Response to Reviewer 2

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 2

- ***Summary:***

  This paper assesses a particular type of error in the satellite-based retrieval of cloud droplet number concentration (Nd) retrieval from passive sensors such as MODIS. The error stems from the fact the shortwave infrared band used in MODIS cloud droplet size retrieval (i.e., cloud droplet effective radius CER) does not correspond to the CER at the exact cloud top, but somewhere below the cloud top due to the penetration of the light into the cloud (termed as "penetration depth bias" in this study), which leads to underestimation of CER and overestimation of Nd. This study investigates the size of this bias under different conditions and also provide a simple parameterization scheme to correct this bias in the observation. The topic of this paper is suitable for AMT. The paper is well-written, concise and easy to follow for the readers with the right background (but perhaps too technical for general readers). Overall, I recommend publication after some revision.

- ***Comments/Suggestions:***

  My biggest concern/criticism for this study and many other studies on Nd retrieval is that most of them are based on highly idealized cloud model, namely, the perfect, 1D, plane-parallel, adiabatic cloud with linear LWC lapse rate and constant Nd. It seems to me that, the meaningfulness of this study depends pretty much on the validity of this ideal cloud model.

  In particular, it is well known that the entrainment process can significantly affect the cloud microphysics at cloud top and thereby deviates the cloud vertical structure from the classic model assumed in Nd retrieval. How may the cloud top entrainment process influence those equations in section 2? What is the typical vertical scale of cloud top entrainment in comparison with the penetration depth of the SWIR band? Do homogenous mixing and inhomogeneous mixing as a result of cloud top entrainment have a different or similar impact on cloud top CER structure and Nd retrieval?At least, these questions should be mentioned, discussed with some references.

We have now included some discussion on entrainment effects in the Discussion section. The suggests that for stratocumulus clouds cloud top entrainment results in extreme inhomogeneous mixing, so that the CER remains constant - this is also backed up by the VOCALS aircraft
The other effects due to the non-constant Nd profile and non-adiabatic liquid water content profiles likely to be small since we estimate from aircraft observations that the entrainment region only contributes around 0.5 optical depths to the total optical depth. The added text is as follows :-

Evaporation effects related to entrainment also have the potential to reduce r_e, N_d and LWC near cloud top and hence negate some of the assumptions upon which the N_d retrievals rest. However, we argue that the entrainment effect upon r_e is likely to be minimal for two reasons: Firstly, the evidence suggests that for stratocumulus clouds extreme inhomogeneous mixing occurs at cloud top, which reduces the LWC and N_d, but does not change r_e (Burnet and Brenguier, 2007; Brenguier et al., 2011; Painemal and Zuidema, 2011). Secondly, the results of Painemal and Zuidema (2011) indicate that entrainment occurs within approximately the first 0.5 optical depths from cloud top on average; the penetration depths calculated here are considerably

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larger than this for reasonably thick clouds (Fig. 2). The effect of the reduced N_d and LWC within the entrainment zone is not so clear-cut; this would negate the assumption of a vertically constant N_d and monotonically increasing LWC used to formulate the total τ. However, given the likely small τ contribution from the entrainment region relative to the total τ, this effect is likely to be small.

What is the COT (τ) used in the Nd retrieval? Note that in MODIS operational retrieval, clouds are assumed to be vertically homogeneous. Because of the "penetration depth bias", the retrieve CER is different from the CER at the cloud top. Another possible bias is that the retrieved COT is different from the true COT. This might be small but should be quantified.

The COT used in our Nd retrieval is that directly from the MODIS products and so may contain biases due to the non-uniform CER profile that is likely to occur in reality combined with the fact that assumes vertically uniform clouds. We have now included a figure that quantifies the percentage the retrieved optical depth (relative to the model profile optical depth) :-

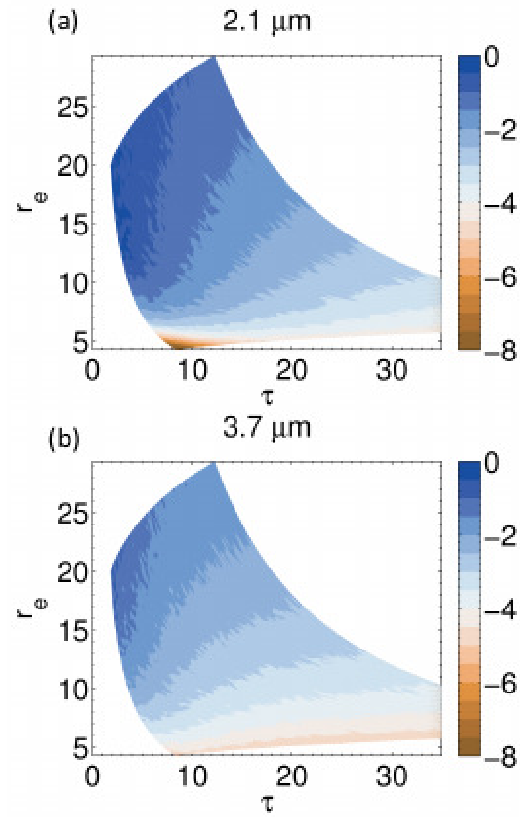

Figure 8. Percentage τ bias (retrieved minus actual value from the input model profile) as a function of τ and r_e.

The following text has also been added to the discussion :-

The MODIS retrieval uses reflectances from both a visible and a shortwave infra-red (SWIR) wavelength channel with the former being primarily determined by τ and the latter by r_e. However, a bi-spectral retrieval is used and so there is also some sensitivity of the retrieved τ to the SWIR reflectance, which will be representative of the r_e below cloud top due to the vertical penetration effect. This, combined with the fact that the MODIS forward retrieval model assumes a vertically uniform cloud, will result in the retrieved τ being biased relative to the real value (assuming the real cloud has an adiabatic profile). Figure 9 shows the difference between the retrieved and model profile τ; the bias is negative and smaller in magnitude than 5 % for the 3.7 µm retrieval. They are slightly larger for the 2.1 µm retrieval, but still lower in magnitude than 5 %, except at $r_e \lesssim 7$ µm. Although it should be noted that some of this bias may be due to other causes related to the inconsistencies between the vertically uniform and adiabatic models, rather than the r_e vertical penetration bias. Since the retrieved N_d is proportional to the square root of τ, this will lead to small N_d biases. Biases in LWP will be similar to those in τ since LWP is proportional to τ, but r_e biases are still likely to dominate (e.g., see Fig. 1). Thus, we have not pursued this further.

In this study, only the solar reflective part of the 3.7 µm band is considered. In reality, the radiance in this band is contributed by two parts during the daytime, the solar reflection and thermal emission. The emission part is "corrected" based on the 11 µm band radiance in the MODIS retrieval. This should be pointed out and if the correction process could somehow confound the results then some discussion is needed. This is especially important as the paper claims that 3.7 µm band is better for Nd retrieval (which I agree) than the 2.1 µm band.

We have added some discussion on this in the methods and now describe how this is dealt with in retrievals :-

and 3.7μm wavelengths, which are hereafter referred to to as $r_{e2.1}$ and $r_{e3.7}$, respectively. The MODIS $r_{e3.7}$ retrieval requires a correction to account for the contribution to the observed radiance from thermal emission, which is based on the observed 11 μm radiance (Platnick and Valero, 1995; King et al., 2015; Platnick et al., 2017). We account for this in our retrievals by removing the thermal contribution during the RT calculation instead of via the 11 μm radiance, which should produce a consistent end result. The RT calculations were performed assuming a black surface, a clear atmosphere (i.e. gaseous absorption is neglected),

And we also add some discussion in the Discussion section :-

Finally, we note that the thermal emission correction for the MODIS $r_{e3.7}$ (see Section 3.1) retrieval has some uncertainty that should be considered; the uncertainty for this is included (combined with other uncertainties) in the MODIS Collection 6 pixel level uncertainty products (Platnick et al., 2017). It is possible that effects additional to those included, such as cloud heterogeneity, surface heterogeneity, etc., may further increase the uncertainty beyond that estimated in the MODIS products, but these are currently not well documented.

For 3.7 μm band, its weighting function is close to two-way transmittance. I'd like to encourage the author to try to come up with an analytical solution of CER* if the weighting function follows the way transmittance.
A paper that might be helpful Zhang et al. 2017 JGR (http://onlinelibrary.wiley.com/doi/10.1002/2016JD025763/full) (Equation 4)

We have now been able to parameterize the correction to CER in order to return the cloud top CER as function of the retrieved optical depth and retrieved CER. This was also suggested by Reviewer 1 - see the response given there for details.

Why is land always masked in Nd retrievals? Why or why not can the same method be applied to land?

We restricted the analysis to ocean retrievals since the Nd and LWP retrievals are most suited to stratocumulus and these types of clouds occur much more frequently over the oceans. Land also add additional complications from surface albedo uncertainties and cloud masking problems, we also tried to avoid. We have added some discussion on these points :-

In this paper we have only considered retrievals over the ocean, although retrievals over land for τ and r_e are available for MODIS. MODIS surface albedo uncertainties are likely to be much higher over land than over the oceans (King et al., 2004; Rosenfeld et al., 2004; Bréon and Doutriaux-Boucher, 2005) since the surface albedo is much more variable over land. In addition, cloud masking is more difficult over land, particularly over non–vegetated surfaces, transitional areas between desert and vegetated surfaces and above high-altitude regions (Platnick et al., 2003). We have ignored land regions in order to avoid such complications and also because stratocumulus clouds are more prevalent over ocean regions (Klein and Hartmann, 1993; Wood, 2012). However, the results shown in this paper may still apply over land. The results of Rosenfeld et al. (2004) and Platnick et al. (2017, their Fig. 14) suggest that surface albedo uncertainties are more important at lower optical depths ($\lesssim 5$) and for the 2.1 µm retrieval (relative to the 3.7 µm one). Thus, for thicker clouds and the 3.7 µm retrieval land surface albedo issues may be less problematic.