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Validation 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 validated 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 overpass 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. Validation 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. The observed effective radius difference between the two decreased with increasing cloud drop number concentration, and increased with increasing cloud geometrical thickness. Also, MODIS retrievals for adiabatic clouds agreed better with the in situ measurements than for sub-adiabatic clouds. Our validation 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 geometric 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 substantial 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 microphysics 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.

An important prerequisite exercise in the effort to utilize satellite observations along with in situ data to study aerosol-cloud interaction is a validation of the satellite data itself. A particular focus of this validation 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,

cloud effective radius, and optical thickness, Accurate measurement of these microphysical 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.

For satellite remote sensing, inferring the cloud drop number concentration (CDNC) requires information about the physical thickness of the cloud. Cloud droplet number concentration is derived from cloud liquid water path (LWP) which is the cloud liquid water content (LWC) integrated over the cloud geometric vertical thickness. Currently, most retrievals 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. By doing so, we have:

$$\mathrm{CDNC} = \frac{C_\mathrm{w}^{1/2}}{k}\frac{10^{1/2}}{4\pi\rho_\mathrm{w}^{1/2}}\frac{\tau^{1/2}}{Re^{5/2}} \quad (1)$$

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° and 40 °C.

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The coefficient k, which represents the effect of droplet spectral shape on radiation, is between 0.7 and 1, and ρ_w is density. Both τ and Re are retrieved cloud optical depth and cloud effective radius, respectively. However, the adiabatic cloud assumption in deriving CDNC 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 measurements (Platnick and Valero, 1995; Min and Harrison, 1996; Min et al, 2004; Dong et al, 2008; Mace, 2010; Painemal and Zuidema, 2010, and many others). The VAMOS Ocean-Cloud-Atmospheric-Land Study (VOCALS) was conducted in the Southeast Pacific (SEP) off the coast of Chili 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 concurrently experiences a sharp gradient or partition between anthropogenic and natural aerosol loading. 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 transition to natural (e.g., sea salt) 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 validate satellite retrievals of cloud microphysical properties with in situ measurements, focusing on issues related to aerosol-cloud interactions described above.

2 VOCALS in situ measurements and MODIS retrievals

Wood et al. (2010) provided an overview of the VOCALS field campaign. Other publications provide a comprehensive synthesis of meteorological conditions and 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 C130 and DOE G-1, supplemented by surface observations from the research vessel Ronald H. Brown (Allen et al., 2010; Bretherton et al., 2010; Rahn and Garreaud, 2010; Chand et al., 2010; and Kleinman et al., 2011). Painemal, D. and Zuidema, P. (private communication, 2010) have used C130 measurements to validate the MODIS cloud effective radius and optical thickness over the SEP during VOCALS. Our study extends to multiple aircraft in situ measurements of the G-1 and the C130, with a focus on both the microphysical 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. The lifting condensation level is a good estimate of cloud base height, which can be estimated by reanalysis data of near-surface air temperature and relative humility. In most applications, cloud geometric thickness can be estimated from satellite inferred cloud top temperature and re-analysis. Therefore, it is important to validate MODIS inferred cloud top temperature against in situ measured cloud top temperature. Hence, this study will focus not only on validation of MODIS retrieved cloud optical depth and effective radius, but also on cloud drop number concentration and cloud top

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temperature for the reasons discussed above. These data are from the level 2 cloud retrieval products of MOD06 and MYD06 (King et al., 1997).

Details of G-1 aerosol and cloud microphysical instruments and measurement procedures are described in Kleinman et al. (2011). The in situ measurements and preprocessing procedures used from the C130 are identical to those from the G-1. For each ascent or descent profile, cloud droplet number concentrations, cloud effective radius, cloud liquid water path (vertically integrated LWC measured by a Particle Volume Monitor; PVM; Gerber et al., 1994), and cloud top temperature 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) with diameter between 0.1 and 3 µm. The cloud drop number concentration was determined using a Cloud and Aerosol Spectrometer (CAS) probe integrated over a diameter range between 2.5 and 50 µm.

The cloud drop effective radius derived from measurements of CAS 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 uppermost portion of a cloud. Despite this understanding there is no consensus in the literature defining an equivalent effective radius that is quantitatively representative of the portion of the cloud that dominates the reflected radiance. For an adiabatic cloud, the mean *Re* is 5/6 of the cloud top *Re*, which is equivalent to the averaged *Re* over the top 30 % of the cloud (Brenguier et al, 2000). Therefore, we use both the mean *Re* and the averaged *Re* over the top 30 % cloud in our comparison. In doing so, we also minimize the uncertainties associated with how the cloud top effective radius was defined.

Cloud dynamical processes such as entrainment may be the primary modulator of cloud microphysical properties in certain situations wherein clouds are non-adiabatic. As discussed previously, the current retrievals of CDNC is 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 G-1 had its usual navigational and meteorological package for measuring position, winds, temperature, and dew point. Both temperature and pressure were measured by this navigational and meteorological package, 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.

In general, 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 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 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 validation. 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 G-1 position at the time of Terra and Aqua overpass through back trajectory calculation, respectively. As re-analysis has a coarse resolution with some uncertainty of the wind field, the back trajectory calculation is based on aircraft measured wind speed and direction. Most of the G-1 measurements took place in late morning; thus our validation focuses on Terra-MODIS for both 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 different footprints of satellite sensors, we compare in situ measurements with two different averaging domains: 5 km and 25 km.

3 Results

The cloud geometric 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 116 cloud profiles taken by both G-1 and C130 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.

As shown in Fig. 3, about half of those 116 clouds had adiabaticities less than 0.7, indicating that most stratocumulus clouds in SEP were sub-adiabatical clouds. The cloud geometric 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 aircrafts measurements, and variation of the cloud adiabaticity over the SEP provides an important context and foundation for the subsequent validation of satellite derived parameters. Cloud effective radius derived from MODIS-Terra is compared against *Re* obtained from G-1 and C130 measurements in Fig. 5. For this validation 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. As noted above to test the latter satellite observations association with projected and un-projected airmasses were used. In the case of projected airmasses trajectory analysis is used to find advecting airmasses that were sampled by both satellite and aircrafts. For the un-projected position comparison, shown in the top two plots of Fig. 5, the correlation coefficient between MODIS 5 km averaged *Re* and in situ measured *Re* for the top 30 % of the cloud is 0.78 with a slope of 1.17 and a bias of 1.86 µm. 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 data set it is reasonable to only use the un-projected positions for validating 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. Detailed statistics for both comparisons of projected and un-projected aircraft position and for 5 km and 25 km averaged domains are listed in Table 1 for all compared parameters

As discussed above, 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, the in situ measured CDNC and cloud thickness provide a complete data set for understanding aerosol-cloud interaction and their impacts on satellite retrievals. As shown in Fig. 6, there is a minimum bias of 1.2 µm between aircraft and satellite measurements of *Re* and this difference decreases with increasing CDNC. For a cloud with small CDNC, the cloud *Re* is large, so the resulting differences between that derived from MODIS and that observed from the G1 and C130 are large. On the other hand, the difference between MODIS retrieval and the in situ *Re* increases with cloud geometrical thickness. These characteristics affect the interpretation of observed aerosol-cloud interaction using satellite retrievals. This issue will be further explored in the next section using theoretical simulations of vertically stratified clouds vs. uniform clouds.

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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, 2011; Kleinman et al., 2011). Cloud microphysical properties also exhibited persistent gradients in CDNC and *Re* presumably as a result of the gradient in aerosol properties. Comparing observed *Re* and LWP from MODIS onboard Terra and Aqua at daily and seasonal scales, the differences between two satellites (three hour difference) are relatively small in *Re* and fairly large in LWP. Therefore, one hour difference criteria used for validation could result in a larger difference in LWP than *Re*. Overall, MODIS inferred LWPs are strongly correlated with in situ measurements, 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.

Cloud drop number concentration, which is derived from MODIS retrieved LWP and effective radius, have correlation coefficients of 0.91 and 0.93 with the in situ CDNC at 5 and 25 km scales, respectively. Those correlation coefficients are better than each individual parameter used in the retrievals: i.e., *Re* and LWP. A lower bias and a better one-to-one relation result more for adiabatic clouds than for sub-adiabatic clouds, since the retrievals are based on adiabatic cloud assumption. If we modified Equation 1 by introducing adiabaticity, A_{ad}, we have

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

As shown in the bottom two plots of Fig. 8, better agreements are archived for both averaging domains. It suggests that knowing cloud adiabaticity is a key factor for more accurate estimation of CDNC from satellite remote sensing.

As discussed above, cloud top temperature is an important cloud macrophysical property. For nine of seventeen cases the temperature derived from MODIS was 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. The overall negative bias of 1.65 degrees implies a positive bias of 200 m for cloud top height. 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 geometric thickness.

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. Brenguier et al. (2000) pointed out that such 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 sub-adiabatic clouds. Our validation indicates that the differences between MODIS retrieved and in situ measured microphysical parameters have strong 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 plan-parallel model (VUPPM) is used as our retrieval model to mimic the MODIS retrieval algorithm. 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 the adiabaticity. The cloud single scattering properties of single scattering albedo, asymmetric factor, extinction coefficient as a function of effective radius at both wavelengths are adopted from MODIS ATBD (King, 1997). For an adiabatic cloud, the mean *Re* is 5/6 of the cloud top *Re*, which is used as a reference *Re* for the ASPPM in our following analysis.

Our sensitivity test indicates that the "retrieved" values of cloud optical depth, effective radius, and LWP are insensitive to the cloud geometric thickness in VUPPM. Further, cloud optical depth, which is primarily determined by the reflectance at a non-absorbing band in the visible wavelength of 0.75 µm, is nearly insensitive to cloud vertical structure, as shown in Fig. 10a. This lack of sensitivity to cloud vertical distribution causes both "retrieved" *Re* and LWP to overestimate the actual *Re* and LWP that is prescribed in ASPPM. For an Adiabatic or sub-adiabatic cloud, more cloud water is located at the top of 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. Therefore, the retrieved LWP is overestimated (Fig. 10c) and consequently cloud effective radius is overestimated. These results confirm the findings from our validation. Furthermore, a cloud with a high drop number for a fixed LWC has a small effective radius. As shown in Fig. 10b, the difference between VUPPM ("retrieved") *Re* and ASPPM *Re* decreases with increasing cloud drop number concentration.

Our validation indicates that observed difference between MODIS retrieved *Re* and in situ measured *Re* is sensitive to the cloud geometric thickness and cloud adiabaticity, which is illustrated in Fig. 11. It is clear that the difference of *Re* between VUPPM and ASPPM increases with the cloud geometric thickness, and slightly decreases with the cloud adiabaticity.

For an adiabatic cloud, the "retrieved" properties based on the simplistic adiabatic assumption underestimate or overestimate the CDNC (Fig. 12a) depending on cloud geometric thickness. It clearly illustrates the importance of knowing the cloud geometric thickness. As discussed previously, the cloud geometric thickness can be estimated from the cloud top temperature with the aid of the lifting condensation level from re-analysis. Therefore, it is important to get the cloud top temperature accurately. Furthermore, as shown in Fig. 12b, the "retrieved" CDNC can be underestimated or overestimated, strongly depending on the cloud adiabaticity. 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 substantial 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, resulting 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 validating 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 overpass at both projected and un-projected aircraft positions for two different averaging domains of 5 km and 25 km. Validation of retrieved quantities that were averaged on the large domain of 25 km compared better statistically with in situ observations than averages made on a smaller domain of 5 km. Validations of projected aircraft positions were slightly better than un-projected aircraft positions for some parameters. Overall, both MODIS retrieved *Re* and LWP were highly correlated with but larger than the in situ measured *Re* and LWP. The observed *Re* difference between the two decreased with increasing cloud drop number concentration, and increased with increased cloud geometrical thickness. Also MODIS retrievals for adiabatic clouds agreed better with the in situ measurements than for sub-adiabatic clouds. Those observed characteristics from validation were 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 parameterization of this effect in numerical models. Strong correlations between satellite retrievals and in situ measurements suggests 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. However, our validation and sensitivity analysis of simulated retrievals demonstrate that both cloud geometrical thickness and

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cloud adiabaticity are factors that impact satellite retrievals of *Re* 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 substantial uncertainties and biases in satellite retrieved cloud effective radius, cloud liquid water path, and cloud drop number concentration. Therefore, as demonstrated by our validation, 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 top temperature and re-analysis near-surface air temperature and relative humility, or directly measured from active cloud radar and lidar sensors (such as CloudSat and Calipso) Although such a relationship varies with metrological 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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Table 1. Statistics of comparison of MODIS retrievals with aircraft measurements for both projected and unprojected positions at both 5 and 25 averaging domains. *r*, *p*, *k*, and *b* are the correlation coefficient, the probability p-value, the slope of linear fit, and the bias, respectively.

Terra (1h)	Total				Adiabatic > 0.7				Adiabatic < 0.7			
5 km	*r*	*p*	*k*	*b*	*r*	*p*	*k*	*b*	*r*	*p*	*k*	*b*
CDNC	0.91	0	1.23	55.94	0.88	0.0009	1.06	49.74	0.97	0.0004	1.46	63.76
LWP	0.76	0.0006	0.85	0.03	0.75	0.0197	0.81	0.03	0.52	0.2287	1.05	0.02
CRE	0.78	0.0004	1.17	1.86	0.78	0.0132	1.13	1.65	0.84	0.0192	1.48	2.10
CTT	0.37	0.1436	0.32	1.65	0.54	0.1077	0.39	1.83	−0.28	0.5454	−0.49	1.34
CTP	0.5	0.0424	1.04	248.45	0.34	0.3436	1.43	247.7	0.69	0.0851	1.57	249.53
Terra (Back)												
5 km												
CDNC	0.94	0	1.30	55.05	0.92	0.0001	1.23	48.87	0.98	0.0001	1.40	62.84
LWP	0.65	0.0064	0.82	0.03	0.69	0.0394	0.79	0.03	0.68	0.0940	2.17	0.03
CRE	0.8	0.0002	1.24	1.79	0.88	0.0020	1.54	1.65	0.74	0.0574	1.07	1.95
CTT	0.40	0.1116	0.81	1.63	0.51	0.1374	0.95	1.83	−0.20	0.6645	0.46	1.29
CTP	0.55	0.0226	1.20	247.20	0.43	0.2093	1.64	246.21	0.79	0.0326	2.07	248.60
Terra (1 h)												
25 km												
CDNC	0.91	0	1.23	55.94	0.88	0.0009	1.06	49.74	0.97	0.0004	1.46	63.76
LWP	0.76	0.0006	0.85	0.03	0.75	0.0197	0.81	0.03	0.52	0.2287	1.05	0.02
CRE	0.78	0.0004	1.17	1.86	0.78	0.0132	1.13	1.65	0.84	0.0192	1.48	2.10
CTT	0.37	0.1436	0.32	1.65	0.54	0.1077	0.39	1.83	−0.28	0.5454	−0.49	1.34
CTP	0.5	0.0424	1.04	248.45	0.34	0.3436	1.43	247.7	0.69	0.0851	1.57	249.53
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LWP	0.65	0.0064	0.82	0.03	0.69	0.0394	0.79	0.03	0.68	0.0940	2.17	0.03
CRE	0.8	0.0002	1.24	1.79	0.88	0.0020	1.54	1.65	0.74	0.0574	1.07	1.95
CTT	0.40	0.1116	0.81	1.63	0.51	0.1374	0.95	1.83	−0.20	0.6645	0.46	1.29
CTP	0.55	0.0226	1.20	247.20	0.43	0.2093	1.64	246.21	0.79	0.0326	2.07	248.60

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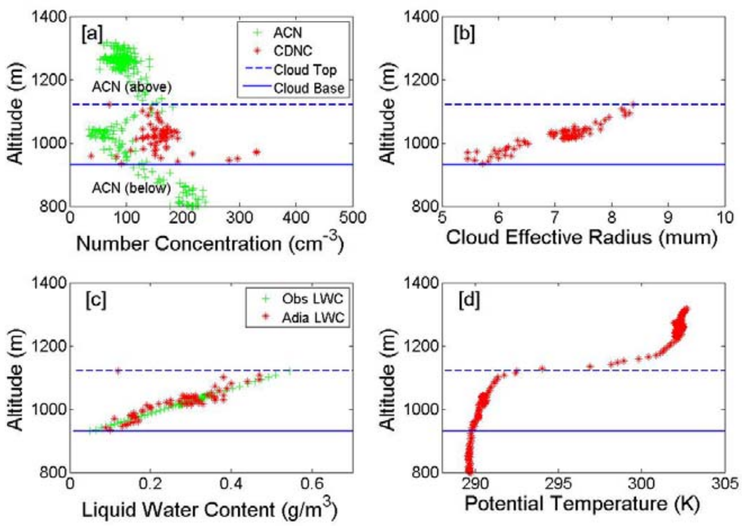

Fig. 1. Vertical distribution of aerosol concentration number (ACN), cloud drop number concentration (CDNC), cloud effective radius (*Re*), cloud liquid water content (LWC), and atmospheric temperature measured by G1 on 6 November 2008.

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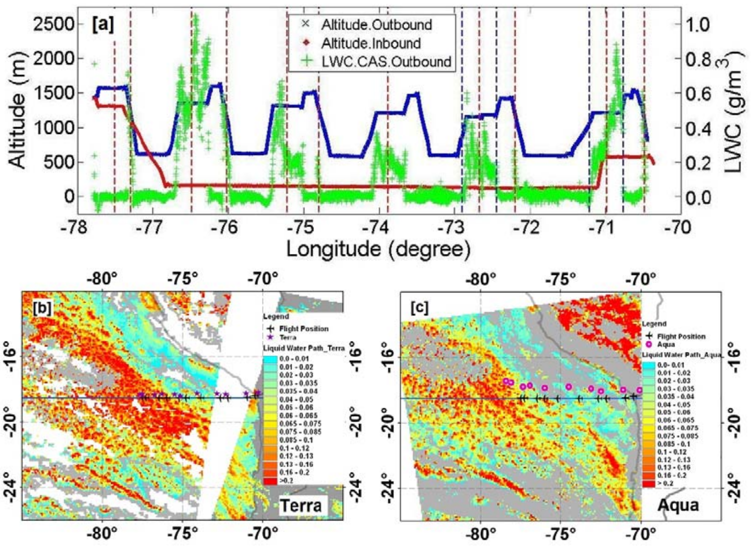

Fig. 2. Longitude – altitude cross section of G-1 flight track for 20081028 and measured LWC along the track; and LWP images from Terra-MODIS and Aqua-MODIS. The blue line in the image indicates the G-1 flight track and the pink stars represent the projection of G-1 position at the time of the satellite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

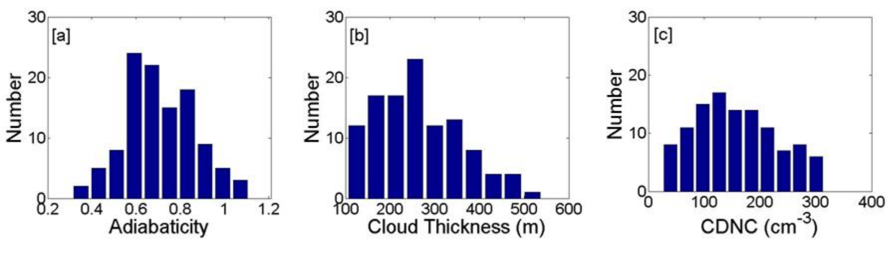

Fig. 3. Distribution of the **(a)** adiabaticity, **(b)** geometric vertical thickness and **(c)** cloud droplet number concentration among 116 clouds profiled by the G-1 and C130 during VOCALS.

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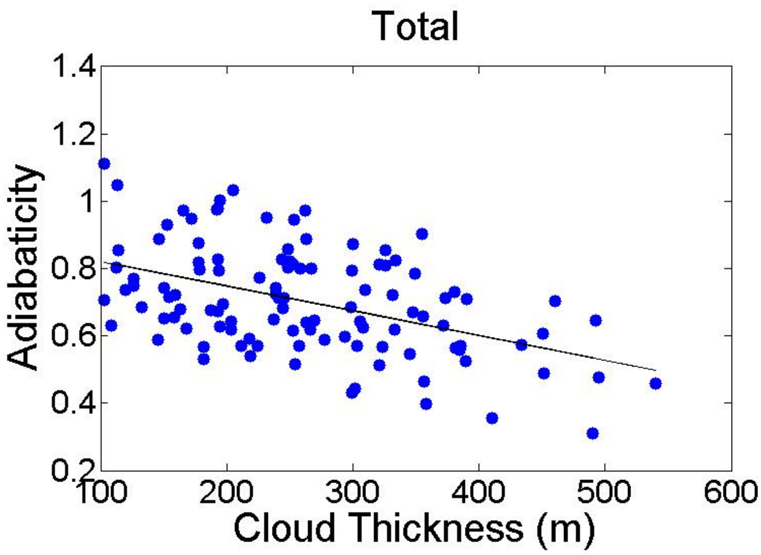

Fig. 4. The adiabaticity of the clouds profiled by the G-1 and C130 aircrafts as a function of geometric thickness for all cases.

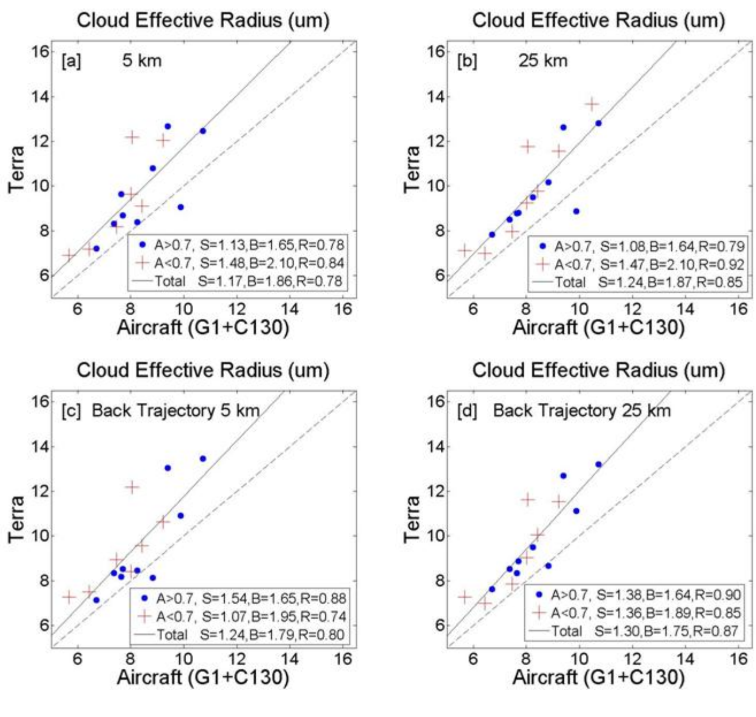

Fig. 5. Comparison of cloud effective radius retrieved from Terra-MODIS with combined in situ measurements from both G1 and C130: Top two plots for un-projected positions at 5 and 25 km domain averages; Bottom two plots for projected positions. The capital letters A, S, B and R represent adiabaticity, slope, bias and correlated coefficient respectively (used in the other figures in this paper). The dashed lines represent 1:1 lines, and the solid lines represent 6/5:1 lines.

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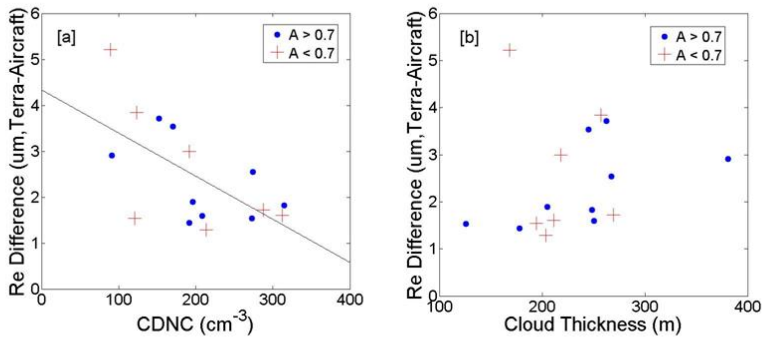

Fig. 6. The difference between Terra-MODIS retrievals and aircraft measurements of cloud effective radius as a function of cloud drop number concentration and cloud geometric thickness.

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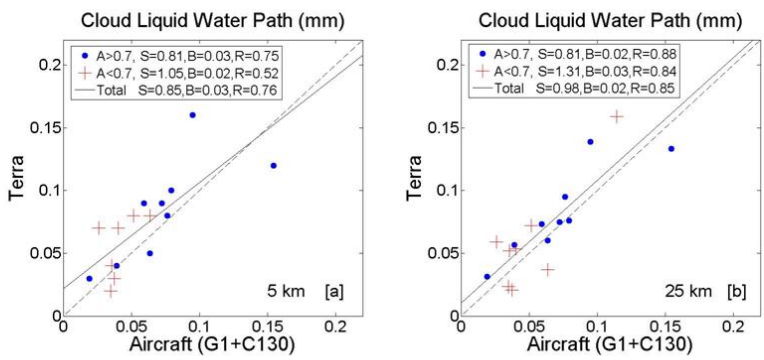

Fig. 7. Comparison of cloud liquid water path derived from MODIS with in situ measurements.

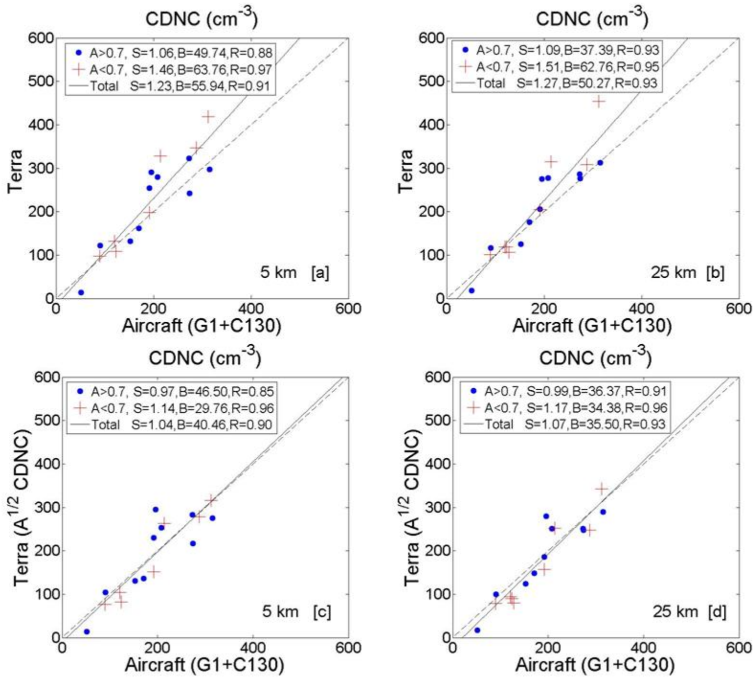

Fig. 8. Comparison of retrieved and modified cloud drop number concentration from MODIS with the in situ measurements: top two plots for the retrieved CDNC, and the bottom two plots for the modified MODIS CDNC. The dashed-lines are for the 1:1 lines; and the solid lines are for the best fit.

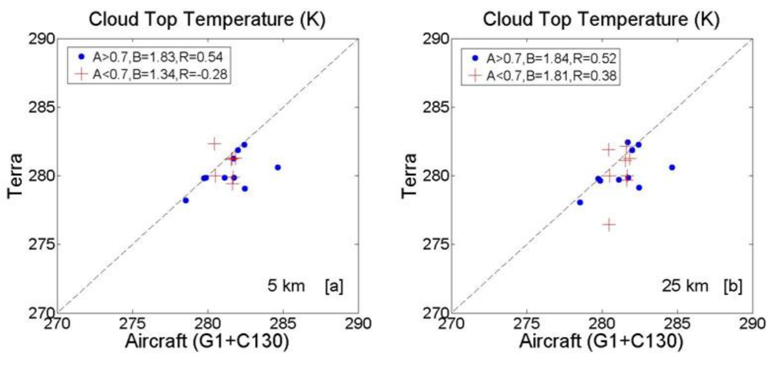

Fig. 9. Comparison of retrieved cloud top temperature from MODIS with the in situ measurements: the dashed-lines are for the 1:1 lines.

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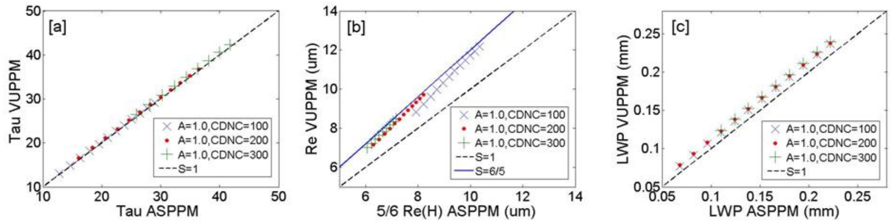

Fig. 10. Comparison of retrieved cloud optical depth (Tau), cloud effective radius (*Re*), and Cloud liquid water path (LWP) from VUPPM with ASPPM for cloud drop number concentrations of 100, 200, and 300 cm^{-3}.

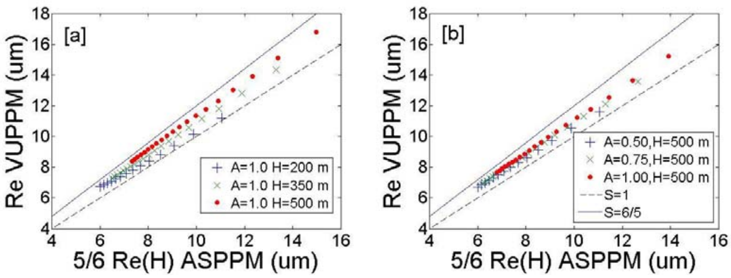

Fig. 11. Comparison of retrieved cloud effective radius (*Re*) from VUPPM and ASPPM for various cloud geometric thickness and cloud adiabaticity.

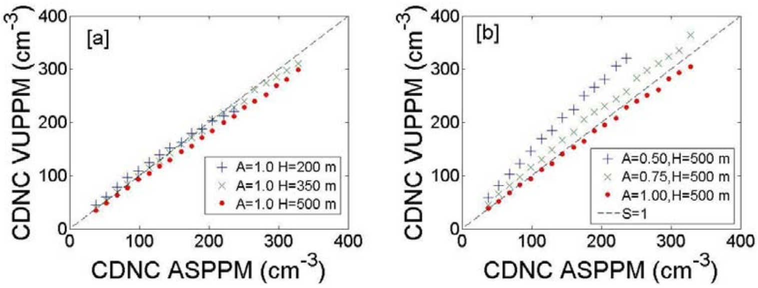

Fig. 12. Comparison of retrieved cloud drop number concentration from VUPPM with ASPPM.