aircraft. For the 25 km comparison, as shown in Fig. 5, the overall statistics for both un-projected and projected positions are slightly better than for the 5 km comparison. The reason for a better agreement with the 25 km averaged MODIS retrieval could be that averaging over a relative large domain reduces the uncertainty associated with temporal-spatial mismatch. Furthermore, there is no statistically significant difference between adiabatic and sub-adiabatic clouds. Detailed statistics for both comparisons

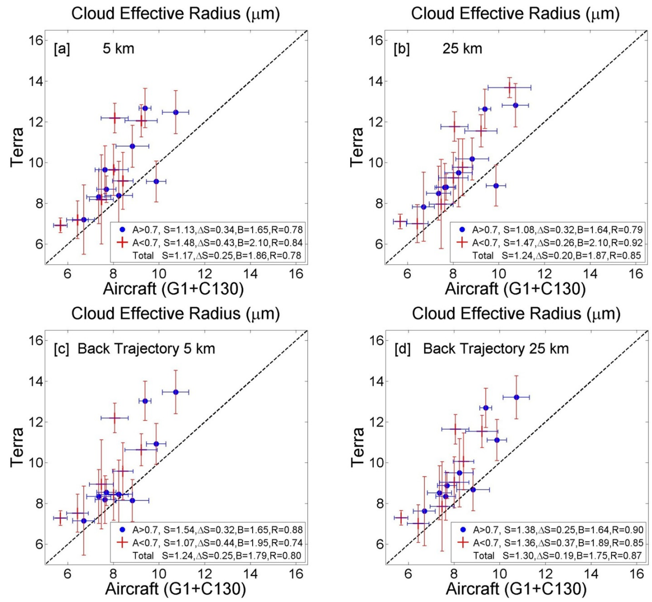

Fig. 5. Comparison of cloud effective radius retrieved from Terra-MODIS with combined in-situ measurements from both G-1 and C-130: top two plots for un-projected positions at 5 and 25 km domain averages; bottom two plots for projected positions. The vertical error bars indicate the MODIS error product, whereas the horizontal error bars denote the standard deviation of aircraft measurements. The capital letters A, S, ΔS, B and R represent adiabaticity, slope, standard deviation of the slope, bias and correlation coefficient, respectively (used in the other figures in this paper). The dashed lines represent 1:1 lines.

of projected and un-projected aircraft position and for 5 km and 25 km averaged domains are listed in Table 3 for all compared parameters. Hereafter all figures and associated discussion are based on the un-projected cases.

Systematic overestimation of R_e from satellite instruments over SEP has been reported by Zheng et al. (2011) and Painemal and Zuidema (2011). They further investigated some potential error sources for the positive bias, including cirrus cloud contamination, drizzling effects, cloud droplet size distribution breadth, above-cloud water vapor absorption, and sensor viewing angles. None of those potential issues can be singled out as the major error sources. The cases we selected were over the closed cell region, the 3-D effect and sub-pixel variability are relatively small. The positive bias exits for the projected and un-projected positions with different averaging domains. The temporal-spatial mismatch cannot explain the difference. The issues associated with both MODIS and in-situ measurement uncertainties have been discussed by King et al. (1997) and Kleinman et al. (2012). We focus our attention to the characteristics of such a positive bias.

As discussed previously, both cloud geometrical thickness and droplet concentration are important parameters in determining cloud microphysical properties. Neither of these parameters is readily inferred from satellite measurements,

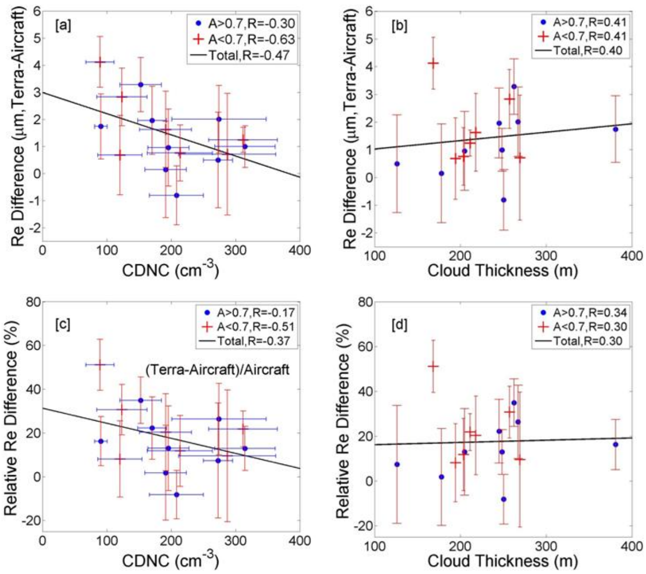

Fig. 6. The difference and relative difference between Terra-MODIS retrievals and aircraft measurements of cloud effective radius (R_e) as a function of cloud drop number concentration (CDNC) and cloud geometric thickness.

whereas the in-situ measured CDNC and cloud thickness provide a more complete dataset for understanding aerosol-cloud interaction and their impacts on satellite retrievals. As shown in Fig. 6a and b, the difference between aircraft and satellite measured R_e decreases with increasing CDNC. For a cloud with small CDNC, the cloud R_e is large, so the resulting differences between the values derived from MODIS and those observed from the G-1 and C-130 are large. Also, the difference between the MODIS retrieval and the in-situ R_e increases with cloud geometrical thickness. Although the correlation coefficients are not high in both plots, as a result of joint impacts of cloud geometrical thickness, droplet number concentration, and cloud adiabaticity, Fig. 6a and b show some dependences of R_e difference between aircraft and satellite measurements on CDNC and cloud thickness. These characteristics affect the interpretation of observed aerosol-cloud interaction using satellite retrievals. Compared to the absolute R_e difference, the trends of relative R_e difference (derived by the ratio of absolute R_e difference to the aircraft measurements) varying with CDNC or cloud geometric thickness are similar (Fig. 6c and d), but the correlation coefficients between relative R_e difference and CDNC or cloud geometric thickness are smaller, only -0.37 and 0.30, respectively.

As noted above both aerosol number concentration and mass loading in the marine boundary layer exhibited a persistent decreasing gradient from the Chilean coast westward (Allen et al., 2011; Lee et al., 2012; Kleinman et al., 2012). Cloud microphysical properties also exhibited persistent gradients in CDNC and R_e presumably as a result of the gradi-

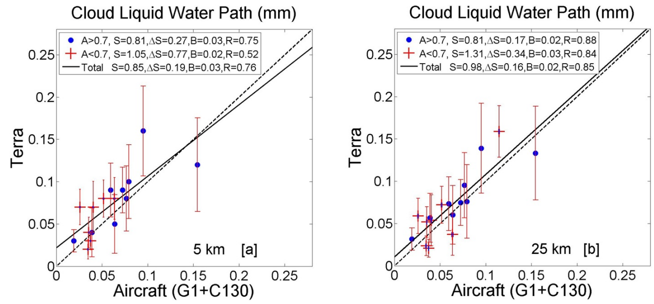

Fig. 7. Comparison of cloud liquid water path derived from MODIS with in-situ measurements.

ent in aerosol properties. Comparing observed R_e and LWP from MODIS onboard Terra and Aqua on daily and seasonal timescales, the differences between the two satellites (three hour difference) are relatively small in R_e and fairly large in LWP. Therefore, the one hour difference criteria used for comparison might be expected to result in a larger difference in LWP than R_e. Overall, MODIS inferred LWPs are strongly correlated with in-situ measurements (Fig. 7), with correlation coefficients of 0.76 and 0.85 for 5 and 25 km averages, respectively. MODIS retrievals overestimate LWP by approximately 0.03 mm and 0.02 mm for 5 km and 25 km domains, respectively. Comparison statistics of the 25 km domain are better than those of the 5 km domain, with a slope closer to 1.

Figure 8 compares cloud drop number concentrations (derived from MODIS retrieved LWP and effective radius, see Eq. 1) to those observed in-situ. Correlation coefficients of 0.91 and 0.93 were found using 5 and 25 km averaging scales, respectively. Those correlation coefficients are better than those for each individual parameter used in the retrievals: i.e., R_e and LWP. A lower bias and a relationship closer to one-to-one are found for adiabatic clouds than for sub-adiabatic clouds, since the retrievals are based on an adiabatic cloud assumption. If we modify Eq. (1) by introducing adiabaticity, A_{ad}, we have

$$N_{CDNC} = \frac{(A_{ad}C_w)^{1/2}}{k}\frac{10^{1/2}}{4\pi\rho_w^{1/2}}\frac{\tau^{1/2}}{R_e^{5/2}} \tag{3}$$

As shown in the bottom two plots of Fig. 8, better agreements are achieved for both averaging domains. It suggests that knowing cloud adiabaticity is a key factor for a more accurate estimation of CDNC from satellite remote sensing. Painemal and Zuidema (2011) also suggested an empirical correction factor, which will give the slope closer to one. Since different regions could have different cloud adiabaticity statistics (Fig. 3), different regions may need different correction factors.

As discussed above, cloud top temperature is an important cloud macrophysical property. As shown in Fig. 9, for nine of seventeen cases the temperature derived from MODIS was

Table 3. Statistics of comparison of MODIS retrievals with aircraft measurements for both projected and un-projected positions at both 5 and 25 averaging domains, r, p, $s(\Delta s)$, and b are the correlation coefficient, the probability p-value, the slope of linear fit (standard deviation of the slope), and the bias, respectively.

Terra (1 h)	Total				Adiabatic > 0.7				Adiabatic < 0.7			
5 km	r	p	$s(\Delta s)$	b	r	p	$s(\Delta s)$	b	r	p	$s(\Delta s)$	b
CDNC	0.91	0	1.23(0.15)	55.94	0.88	0.0009	1.06(0.21)	49.74	0.97	0.0004	1.46(0.18)	63.76
LWP	0.76	0.0006	0.85(0.19)	0.03	0.75	0.0197	0.81(0.27)	0.03	0.52	0.2287	1.05(0.77)	0.02
CRE	0.78	0.0004	1.17(0.25)	1.86	0.78	0.0132	1.13(0.34)	1.65	0.84	0.0192	1.48(0.43)	2.10
CTT	0.37	0.1436	0.32(0.21)	1.65	0.54	0.1077	0.39(0.22)	1.83	−0.28	0.5454	−0.49(0.75)	1.34
CTP	0.5	0.0424	1.04(0.47)	248.45	0.34	0.3436	1.43(1.22)	247.7	0.69	0.0851	1.57(0.73)	249.53
Thickness	0.62	0.0079	0.71(0.23)	52.12	0.66	0.0385	0.63(0.25)	57.33	0.51	0.2446	0.74(0.56)	43.61
Terra (Back)	**Total**				**Adiabatic > 0.7**				**Adiabatic < 0.7**			
5 km	r	p	$s(\Delta s)$	b	r	p	$s(\Delta s)$	b	r	p	$s(\Delta s)$	b
CDNC	0.94	0	1.30(0.12)	55.05	0.92	0.0001	1.23(0.18)	48.87	0.98	0.0001	1.40(0.13)	62.84
LWP	0.65	0.0064	0.82(0.25)	0.03	0.69	0.0394	0.79(0.31)	0.03	0.68	0.0940	2.17(1.05)	0.03
CRE	0.8	0.0002	1.24(0.25)	1.79	0.88	0.0020	1.54(0.32)	1.65	0.74	0.0574	1.07(0.44)	1.95
CTT	0.40	0.1116	0.81(0.22)	1.63	0.51	0.1374	0.95(0.26)	1.83	−0.20	0.6645	0.46(0.70)	1.29
CTP	0.55	0.0226	1.20(0.47)	247.2	0.43	0.2093	1.64(1.20)	246.21	0.79	0.0326	2.07(0.71)	248.60
Thickness	0.36	0.1503	0.65(0.36)	80.35	0.29	0.4232	0.52(0.46)	94.46	0.54	0.2134	1.31(0.72)	54.16
Terra (1 h)	**Total**				**Adiabatic > 0.7**				**Adiabatic < 0.7**			
25 km	r	p	$s(\Delta s)$	b	r	p	$s(\Delta s)$	b	r	p	$s(\Delta s)$	b
CDNC	0.93	0	1.27(0.13)	50.27	0.93	0.0001	1.09(0.15)	37.39	0.95	0.0002	1.51(0.20)	62.76
LWP	0.85	0	0.98(0.16)	0.02	0.88	0.0019	0.81(0.17)	0.02	0.84	0.0083	1.31(0.34)	0.03
CRE	0.85	0	1.24(0.20)	1.87	0.79	0.0115	1.08(0.32)	1.64	0.92	0.0012	1.47(0.26)	2.10
CTT	0.42	0.0823	0.50(0.27)	1.83	0.52	0.1195	0.44(0.25)	1.84	0.38	0.3481	1.12(1.10)	1.81
CTP	0.59	0.01	1.29(0.44)	244.71	0.46	0.1841	1.75(1.20)	245.51	0.72	0.0433	1.29(0.50)	243.71
Thickness	0.62	0.0079	0.71(0.25)	52.12	0.66	0.0385	0.72(0.22)	57.33	0.51	0.2446	0.34(0.52)	43.61
Terra (Back)	**Total**				**Adiabatic > 0.7**				**Adiabatic < 0.7**			
25 km	r	p	$s(\Delta s)$	b	r	p	$s(\Delta s)$	b	r	p	$s(\Delta s)$	b
CDNC	0.93	0	1.23(0.14)	47.61	0.93	0.0001	1.08(0.19)	34.61	0.98	0.0001	1.44(0.13)	61.58
LWP	0.69	0.0024	0.74(0.18)	0.03	0.63	0.0486	0.65(0.25)	0.03	0.24	0.6011	0.36(0.65)	0.02
CRE	0.87	0	1.30(0.19)	1.75	0.90	0.0009	1.38(0.25)	1.64	0.85	0.0149	1.36(0.37)	1.89
CTT	0.44	0.0809	0.40(0.20)	1.59	0.6	0.1154	0.44(0.22)	1.79	−0.05	0.9608	−0.09 (0.7)	1.25
CTP	0.56	0.0189	1.31(0.50)	246.30	0.49	0.1463	1.94(1.20)	244.92	0.80	0.0322	2.47(0.84)	248.26
Thickness	0.36	0.1503	0.66(0.25)	80.35	0.29	0.4232	0.64(0.26)	94.46	0.54	0.2134	0.55(0.49)	54.16

within 0.3 degrees of the temperature measured by the aircraft. The cloud top temperature for the remaining eight cases was underestimated by MODIS, with a total bias of −1.65 degrees. A large domain average does not necessarily improve the comparison statistics, due to inhomogeneous cloud top heights. In some applications, cloud geometric thickness can be estimated from satellite inferred cloud top temperature and re-analysis, as the lifting condensation level is a good estimate of cloud base height. A negative bias of 1.65 degrees implies a positive bias of 200 m for cloud top height, estimated from the re-analysis lapse rate. Given the fact that the mean cloud thickness is of the same magnitude, such bias could result in a substantial error in the estimated cloud geometrical thickness for thin clouds.

The cloud geometrical thickness can be estimated through the adiabatic assumption, i.e., Eq. (2) (Bennartz, 2007). As shown in Fig. 10a, if simply uses the in-situ measured LWP without considering cloud adiabaticity, the estimated cloud geometric thicknesses correlates with the in-situ measured cloud geometrical thicknesses but are biased low. The bias indicates that cloud adiabaticity is also a key parameter for better estimating cloud geometrical thickness, since most clouds over SEP were sub-adiabatic. Figure 10b shows the comparison of the estimated cloud geometrical thickness from Terra MODIS LWP retrievals (which are also calculated by using Eq. 2) with the in-situ measurements. The correlation coefficient between the estimated and the observed cloud geometrical thickness are 0.62 with a mean bias of 52 m. The positive bias is due to the overestimation of LWP by the MODIS

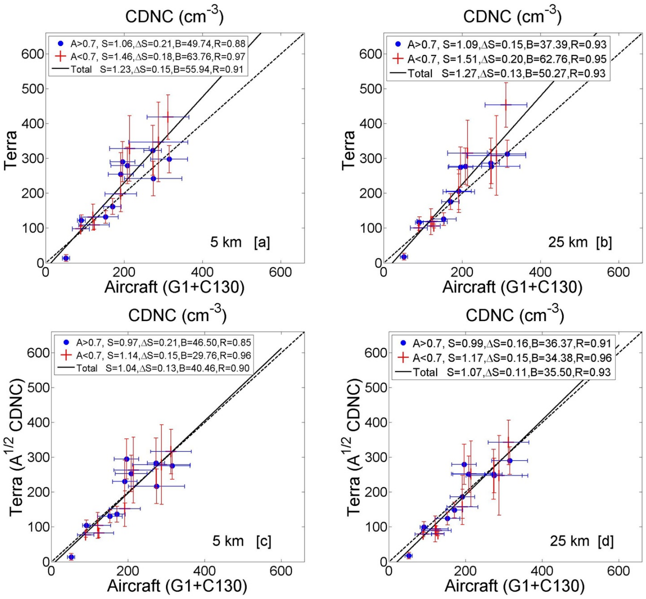

Fig. 8. Comparison of retrieved and modified cloud drop number concentration (CDNC) from MODIS with the in-situ measurements: top two plots for the retrieved CDNC, and the bottom two plots for the modified MODIS CDNC. The dashed-lines are for the 1:1 lines; and the solid lines are for the best fit.

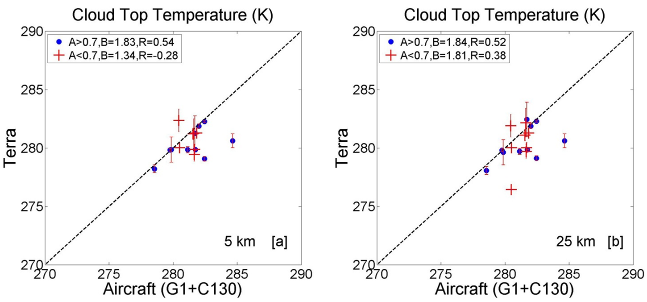

Fig. 9. Comparison of retrieved cloud top temperature from MODIS with the in-situ measurements: the dashed-lines are for the 1:1 lines.

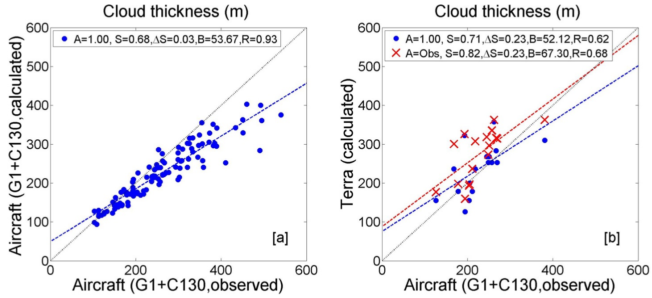

Fig. 10. Comparison of retrieved cloud geometrical thickness with the in-situ measurements.

retrievals. Considering cloud adiabaticity slightly improves the correlation coefficient to 0.68. Those correlation coefficients, however, are lower than that between the estimated and observed cloud LWP. A possible reason might be due to the representativeness of measuring cloud thickness from a single in-situ cloud profile in a much larger area of MODIS observation domain.

4 Simulations with a vertically stratified cloud

In-situ measurements of microphysical parameters in stratocumulus clouds during VOCALS confirm previous observations in similar clouds, showing quasi-constant cloud drop number concentrations and quasi-adiabatic profiles of LWC and effective radius as a function of altitude (Slingo et al., 1982; Brenguier et al., 2000; Painemal and Zuidema, 2011). Such vertical profiles of cloud microphysical properties are inconsistent with the current MODIS retrieval assumption (King et al., 1997). Brenguier et al. (2000) pointed out that such an inconsistency could result in errors in the retrieved effective radius, and proposed a procedure for the retrieval of cloud geometrical thickness and cloud droplet number concentration from the measured cloud radiances based on the adiabatic stratified model. As shown above, most stratocumulus clouds observed in SEP during VOCALS were subadiabatic clouds. Our comparison indicates that the differences between the MODIS retrieved and the in-situ measured microphysical parameters have some dependencies on the cloud geometrical thickness and cloud droplet number concentration. Therefore, additional analysis is required to better understand the discrepancies between the values of microphysical properties measured in-situ and those derived from remote sensing of cloud radiances, in terms of cloud geometrical thickness, cloud droplet number concentration, and cloud adiabaticity.

We have developed a radiative transfer model of a vertically stratified cloud to simulate satellite observed reflectance at both 0.75 and 2.16 µm wavelengths (similar to those used for MODIS cloud properties retrieval algorithm, King et al., 1997). The vertical distribution of cloud LWC can vary adiabatically, sub-adiabatically, or uniformly in the model. The vertically uniform plane-parallel model (VUPPM), i.e., a constant LWC, is used as our retrieval model to mimic the MODIS retrieval algorithm. In this study, we set a series of cloud optical depth (from 0.5 to 80) and cloud effective radius (from 4 µm to 28 µm) as the input parameters to the VUPPM radiative transfer model. Given the cloud optical depth and effective radius, LWP is known (by using equation $\mathrm{LWP} = 2/3 \times \rho_\mathrm{w} \times \tau \times R_\mathrm{e}$) and for an assumed CDNC the cloud geometric thickness is also known. This allows radiative transfer calculations to be performed in order to build a lookup table for converting reflectances into cloud optical depth (COD) and R_e. Note that the reflectances produced from the plane parallel model are fairly insensitive to the choice of the CDNC, cloud geometric thickness pair used for the model cloud. The reflectances from the lookup table are then used to obtain COD and R_e values by comparing with the reflectances calculated from radiative transfer for more realistic cloud profiles.

To mimic realistic cloud stratification of adiabatic clouds, the adiabatic stratified plane-parallel model (ASPPM) is used, in which the cloud drop number is assumed to be constant vertically, and the vertical profile of effective radius and the cloud optical depth are calculated from defined LWC and CDNC. To simulate sub-adiabatic clouds, the rate of increase of LWC with altitude is set to be consistent with their adiabaticity. For ASPPM simulations, we set three adiabaticity values of 0.5, 0.75 and 1.0; twenty CDNC values from 40 to 420 by a step of 20; and ten cloud thickness values from 100 m to 550 m by a step of 50 m, respectively. The cloud single scattering properties of single scattering albedo, asymmetric factor, and extinction coefficient as a function of effective radius at both wavelengths are adopted from MODIS Algorithm Theoretical Basis Documents (ATBD's) (King et al., 1997). The COD and R_e values obtained from the ASPPM reflectances using the plane parallel lookup tables are then compared to the known values that went into the ASPPM model cloud for clouds. CDNC is calculated from the retrieved COD and R_e using Eq. (1) and is also compared to the known ASPPM value.

There is a notable issue about the determination of equivalent effective radius for adiabatic or sub-adiabatic clouds. Currently, two methods have been used to calculate the equivalent R_e: one is based on the given LWP and cloud optical depth, the other is based on the reflected or transmitted solar radiation. For the first method, Brenguier et al. (2000) stated that for the same cloud, i.e., the same optical depth and LWP, the equivalent effective radius in a vertical uniform cloud would be 5/6 of the R_e at the top of an adiabatically stratified cloud. For the second method, based on photon transport, Platnick (2000) proposed the Platnick weighting function to determine the equivalent R_e for clouds with different vertical structures. Some argue that LWP is a byproduct of the MODIS retrieval and is not completely constrained. Therefore, the coefficient of 5/6 should not be used. As stated previously, we also believe that the satellite measured reflectance is only sensitive to the uppermost portion of a cloud, especially for infrared absorption bands, and that the second method should be used. However, the Platnick weighting function varies case by case for real clouds. We simply used the average R_e of the top 30 % of the cloud from in-situ measurements as the equivalent R_e. In order to simplify the comparisons between model simulations of ASPPM and VUPPM, we use one correction coefficient times the cloud top R_e to approximate the equivalent cloud effective radius of non-uniform clouds. ASPPM simulations indicate that 5/6 of the R_e at the top of an adiabatically stratified cloud is close to the average R_e of top 30 % of that cloud. Therefore, we will use the factor of 5/6 as our correction coefficient in our following analysis.

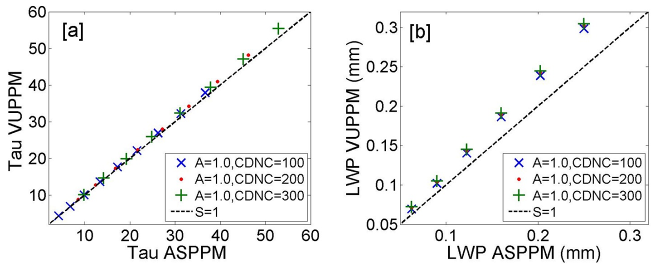

Fig. 11. Comparison of retrieved cloud optical depth (Tau) and Cloud liquid water path (LWP) from VUPPM with ASPPM for cloud drop number concentrations (CDNC) of 100, 200, and 300 cm^{-3}.

Cloud optical depth, which is primarily determined by the reflectance at a nonabsorbing band in the visible wavelength of 0.75 µm, is nearly insensitive to cloud vertical structure, as shown in Fig. 11a. For an adiabatic or sub-adiabatic cloud, more cloud water is located at the top of the cloud, resulting in higher cloud optical depths near the cloud top, enhancing photon path length. At a water (or ice) absorbing band, the enhanced photon path length near the cloud top results in increased absorption and suppressed cloud reflection as compared to a vertically uniform cloud (Nakajima and King, 1990; Li et al., 1994; Platnick and Valero, 1995). Therefore, the retrieved LWP is overestimated (Fig. 11b) and cloud effective radii are overestimated (Fig. 12a and d), which are consistent with the results of Brenguier et al. (2000). As shown in Fig. 12b and c, both difference and relative difference between VUPPM ("retrieved") R_e and ASPPM R_e increase with increasing cloud geometrical thickness for a given adiabaticity and cloud drop number concentration, and the impacts of cloud geometric thickness decrease with increasing CDNC. Furthermore, a cloud with a high drop number for a fixed LWC has a small effective radius. The difference between retrieved R_e and ASPPM R_e decreases with increasing cloud drop number concentration for a given cloud geometrical thickness and adiabaticity, as shown in Fig. 12e, and the impacts of CDNC decrease with decreasing cloud adiabaticity. The relative difference between retrieved R_e and ASPPM R_e slightly increases with CDNC for a given cloud geometrical thickness and adiabaticity (Fig. 12f). The impacts of CDNC and cloud geometric thickness on the relative difference between retrieved R_e and ASPPM R_e are weaker than on the absolute difference. In general, for the absolute R_e difference, the observed results are consistent with the simulation, but for the relative R_e difference, the observed results does not show the same varying trend as simulation (e.g., the relative R_e difference as a function of CDNC), this can be explained by the poor correlation between relative R_e difference and CDNC or cloud geometric thickness in the observation.

For an adiabatic cloud, the "retrieved" properties based on the simplistic adiabatic assumption underestimate or

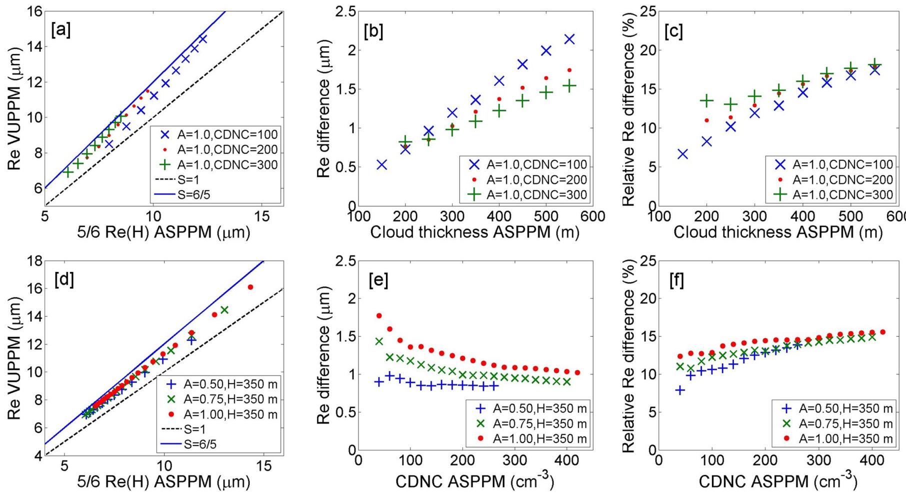

Fig. 12. Comparisons of retrieved R_e from VUPPM and ASPPM for a given adiabaticity **(a)** and a given cloud geometric thickness **(d)**; The R_e difference as a function of cloud geometric thickness **(b)** and cloud drop number concentration (CDNC) **(e)**; The relative R_e difference as a function of cloud geometric thickness **(c)** and CDNC **(f)**.

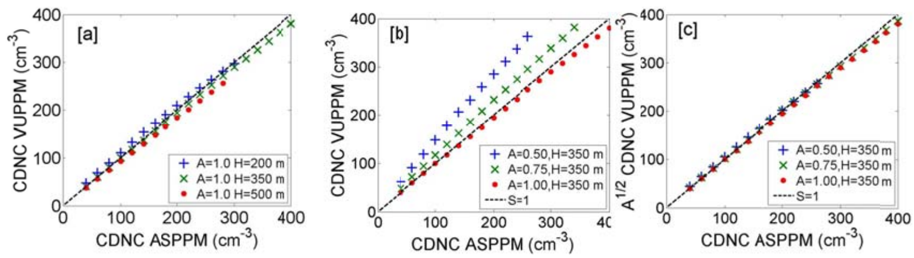

Fig. 13. Comparison of retrieved cloud drop number concentration (CDNC) from VUPPM with ASPPM.

overestimate the CDNC (Fig. 13a) depending on cloud geometric thickness. It illustrates the importance of knowing the cloud geometric thickness. Furthermore, as shown in Fig. 13b, the "retrieved" CDNC can be overestimated due to the cloud sub-adiabaticity. With the adjustment of adiabaticity of Eq. (3), as shown in Fig. 13c, better agreements can be achieved. In this sensitivity test, the cloud geometric thickness is assumed to be 350 m. As the clouds in SEP exhibit a coherent relationship between cloud geometric thickness and adiabaticity, variations in both cloud geometric thickness and adiabaticity would introduce uncertainties in the estimation of cloud CDNC from satellite remote sensing.

5 Discussion and summary

The climate of the SEP is unique in that it involves important interactions among sea-surface temperature (SST), coastal topography and geometry, oceanic heat transport, clouds and aerosols. The low SST in combination with warm dry air aloft results in the formation of a persistent layer of marine stratocumulus clouds. This cloud layer helps maintain the cool SST resulting in tight coupling between the upper ocean and the atmosphere. In particular, these marine stratocumulus clouds span a region that concurrently experiences a sharp gradient or partition between anthropogenic and natural aerosol loading, which, combined with other meteorological factors, results in a gradient in cloud droplet radius and drizzle away from the coast. We utilized the unique characteristics of the SEP and in-situ data from multi-aircraft observations during VOCALS as a laboratory for evaluating satellite remote sensing of cloud microphysical properties and for studying the extent to which these retrieved properties are sufficiently constrained and consistent to reliably quantify the influence of aerosol loading on cloud droplet sizes. We particularly focused on how vertical stratification and adiabaticy impacts the accuracy of retrieved cloud microphysical properties. After carefully constraining the spatial-temporal coincidence between satellite retrievals and in-situ measurements, we selected 17 non-drizzle comparison pairs. For these cases the mean aircraft profiling times were within one hour of Terra overpasses at both projected and un-projected aircraft positions for two different averaging domains of 5 km and 25 km. Retrieved quantities that were averaged over a domain of side 25 km compared better statistically with in-situ observations than averages made over a smaller domain of side 5 km. Comparisons of projected aircraft positions were slightly better than un-projected aircraft positions for some parameters. Overall, both MODIS retrieved R_e and LWP were highly correlated with but larger than the in-situ measured R_e and LWP. The observed R_e difference between the two decreased with increasing cloud drop number concentration, and increased with increasing cloud geometrical thickness. There was a weaker correlation for the relative R_e difference. The observed characteristics from the comparison are consistent with our theoretical simulations of a vertically stratified cloud model.

The relative change in cloud droplet number concentration or cloud effective radius with respect to the relative change in aerosol number concentration is an indicator of the strength of the aerosol indirect effect and is commonly used in observational studies to quantify this relationship particularly for the purposes of developing parameterizations of this effect in numerical models. Strong correlations between satellite retrievals and in-situ measurements suggest that satellite retrievals of cloud effective radius, cloud liquid water path, cloud geometrical thickness, and cloud drop number concentration can be used to investigate aerosol indirect effects qualitatively. However, our comparison and sensitivity analysis of simulated retrievals demonstrate that both cloud geometrical thickness and cloud adiabaticity are factors that impact satellite retrievals of R_e and cloud drop number concentration. Current passive satellite remote sensing techniques are unable to detect geometric thickness and adiabaticity directly. In-situ measurements during VOCALS showed substantial variations of both over the SEP. The large variability of cloud geometric thickness and adiabaticity, the dependency of cloud microphysical properties on both of them as demonstrated in our sensitivity study of simulated retrievals, and the inability to accurately account for both in retrievals lead to some uncertainties and biases in satellite retrieved cloud effective radius and cloud drop number concentration. Therefore, as demonstrated by our comparison, those issues and the associated uncertainties and biases would compromise quantitative assessments of aerosol indirect effect. These retrieval uncertainties and biases, in addition to other unquantified meteorological influences and microphysical mechanisms, such as cloud nucleation processes, drizzle, entrainment, meteorological covariance of aerosols and clouds, result in a large range of assessed strength of aerosol indirect effects (Shao and Liu, 2005).

Based on in-situ measurements, the clouds in SEP exhibit a coherent relationship between cloud geometric thickness and adiabaticity. The cloud physical thickness can be estimated from satellite inferred cloud LWP, or from satellite retrieved cloud top temperature and re-analysis near-surface air temperature and relative humidity, or directly measured from active cloud radar and lidar sensors (such as CloudSat and CALIPSO). Although such a relationship varies with meteorological and aerosol conditions, it provides a first order constraint on cloud adiabaticity with information of cloud geometric thickness from satellite and re-analysis. If the cloud adiabaticity is known, as outlined above, the satellite estimation of cloud drop number concentration improves its agreement with the in-situ measured CDNC.

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