Response to Reviewer 1

Monday, March 19, 2018
2:37 PM

We thank both of the reviewers for taking the time to read and comment on the paper; your have helped to greatly improve the paper. The reviewer comments are repeated below in green italics and our responses are in black.

Responses to Reviewer 1

The manuscript describes a method that, in principle, corrects errors in adiabatic satellite cloud droplet number concentration (Nd) due to the inconsistency of utilizing satellite cloud effective radius (r_e) that represents values slightly below the cloud top, whereas satellite cloud optical depth (tau) fully captures the optical thickness of the clouds. To achieve this goal, the authors simulate a number of idealized cloud profiles with a 1D radiative transfer model, and then retrieve r_e and tau from the synthetic reflectances. Next, the authors derive an "effective" tau that corresponds to the optical thickness where the retrieved r_e and the synthetic r_e match each other (the vertical penetration effect). They use the difference between the retrieved and the effective tau (applying a fit to their theoretical calculations) to quantify the error in MODIS-based Nd that does not account for the fact that the satellite r_e is not exactly that at the cloud top due to the vertical photon penetration, which is in turn dependent on the sensor wavelength and the specific thickness of the cloud (and probably solar zenith angle and viewing geometry).

The manuscript makes an interesting use of the results in Platnick (2000), which shows that the retrieved r_e should differ from the observed r_e by a few um (or less) due to the photon penetration. The manuscript is concise and well-written, however when I first browsed the paper, I got confused about whether the authors wanted to show a real satellite bias in tau (and Nd) or a methodological bias (I realized it was the latter).

My fundamental criticism of Grosvenor et al. is that, from a remote sensing point of view, the problem is not that the satellite tau should be reduced because r_e is not at the cloud top. Instead, it is that is smaller than the observed r_e at the top due to vertical stratification, and probably r_e should be somehow increased (i.e. r_e drives the uncertainty in Nd). This is the correct interpretation, as it is well known from the early work by Nakajima (King and co-authors) that satellite tau is almost insensitive to the cloud vertical structure, and only r_e can be greatly affected by the vertical stratification. So, the Nd bias should be expressed in terms of a delta r_e. Another inconsistency (related to my previous comment) is with the use of the (pseudo) adiabatic model, which if I interpret correctly, it implies that the liquid water path (LWP) is proportional to r_e*tau.
So, any error calculation applied to Nd has to be also valid for LWP.

However, if we apply equation (13) to LWP, i.e.:

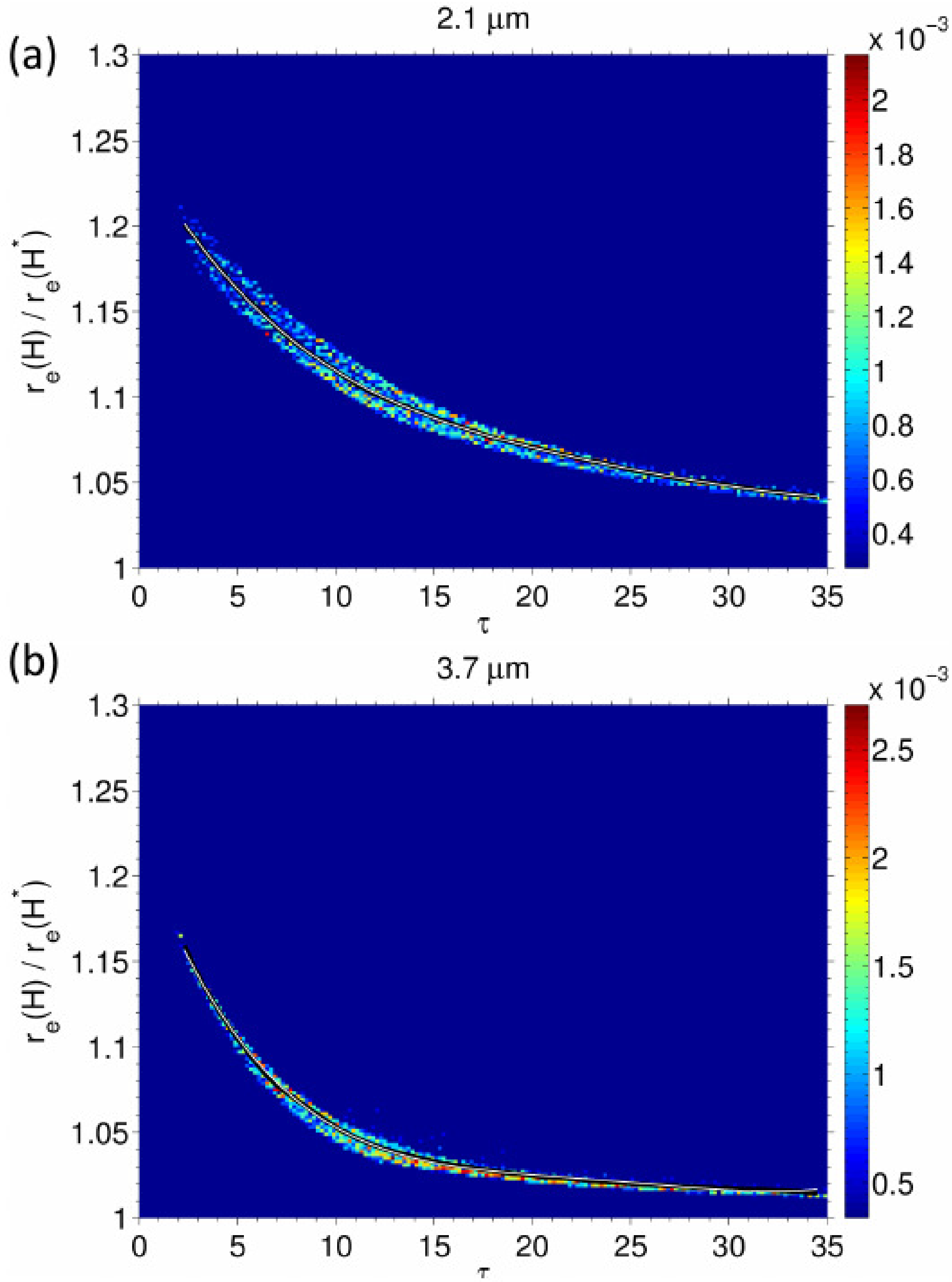
LWP_uncorrected/LWP_corrected=(tau/(tau-dtau))

Using a dtau=4.5 for tau=10 (figure 1a), then LWP_uncorrected/LWP_corrected=10/6.5=1.54. A 54% overestimation in LWP is clearly a mathematical contradiction. On the other hand, if, for instance, we utilize the results in Platnick (2000) for a cloud top r_e =12 um, and a retrieved r_e= 10.7 um (2.1 um wavelength), we get:

LWP_uncorrected/LWP_corrected=r_uncorrected/r_corrected=10.7/12=0.89.

That is, the retrieved r_e yields an underestimation of LWP. Again, this result points to a main reasoning problem in the manuscript, which is, the error should not be expressed in terms of tau.

We were originally considering the special case of the Nd retrieval that makes the assumption that at cloud top and the application to LWP was not considered; the original method using the tau correction only applies to the Nd retrieval and not to the LWP calculation, which we did not make We originally chose to use a tau correction since the correction for tau seemed simpler to and less prone to uncertainties in the parameterization. Further work following from your (and those of the other reviewer) has shown that dre/re can also be modelled fairly accurately with a fitted curve and so we now also present results using this formulation and make some estimates of LWP bias too. The following new figures are included showing 2D histograms of the re correction (divided by re)vs the optical depth, along with the parameterized fit to the data (as previously shown the tau correction) :-



Lastly, the authors say that there are several other errors that can bias r_e and tau. This is a key statement, and a literature review will show that biases in r_e are not dominated by the cloud stratification (I am not aware of any studies that actually show an adiabatic signature in the satellite r_e bias). For instance, If one calculates the difference between MODIS r_e at 2.1 um and 3.7 um, the difference is positive everywhere over the ocean (the difference can be larger than 5 um, see Fig. 10 in Zhang and Platnick, 2011). This result suggests that the error discussed in Grosvenor et al. is negligible. So, I find it surprising that the authors found errors up to 50 % in Nd (Figure 6), which is very large. Since their results are only valid in a plane parallel world (sub-pixel variability is not accounted for) and with the use of idealized profiles, the validity of the correction cannot be demonstrated. The authors do discuss some of these issues but, unfortunately, the main concern remains, that is, it is unclear that the correction will yield an improved estimate of cloud droplet number concentration.

We agree that other r_e biases are important for Nd retrievals and are probably of equal or stronger magnitude than the changes in r_e due to the vertical profile changes. In the original paper we wrote 16, line 10) :-

- "It is also clear that the suggested correction for the vertical penetration effect should only be applied to the retrievals of Nd with consideration of other bias sources. These other potential error sources are numerous and include re biases due to sub-pixel heterogeneity (Zhang and Plantnick, 2011; Zhang et al., 2012, 2016); 3D radiative effects (Marshak et al., 2006);…" (etc.)

And on p.10, line 12:-

- "Thus, the application of the correction described in this paper in isolation has the potential enhance any negative bias in Nd caused by a positive re bias."

we caution the reader that the bias correction should only be applied after other biases have been accounted for. We realize that this limits the current usefulness of the correction until the other have been quantified - we therefore have added the following text to the and of the above :-

- "; it is thus recommended that the bias correction is not applied until the other error sources been fully characterized."

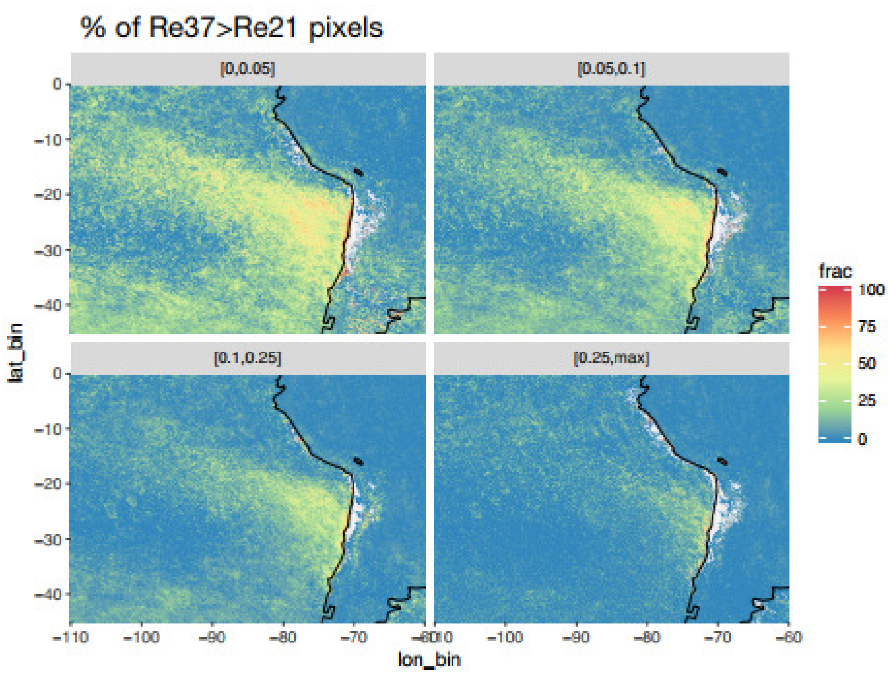
Also we have modified the following paragraph in the conclusions to make this point clearer and to recommend restriction to low heterogeneity situations (see later for the justification for this) :-

We caution that the correction for the N_d and LWP vertical penetration biases presented here should only be considered in combination with corrections for other biases that affect τ and r_e. Zhang et al. (2016) suggest a correction for the sub-pixel heterogeneity bias effect, but corrections may not currently exist for all biases and it is likely that some unidentified biases still exist. Therefore, we recommended that our correction is currently only applied to homogeneous cloud scenes in order to minimize possible entanglements with biases resulting from heterogeneity effects, which are not accounted for. Such conditions can be obtained by limiting retrievals to associated heterogeneity (H_σ) values (available in MODIS MYD06 Collection 6 products) to less than about 0.1. Otherwise N_d and LWP biases could be made worse; for example, in situations where the fortuitous cancellation of opposing errors leads to initially small N_d errors. The latter was suspected to have occurred for the comparison between MODIS N_d retrievals and in-situ aircraft observations as presented in Painemal and Zuidema (2011). We showed that the SE Pacific, which is the region examined in that study, had a mean vertical penetration depth error of 35% suggesting that another unidentified N_d bias may have been operating in order to give good agreement.

However, we feel that it is useful and important to quantify the vertical penetration bias nevertheless and to suggest ways to remedy it (albeit in the sense of an idealised retrieval with no other bias sources). The addition of a previously unconsidered underlying bias is important since, for example, would disrupt the cancellation of the other errors that led to the good agreement between aircraft MODIS Nd seen in Painemal and Zuidema (2012), possibly suggesting that another unaccounted for error source exists.

The question is whether the vertical penetration effect occurs in addition to the other errors; e.g., whether (scenario A) the presence of cloud heterogeneity somehow prevents the effects of the vertical stratification from influencing the retrieved r_e and makes it irrelevant, or whether (scenario B) the vertical stratification is influencing r_e in the expected way (i.e. a tendency to cause re_37>re_21), with a corresponding counter-influence in the opposite direction due to heterogeneity. We argue for scenario B, but it is hard to prove this within the scope of this study, since it would likely require computationally expensive 3D radiative transfer modelling of known cloud fields (e.g., from LES models), followed by r_e and tau retrievals.

Some evidence for scenario B is that it may explain why VOCALS aircraft measurements showed that 21 and re_37 were very similar; it is possible that sub-pixel (or other) heterogeneity effects tended to increase re_21 relative to re_37, but that the vertical penetration effect has the opposite tendency, resulting in overall similar values. We also note that there are many situations when the expected vertical stratification of r_e does occur (i.e. re_37>re_21), as demonstrated in the following figure (included in the revised paper):-



It shows the percentage of pixels where re_37>re_21 for 90 days (Jan, Feb, Mar) of 0.1° resolution Collection 6 MODIS observations (single layer liquid clouds only; filtered to exclude tau<5 and partially cloudy pixels). The four panels are for four different bins of the heterogeneity parameter (the standard deviation of the 250m resolution 0.86um reflectance divided by the mean reflectance) with bin ranges labelled above the panels. It is clear that for many regions the relative r_e values that are consistent with an adiabatic profile occur more than 50% of the time, particularly when the cloud heterogeneity is low. Similarly, the Bennartz (2017) Nd dataset requires that re_37>re_21 in order for a datapoint to be included in the dataset indicating that there are a lot of times when this is the case.

Some discussion on these issues has been added to the Discussion section of the revised paper :-

Our paper quantifies the vertical penetration bias in isolation to the other effects mentioned above. It should be questioned, though, whether the presence of cloud heterogeneity and other effects somehow prevent the effects of the vertical stratification from influencing the retrieved r_e, making it irrelevant. This could be a potential explanation for why it is often observed that $r_{e2.1}$ is larger than $r_{e3.7}$ (Zhang and Plantnick, 2011) in contrast to the direction expected from adiabatic clouds given the vertical penetration effect, since it is known that sub-pixel heterogeneity effects tend to cause a positive $r_{e2.1}$ bias relative to $r_{e3.7}$ (Zhang et al., 2012). We argue, though, that the vertical stratification effects occurs in addition to other effects (heterogeneity, etc.) with the latter cancelling out and often exceeding the former such that the positive difference between $r_{e2.1}$ and $r_{e3.7}$ would be even larger without the vertical stratfication effect. The cancellation of biases may also explain why VOCALS aircraft measurements (Painemal and Zuidema, 2011) tended to show that $r_{e2.1}$ and $r_{e3.7}$ were very similar. We also note that there are many situations when the expected result due to vertical stratification of r_e does occur (i.e. $r_{e3.7} > r_{e2.1}$), as demonstrated in Figure 8. This shows the percentage of pixels for which $r_{e3.7} > r_{e2.1}$ for 90 days of MODIS SE Pacific observations divided

into four different heterogeneity bins. Heterogeneity is characterized by the H_σ parameter (Liang et al., 2009), which is the standard deviation of the 250 m resolution 0.86 µm reflectance divided by the mean reflectance. It is clear that for many regions relative r_e values that are consistent with an adiabatic profile occur more than 50% of the time, particularly when the cloud heterogeneity is low. This suggests that it may be possible to use H_σ to determine the situations in which the bias correction is more applicable. However, it is hard to definitively prove our argument within the scope of this study, particularly for more heterogeneous regions, since it would likely require computationally expensive 3D radiative transfer modelling of known cloud fields (e.g., from LES models), followed by r_e and τ retrievals.

References

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