

## Review of Q. Min et al., 2012 (M12)

This paper (M12) compares in-situ derived values of effective radius, droplet concentrations and liquid water path (from aircraft profiles) with Terra satellite derived values (using the adiabatic cloud assumption) that were within one hour of the flight profiles. It also performs radiative transfer calculations for an adiabatically stratified liquid water profile cloud and compares them with those from a vertically uniform model (similar to what is used for MODIS cloud retrievals of  $R_e$  and optical depth).

The paper is quite similar to another recent paper (Painemal, JGR, 2011; P11) that also uses data from the VOCALS campaign. The main difference is that M12 also uses data from both the G-1 aircraft and the C-130, whereas P11 used only C-130 data. Section 4 of M12 also makes it unique from P11. These differences probably make M12 sufficiently different to merit publication.

However, there are a number of serious issues, such as wrong statements and misinterpretations that first need addressing. The main issues are listed below. Typos and grammar corrections (plus additional comments) are documented in the modified manuscript further below.

### Main issues:-

Abstract, p. 1434

“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.”

>>> I think that these statements go a little far, especially when the comparisons between the retrieved and measured CDNC (and other variables) are fairly reasonable, (e.g. Fig. 8), particularly if some sub-adiabaticity is assumed. Have you also looked at the errors associated with the satellite retrievals of optical depth and  $R_e$  to see if they can account for the differences? Likewise there should be more discussion of the errors in the aircraft observation measurements.

p.1425 –

“. For an adiabatic cloud, the mean  $R_e$  is  $5/6$  of the cloud top  $R_e$  “

>>> This is not what is stated in Brenguier (2000). The effective radius in a vertically uniform cloud (for the same optical depth and LWP) would be  $5/6$  of the effective radius at the top of an adiabatically stratified cloud.

The effective radius is proportional to  $h^{1/3}$  for an adiabatic cloud. Therefore, the mean  $R_e$  over an adiabatic cloud would be  $\frac{3}{4}$  of the cloud top  $R_e$ . Thus, I think that there is some confusion here.

“, which is equivalent to the averaged  $R_e$  over the top 30% of the cloud (Brennguier et al, 2000).”

>>> This doesn't make sense since the mean over the whole cloud cannot be exactly the same as the mean over the top 30% of the cloud. If you mean that the mean  $R_e$  over the top 30% of the cloud is equal to the cloud top  $R_e$   $\cdot 5/6$  then I think that this is also wrong. My calculations suggest that the mean  $R_e$  over the top 30% of an adiabatically stratified cloud would be the cloud top  $R_e \cdot 0.95$ . So the quoted means over the upper 30% will actually probably be close to the cloud top  $R_e$ , which is actually what the satellite likely samples (likely the  $R_e$  1-3 optical depths from the top of the cloud – see Painemal, 2011) for refs.

Confusion on this appears throughout the paper and needs to be rectified. Presumably the statistics in Fig. 5 and Table 1 are calculated using the actual values (and not  $\cdot 6/5$ ). The addition of the  $6/5$  line in these plots adds to the confusion. Removal of the mentioning of the  $5/6$  factor until section 4 (where it actually applies) would help to reduce the confusion.

p. 1427 and Fig. 3

I am concerned here about the possibility of uncertainties in the cloud top and cloud base heights affecting this outcome. The theoretical adiabatic max LWP varies with the square of the cloud depth and would be very sensitive to the assumed cloud depth. The datapoints here need errorbars to estimate this effect.

For example, small amounts of LWC above the position of max LWC (hereafter  $z_{max}$ ) in an otherwise adiabatic profile would could act to increase the theoretical adiabatic LWP substantially, leading to a much lower value of the adiabaticity as calculated here. However, as long as the LWP above  $z_{max}$  is not substantial, the effective radius seen by a satellite looking down would be close to that at  $z_{max}$  and the overall LWP would be similar to the adiabatic case.

Thus, the parameter  $A$  might not be a good measure of how well the satellite retrieval is likely to be unless all of the profiles are linear with very little cloud depth above  $z_{max}$ . Can it be verified that this was the case? Perhaps a better measure might be the ratio of the max LWC of the observed profile to that expected from an adiabatic ascent to there from cloud base?

p.1430 and other places.

Using the CTT and the estimated cloud base height from reanalysis would be quite an indirect way of inferring cloud top height anyway. The estimation of the cloud base height would also introduce large errors.

Cloud geometric height is usually estimated using the measured LWP and assuming a linear increase of LWC with height (along with  $N_d$ , as in Bennartz 2007). It would be better to test this method using the

in-situ data. Or the mention about cloud depth might be removed as it is not key here (although the CTT comparison is still useful)

At the least the LWP method should be mentioned.

p.1430

“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.”

>>> I disagree – they are not particularly strong for the cloud thickness dependency (Fig. 6b). And also, are the percentage changes in  $R_e$  are strong as a function of CDNC (since CDNC is a strong function of  $R_e$ )? Might be better to plot Fig. 6 as percentage differences.

p.1431

“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.”

>>> This statement needs justifying through some analysis or a reference. Otherwise it should be suggested as a speculation rather than fact.

“As shown in Fig. 10b, the

difference between VUPPM (“retrieved”)  $R_e$  and ASPPM  $R_e$  decreases with increasing

cloud drop number concentration.”

>>> It looks to me like the difference between the expected VUPPM of  $5/6 * R_{e\_ASPPM}$  at cloud top and the actual VUPPM increases with increasing CDNC from Fig. 10b.

p.1432

“It clearly illustrates the importance of knowing the cloud geometric

thickness.”

>>> I don't really agree with this – the CDNC retrieval seems fairly robust regardless of the cloud depth for the adiabatic clouds.

“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.”

>>> It is not clear what  $N_d$  has been calculated for the ASPPM values for the sub-adiabatic clouds in Fig. 12b. Has the expected reduction in  $N_d$  with reducing effective  $C_w$  been taken into account? ( $N_d$  proportional to  $C_w^{(1/2)}$  ).

I.e. are these results just what would be expected based on the adiabatic model? Or are there some other deviations due to the VUPPM assumption?

#### Section 4

The definition of the cloud profile used for the VUPPM LWC should be explained.

## 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~~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. Validation at projected aircraft positions was slightly better than un-projected aircraft positions for some parameters. Overall, both MODIS15 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

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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

~~microphysies-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 ~~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, 1421

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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:

CDNC=

$C^{1/2}$

w

k

$10^{1/2}$

$4^{1/2}$

w

$1/2$

$Re^{5/2}$

(1)

**Comment [D1]:** It would be good to quote e.g. Bennartz, JGR, 2007 or Boers, JGR, 2006, which show the derivations of this formula.

Where  $C_w$  is the moist adiabatic condensate coefficient, and is constant over a short altitude range (Breguier, 1991). Its value depends slightly on the temperature of the

cloud layer, ranging from  $1$  to  $2.5 \times 10^{-3} \text{ gm}^{-4}$  for a temperature between  $0$  and  $40^\circ\text{C}$ .

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The coefficient  $k$ , which represents the effect of droplet spectral shape on radiation, is between  $0.7$  and  $1$ , and  $\rho_w$  is density. Both  $\tau$  and  $R_e$  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~~ 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

concurrently experiences a sharp gradient or partition between anthropogenic and natural aerosol loading. Aerosols near the Chilean coast are dominated

by  $\text{SO}_2$  emissions from copper smelters. Away from the coast towards the open-ocean

the aerosol loading quickly transition transitions 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.

**Comment [D2]:** What pressure are these values quoted for?

**Comment [D3]:** Why not quote for sub-zero temperatures, rather than v. warm temperatures since cloud bases are unlikely to at such warm temperatures?

**Comment [D4]:** This is perhaps ambiguous.  $k$  is the ratio between the volume mean radius cubed and the effective radius cubed, i.e.  $(r_v/r_e)^3$

**Comment [D5]:** A reference should be provided here (e.g. Martin, JAS, 1994)

**Comment [D6]:** Not needed

**Comment [D7]:** This requires a bit more explanation/re-writing or a reference. Do you mean that vertical variations are inconsistent with the satellite  $\tau$ ,  $R_e$  retrieval assumptions?

**Comment [D8]:** This reference is not listed in the references section.

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.

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## 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, ~~and~~ 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.

20 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 ~~using by reanalysis data of~~ near-surface air temperature and relative ~~humility~~ humidity ~~reanalysis data~~.

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 the 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 the G-1 aerosol and cloud microphysical instruments and measurement procedures are described in Kleinman et al. (2011). The in situ measurements and pre-processing 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~~ radii, cloud liquid water ~~path~~ paths (vertically integrated LWC measured by a Particle Volume Monitor; PVM; Gerber et al., 1994), and cloud top ~~temperature~~ 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) ~~with for diameter~~ diameters between 0.1 and 3  $\mu\text{m}$ . 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  $\mu\text{m}$ .

The cloud drop effective radius derived from CAS 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 the 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 (Breguier et al, 2000). Therefore, we use both the mean Re and the

averaged Re over the top 30% of the clouds 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 potentially leading to clouds that are non-adiabatic.

As discussed previously, the current retrievals of CDNC is-are based on the adiabatic assumption.

It is important to understand the impact of cloud adiabaticity on satellite

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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 instru15

ments. Figure 2 shows the longitude-altitude cross section of the G-1 flight track and measured

**Comment [D9]:** This is not what is stated in Breguier (2000). The effective radius in a vertically uniform cloud (for the same optical depth and LWP) would be 5/6 of the effective radius at the top of an adiabatically stratified cloud.

The effective radius is proportional to  $h^{1/3}$  for an adiabatic cloud. Therefore, the mean Re over an adiabatic cloud would be  $\frac{1}{3}$  of the cloud top Re. Thus, I think that there is some confusion here.

**Comment [D10]:** This doesn't make sense since the mean over the whole cloud cannot be exactly the same as the mean over the top 30% of the cloud.

If you mean that the mean Re over the top 30% of the cloud is equal to the cloud top Re \* 5/6 then I think that this is also wrong. My calculations suggest that the mean Re over the top 30% of an adiabatically stratified cloud would be the cloud top Re \* 0.95. So the quoted means over the upper 30% will actually probably be close to the cloud top Re, which is actually what the satellite likely samples (likely the Re 1-3 optical depths from the top of the cloud – see Painemal, 2011) for refs.

Again, there seems to be confusion throughout the paper on these issues.

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.

20 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 [the position of the G-1 aircraft position](#) at the time of [the](#) Terra and Aqua overpasses, [respectively, as calculated through from back trajectory calculation trajectories,](#)

[respectively](#). 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

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and direction. Most of the G-1 measurements took place in [the](#) late morning; thus our validation 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 Clouds and Earth's Radiant Energy System (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-adiabatic clouds. The cloud geometric thickness varied from 100m to 500 m. The measured CDNC varied from 25 to 300  $\text{cm}^{-3}$ . 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 provides an important context and foundation for the subsequent validation of satellite derived parameters. Cloud effective radius derived from MODIS-Terra  $a_{\text{re}}^{\text{MODIS}}$  compared against  $R_e$  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

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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

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 aircraft.

For the un-projected position comparison, shown in

the top two plots of Fig. 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 the MODIS 5 km averaged values

$R_e$  and in situ measured  $R_e$  for the top 30% of the cloud observations is 0.78 with a slope of 1.17

**Comment [D11]:** I am concerned here about the possibility of uncertainties in the cloud top and cloud base heights affecting this outcome. The theoretical adiabatic max LWP varies with the square of the cloud depth and would be very sensitive to the assumed cloud depth. The datapoints here need errorbars to estimate this effect.

For example, small amounts of LWC above the position of max LWC (hereafter  $z_{\text{max}}$ ) in an otherwise adiabatic profile would act to increase the theoretical adiabatic LWP substantially, leading to a much lower value of the adiabaticity as calculated here. However, as long as the LWP above  $z_{\text{max}}$  is not substantial the effective radius seen by a satellite looking down would be close to that at  $z_{\text{max}}$  and the overall LWP would be similar to the adiabatic case.

Thus, the parameter A might not be a good measure of how well the satellite retrieval is likely to be unless all of the profiles are linear with very little cloud depth above  $z_{\text{max}}$ . Can it be verified that this was the case? Perhaps a better measure might be the ratio of the max LWC of the observed profile to that expected from an adiabatic ascent to there from cloud base?

and a bias of  $1.86 \mu\text{m}$  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  $1.79 \mu\text{m}$ . These results

are statistically equivalent, indicating that in this data set/dataset 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, whereas the in situ measured

CDNC and cloud thickness provide a more complete data set/dataset for understanding aerosol

cloud interactions and their impacts on satellite retrievals. As shown in Fig. 6, there

is a minimum bias of  $1.2 \mu\text{m}$  between aircraft and satellite measurements of  $R_e$  and

this difference decreases with increasing CDNC. For a cloud with small CDNC, the

cloud  $R_e$  is large, so the resulting differences between that the values derived from MODIS and

that those observed from the G1 and C130 are large. On the other hand, the difference

between the MODIS retrieval and the in situ  $R_e$  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  $R_e$  presumably as a

**Comment [D12]:** You need to make it clear here that hereafter in the paper you will only refer to the unprojected cases (presumably?) Also what is being used for Fig. 6 – 5 or 25 km averaging?

**Comment [D13]:** They don't provide an absolutely complete dataset

**Comment [D14]:** This sentence doesn't make sense – should there be a “whereas” before “the in-situ” ?

**Comment [D15]:** It is hard to make this claim from from Fig 6b.

result of the gradient in aerosol properties. Comparing observed Re and LWP from MODIS onboard Terra and Aqua at-on daily and seasonal scales/timescales, the differences between the two satellites (three hour difference) are relatively small in Re and fairly large in LWP.

**Comment [D16]:** Other factors such as the variation of precipitation rates are also likely to have played a role.

**Comment [D17]:** This statement needs a reference.

Therefore, the 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 (Fig. 7), with correlation coefficients of 0.76 and 0.85 for 5 and 25 km averages, respectively. MODIS retrievals overestimate LWP by approximately 0.03mm and 0.02mm 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.

Fig. 8 compares MODIS cloud drop number concentrations, which is (derived from MODIS retrieved LWP and

effective radius, see Equation 1) to those observed in-situ. Correlation, have correlation coefficients of 0.91 and 0.93 with the in situ CDNC were found at using

5 and 25km averaging scales, respectively. Those correlation coefficients are better than those for each individual parameter used in the retrievals: i.e., Re and LWP. A lower bias and a better relationship closer to

one-to-one relation results more for adiabatic clouds than for sub-adiabatic clouds, since the retrievals are based on an adiabatic cloud assumption. If we modified/modify Equation 1 by introducing adiabaticity, A<sub>ad</sub>, we have

$$NCDNC = \frac{(A_{ad}C_w)^{1/2}}{k} \left( \frac{4}{w} \right)^{1/2} Re^{5/2} \quad (2)$$

As shown in the bottom two plots of Fig. 8, better agreements are archived/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.

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 1429

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the remaining eight cases was underestimated by MODIS, with a total bias of ~~-1.65~~ ~~-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 200m 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 [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 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.**

**Comment [D18]:** However, using the CTT and the estimated cloud base height from reanalysis would be quite an indirect way of inferring cloud top height anyway. The estimation of the cloud base height would also introduce large errors.

Cloud geometric height is usually estimated using the measured LWP and assuming a linear increase of LWC with height (along with  $N_d$ , as in Bennartz 2007). It would be better to test this method using the in-situ data. Or the talk about cloud depth might be removed as it is not key here (although the CTT comparison is still useful)

At the least the LWP method should be mentioned.

**Comment [D19]:** I disagree – they are not particularly strong for the cloud thickness dependency (Fig. 6b). And also, are the percentage changes in  $R_e$  are strong as a function of CDNC (since CDNC is a strong function of  $R_e$ )? Might be better to plot Fig. 6 as percentage differences.

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  $\mu\text{m}$  wavelengths (similar to those used for MODIS cloud properties retrieval algorithm, King et al., 1997). The

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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, and extinction coefficient as a function of effective radius at both wavelengths are adopted from MODIS ATBD (King, 1997). For an adiabatic cloud, the mean  $R_e$  is 5/6 of the cloud top  $R_e$ , which is used as a reference  $R_e$  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 nonabsorbing band in the visible wavelength of 0.75  $\mu\text{m}$ , is nearly insensitive to cloud vertical structure, as shown in Fig. 10a. This lack of sensitivity to cloud vertical distribution causes both “retrieved”  $R_e$  and LWP to overestimate the actual  $R_e$  and LWP that is prescribed in ASPPM. For an ~~Adiabatic-adiabatic~~ or sub-adiabatic cloud, more cloud water is

**Comment [D20]:** This is not clear. A better way to put this would be that LWC is increasing linearly with height, but at a sub-adiabatic rate.

**Comment [D21]:** See earlier comments – this is not correct.  
Also it needs to be made clear that the ASPPM retrieved  $R_e$  ( $R_e(H)$ ) as written in Fig. 10) will be the  $R_e$  a little way below cloud top (1-3 optical depths) and so not strictly equal to  $R_e(H)$ . However, it is likely to be quite close.

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.

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

**Comment [D22]:** This statement needs justifying through some analysis or a reference. Otherwise it should be suggested as a speculation rather than fact.

**Comment [D23]:** What does this mean? What part of the validation and how?

**Comment [D24]:** It looks to me like the difference between the expected VUPPM of  $5/6 * Re_{ASPPM}$  at cloud top and the actual VUPPM increases with increasing CDNC from Fig. 10b.

**Comment [D25]:** I don't really agree with this – the CDNC retrieval seems fairly robust regardless of the cloud depth for the adiabatic clouds.

**Comment [D26]:** As mentioned before, this would be quite an indirect and likely inaccurate way of estimating H, so I don't agree with this line of reasoning.

**Comment [D27]:** It is not clear what Nd has been calculated for the ASPPM values for the sub-adiabatic clouds in Fig. 12b. Has the expected reduction in Nd with reducing effective Cw been taken into account? (Nd proportional to  $Cw^{1/2}$ ).  
I.e. are these results what would be expected based on the adiabatic model?

## 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

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Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper | 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 adiabaticity 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. ~~Validation of retrieved~~ Retrieved quantities that were averaged ~~on over the a large~~ domain of ~~side~~ 25 km compared better statistically with in situ observations

than averages made ~~over on~~ a smaller domain of ~~side~~ 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

**Comment [D28]:** Precipitation and other factors may also play a role.

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~~The observed  
characteristics from the validation were consistent with our theoretical simulations  
of a vertically stratified cloud model.

**Comment [D29]:** I disagree.

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  
parameterizations of this  
effect in numerical models. Strong correlations between satellite  
retrievals and in situ measurements suggests-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. 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  $R_e$  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 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

**Comment [D30]:** The effect on LWP looked fairly  
minor (Fig. 10c)?

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 ~~humidity~~humidity, or directly measured from active cloud radar and lidar sensors (such as CloudSat and Calipso) Although such a relationship varies with ~~metrological-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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Table 1. Statistics of the comparison of MODIS retrievals with aircraft measurements for both projected (labeled “Back”) and unprojected positions and both 5 and 25 km averaging domains.  $r$ ,  $p$ ,  $k$ , and  $b$  are the

correlation coefficient, the probability p-value, the slope of linear fit, and the bias, respectively.

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**Comment [D31]:** This should be given a little more explanation.  
You should also explain the parameters (CDNC, etc.) and their units.

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## Figures

Fig. 1. Vertical ~~distribution-distributions~~ 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 the G-1 flight track for 20081028 and measured LWC

along the track; and LWP images Terra-MODIS and Aqua-MODIS. The blue line in the

image indicates the G-1 flight track and pink stars represent the projection of the G-1 position at

the time of the satellite overpass ~~through-from~~ back trajectory calculations.

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Figure 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.

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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.

**Comment [D32]:** 2b and 2c are very hard to read. Particularly, the stars and circles are hard to see, as is the text for the LWP values. It would be helpful if these images were made larger and at higher resolution. E.g. they could be placed on top of each other in 3 rows.

**Comment [D33]:** What about the circles?

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

**Comment [D34]:** You need to add what spatial averaging was used here.

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

**Comment [D35]:** Include the fact that the left plot is for 5km averaging and the right for 25km in the caption.

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

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Figure 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 ( $R_e$ ), and Cloud liquid water path (LWP) from VUPPM with ASPPM for cloud drop number concentrations of 100, 200, and 300  $\text{cm}^{-3}$ .

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Figure 11. Comparison of retrieved cloud effective radius ( $R_e$ ) from VUPPM and ASPPM for Various cloud geometric thickness and cloud adiabaticity.

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

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