Interactive comment on “Top-down and Bottom-up aerosol-cloud-closure: towards understanding sources of uncertainty in deriving cloud radiative flux” by Kevin J. Sanchez et al.

Anonymous Referee #2

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Reviewer overview:

Summary: This manuscript presents an observational analysis to understand sources of uncertainty in deriving cloud radiative flux. The observations are from a number of platforms, including ground based, UAV, and satellite measurements. They used a 1-D microphysical model in conjunction with observations to derive microphysical and optical properties of observed clouds. The differences were found in radiative fluxes between the simulated and the observed. They concluded that the cloud-top entrainment is an important source of uncertainty for the cloud radiative flux calculation; it is particularly true for decoupled cloud boundary layers because ground-based measurements are no longer enough to obtain reliable data in the decoupled cloud layer. Authors’ overall analysis technique is good and their conclusion is important and interesting. My main criticism is that some discussions and figures are not clear and confusing. I recommend publication after following comments are addressed.

We thank the reviewer for their comments that significantly contributed to improving the original manuscript. Please see below responses to each of the authors comments and suggestions.

The authors want to note that values in Table 3 have slightly changed. These changes were brought about by reviewer #2’s comment to present cloud optical thickness. It was noticed that the ‘observed’ optical thickness was not consistent between calculations that including and excluding cloud top entrainment. The observed optical thickness is calculated from the observed cloud droplet extinction. The observed droplet extinction is calculated by subtracting the simulated cloud droplet extinction and fitted difference in droplet extinction ($\delta\sigma_{ext}$) (Figure 8b,d,f). This was necessary to take into account the fact that the UAV’s often missed portions of the cloud. The linear fit made it possible to fill the gaps. Since the observations should be consistent, the observations from the fit that excluded entrainment was compared to simulations with entrainment.

I am wondering about the significance of showing the cloud-top extinction in Table 2 and 3. Even though the cloud-top radiative flux differences (Delta FR) in the two decoupled cases are larger than those in the coupled cases, delta sigma_ext values are similar for all the cases as shown in Table 3. The cloud-top value delta sigma_ext doesn’t seem to mean a lot in terms of cloud optical property. Because the cloud-top radiative flux (RF) depends on the optical depth as shown in (2), it is probably more appropriate to show cloud optical depth (tau).

Cloud optical depth has been added to Tables 2 and 3.

Page 2, line 71: “Such decoupled layers often contain two distinct cloud layers, . . . a lower layer within the well-mixed surface layer and a higher decoupled residual layer between the free atmosphere and surface layer”. I don’t think the surface layer can be well mixed because turbulent eddies there are too small near the surface to produce strong mixing. You probably meant surface based mixed layer. That is, a mixed layer that is connected to, but deeper than the surface layer. Why do you call a decoupled layer "residual layer"? Is there turbulence source in the decoupled layer? Does it have clouds?

We have modified the text to say "surface mixed layer". We have also changed "residual layer" to "decoupled layer". The decoupled layer can have clouds and therefore a source of turbulence which is described by the following text that has been added:

"The cloud layer drives the turbulent motion and a zone of negative buoyancy flux develops below cloud. The turbulent motion is driven by radiative cooling at cloud top, causing air to sink [*Lilly et al.*, 1968]."

Page 3, line 75: "the surface mixed layer". Surface based mixed layer?

We have chosen to use "surface mixed layer" to define the lower layer in a decoupled boundary layer. This is consistent with a previous Mace Head paper on decoupling boundary layers (Milroy et al. 2011)

Page 3, line 77 and line 80: " . . . involve cloud heating and surface cooling" and " i.e., evaporative cooling at the surface" I am not sure what is meat by the "surface cooling" or "evaporative cooling". Note that the surface evaporative cooling by surface moisture flux only cools the ocean surface, not the sub-cloud layer. I do not think the "surface evaporative cooling" directly contributes to the decoupling. Could you give a bit more explanation on this? An increase in the moisture flux with increasing SST enhances the cloud layer buoyancy flux, which intensifies the cloud-top entrainment to mix warmer and drier air into clouds, leading to negative buoyancy flux below cloud base.

The text in this section has been largely modified to more accurately explain the processes. The text has been restated in the response to reviewer 1 and is also shown below:

> **"Marine boundary layer decoupling is often seen in the tropics and has been attributed to processes that involve cloud heating from cloud-top entrainment, leading to decoupling of the boundary layer (Bretherton et al., 1997;Bates et al., 1998;Albrecht et al., 1995;Zhou et al., 2015;Stevens, 2002). In addition, Bretherton and Wyant (1997) have shown that the decoupling structure is mainly driven by a high latent heat flux that results in a large buoyancy jump across the cloud base. This high latent heat flux is attributed to easterlies bringing air over increasing SST, where the boundary layer becomes deeper and more likely to decouple (Albrecht et al., 1995). The cloud layer drives the turbulent motion and a zone of negative buoyancy flux develops below cloud. The turbulent motion is driven by radiative cooling at cloud top, causing air to sink (Lilly, 1968). The zone of negative buoyancy occurs because the deepening of the boundary layer causes the lifting condensation level of the updraft and downdraft to separate. This is important because latent heating in the cloud contributes significantly to the bouyancy in the cloud (Schubert et al., 1979). If this zone of negative buoyancy flux becomes deep enough, it is dynamically favorable for the cloud layer to become decoupled from the cloud layer (Bretherton et al., 1997). Bretherton and Wyant (1997) also show that drizzle can have a substantial impact on enhancing the negative buoyancy flux below cloud, but drizzle is not necessary for decoupling mechanism they proposed. Other factors, such as the vertical distribution of radiative cooling in the cloud, and sensible heat fluxes, play less important roles. Turton and Nicholls (1987) used a two-layer model to show that decoupling can also result from solar heating of the cloud layer; however, only during the day. Furthermore, Nicholls and Leighton (1986) showed observations of decoupled clouds with cloud-top radiative cooling and the resulting in-cloud eddies do not mix down to the surface (further suggesting radiative cooling plays a less important role). Russell et al. (1998) and Sollazzo et al. (2000)**

showed that, in a decoupled atmosphere the two distinct layers have similar characteristics (e.g., aerosol and trace gases composition), with different aerosol concentrations that gradually mix with each other, mixing air from the surface-mixed layer into the decoupled layer and vice versa. These previous studies also show that aerosol concentrations in the decoupled layer are lower than those in the surface-mixed layer implying an overestimation in cloud shortwave radiative flux when using ground-based aerosol measurements. "

Page 8, line 281-282 about Figure 8. Could you put the flight code (D05Sc, C11Sc and C21Cu) inside the plot boxes? That would be easy to see. The caption of Figure 8 mentions the difference between UAV-observed (green measurements) and ACPMsimulated (black line) to calculate delta sigma_ext. But it looks like you also calculate the cloud free values too. Although the (a)-(f) are labeled in each plot, they are not used in the caption.

The flight code has been put inside the plot boxes. We have removed "(green measurements)" since we do calculate delta sigma_ext for cloud free values as the reviewer has pointed out. We have also included the letters in the caption to refer to each plot in the figure.

Page 10, line 354-357: "The UAV observations show both C11Sc have sub-adiabatic lapse rate measurements, compared to simulated moist-adiabatic lapse rates within the cloud (Table 2). . .. The sub-adiabatic lapse rate is attributed to cloud-top entrainment . . .. at cloud-top (e.g., Figure 7a)" Where is the comparison between the observed and simulated lapse rate? I only see the simulated values in Table 2. Could you draw a line in Figure 7a to show the adiabatic lapse rate? It is hard to see the lapse rate is sub-adiabatic

The sub-adiabtic lapse-rate results are now expressed in the text rather than the table because there were only sub-adiabatic lapse rates for two of the cases. Table 2 is cited to show the measured and simulated lapse rate.

The following text, at the end of section 3.2, compares δRF when using the adiabatic lapse rate and the observed lapse rate (now refered to as the lapse rate adjustment entrainment method):

"Finally, the lapse rate adjustment entrainment method [Sanchez et al., 2016] does improve ACPM accuracy between in-situ and satellite-retrieved cloud optical properties relative to the adiabatic simulations, but has greater $\delta\sigma_{ext}$ throughout the cloud than the inhomogeneous mixing entrainment method. For the lapse rate adjustment entrainment method δRF decreased from 88 Wm^{-2} to 61 Wm^{-2} and 48 Wm^{-2} to 32 Wm^{-2} for D05Sc and D11Sc respectively."

We have not added a line to show the adiabatic lapse rate to in figure 7a because the line, with a 1 K km^{-1} greater lapse rate, would not be noticeably different than the measured lapse rate due to the large x-axis range. The reference to Figure 7a has been removed.

Page 11-12, 391-399: "For both C11Sc and D05SC,. . .. . . exhibit an approximately linear, proportional relationship (Figure10; Eq. 4.) . . . ". This paragraph is a bit confusing. What flights do those curves come from in Fig. 10? Could you state clearly which part you were referring to that is linear? In Fig. 10, the cloudy part (green curve) is not linear because qv is not conserved variable for condensation/evaporation process.

The following text has been modified to indicate q_t and θ_e have a linear relationship, and that it is shown between the two orange circles:

"For both C11Sc and D05Sc, $\theta_{e,c}(z)$ is directly measured in-cloud, and q_t and θ_e exhibit an approximately linear relationship (Figure 10; Eq. 4). The linear relationship of q_t and θ_e (between the non-mixed sources of air indicated by orange circles in Figure 10) is assumed to be a result of the cloud reaching a steady-state, with air coming from cloud-base and cloud-top (e.g. cloud lifetime >> mixing time)."

The flight codes are added to figure 10.

What is meant by "entrained air"? Does it consist of both free air and turbulent air or only free atmosphere and non-mixed air? Does it contain any cloud droplets? If not, why is it (red curve) not linear, particularly for the top panel plot?

The entrained air is the air that is mixed into cloud top which is the air directly above the cloud (within 100 m) and do not contain cloud droplets. The air directly above the cloud may or may not be the free troposphere. For example, in the bottom panel of figure 10, the points in between the 2 circles represent the mixed air layer that you have referred to. Though this air is not necessarily from the free troposphere, it is what will mix with the cloud top. A point in the orange circle (Figure 10) could have been used to represent pure free tropospheric air that would entrain into the cloud, however using the red points in the mixed air yields the same result because it is on the mixing line and they are more physical representation to use since these are directly above the cloud. The entrained fraction (X in equation 5) will change, but approximately the same amount of liquid water will evaporate no matter which point is used on this mixing line for the entrained air properties. We have changed "entrained air sources" to "entrained air properties used in simulations" in the figure caption.

The red curve appears not to be linear (in the top panel of figure 10) mainly because the mixed air (between the two orange circles in Figure 10) has a smaller layer with no cloud so essentially the line is shorter. It is also possible that the UAV partially re-entered the very top of the cloud momentarily, causing an increase in RH even though σ_{ext} does not increase because the change is below the detection limit. Also, as mentioned in the manuscript the RH sensor is not particularly accurate when RH is greater than 90%, and the water vapor content (y axis of figure 10) is calculated from the RH. The variability in the entrained water vapor is included in the errors in Table 3.

What is the flight code (or number) for these two plots in Fig. 10? Please identify the blue dashed line in the text when discussing the entrainment conditions. There is no (a) and (b) in Fig 10. "Measurements above cloud-top (RH < 95%) with qv > 5.1 g kg-1 and qv > 6.5 g kg-1 are used to represent the properties of the entrained air". How do you choose this criterion for the entrained air? You should specify clearly the properties of the non-mixed sources of air: what are the values of theta_e and q_v of the air source? The orange circles include too many possibilities of these values.

The flight code has been added to the figure.

We have now indicated the simulated adiabatic and entrainment conditions in the text:

"The observed in-cloud qv in Figure 10a and b is less than the conservative variable qt, however, the figure also includes qt based on simulated adiabatic (marked with an 'X') and cloud-top entrainment (dashed black line) conditions."

Blue cloud-free air (blue points) are now mentioned with the addition of the following sentence:

"The cloud-free air is shown in blue in Figure 10, where the below cloud measurements have lower θe than in-cloud and the above cloud measurements have higher θe than in-cloud."

(a) and (b) have been added to figure 10.

The quoted text has been supplemented to include the criteria for choosing entrained air: "Measurements above cloud-top (RH < 95%), labeled entrained air, with $q_v > 5.1$ g kg^{-1} and $q_v > 6.5$ g kg^{-1} are used to represent the properties of the entrained air for C11Sc and D05Sc, respectively (Figure 10). These conditions were chosen because these values are on the mixing line, between the non-mixed sources identified by the orange circles."

The properties of the entrained air (theta_e and q_v) are given by the red "entrained air" points in Figure 10. The orange circles are not meant to define values, but simple point out approximate end points to the mixing line. As stated in the response to the previous comment, using the properties of the "entrained air", shown in red, is equivalent to using the an observation from the top of this mixed layer.

Line 391: "Figure 11 shows the relative humidity and theta_e profiles used in Figure 10. . . .". The discussion following this sentence seems to be related to Figure 10. There is no discussion on Figure 11. Fig. 11 caption says " . . .used in Figure 9". It should be Figure 10?

The main point of figure 11 was to show the measurements used to make figure 10 as a vertical profile.

The figure 11 caption reference to figure 9 has been changed to figure 10.

Page 12, line 401-405. "Figure 12 shows . . .approaches zero". There is not much discussion on Fig. 12. What does Figure 12 suggest? What is the definition of Delta theta_ent ? Which curve best represents observation? Does the figure mean that sigma_ext is sensitive or not sensitive to the entrained air properties?

The figure caption has been changed to the following to define delta theta_ent and delta q_t:

"Figure 12. Sensitivity of simulated cloud extinction based on variability of entrained air potential temperature (θent, K) and entrained air total water mixing ratio (qt,ent, g kg-1) for the C11Sc case. The Δθent and Δqt,ent terms define the change in the entrained θ and qt values where no change (Δθent = 0 and Δqt,ent = 0) is equivalent to the adiabatic simulation with entrainment from Figure 8c."

The intent with Figure 12 was not to fit the data, but instead show how the sensitive the simulated droplet extinction is to changes in properties of the entrained air. The sigma_ext is not very sensitive to the entrainment properties that were measured, but under different circumstances (lower θ and q_t) sigma_ext can be very sensitive.

The last sentence has been added to the quoted text to clarify the connection with Figure 12 and equation 5:

"Figure 12 shows the sensitivity of the simulated cloud extinction profile, for the 11 August case, based on measurement uncertainties related to the entrained qt and θ. The key variable for identifying the entrained fraction (Eq. 5), $\theta_{e,ent}$, is a function of qt and θ, so a decrease in either parameter results in a proportional decrease in $\theta_{e,ent}$. Eq. (5) shows that entrainment fraction becomes more sensitive to the uncertainty related to the measurement of θ_e as the difference between $\theta_{e,ent}$ and $\theta_{e,CB}$ approaches zero. This is also shown in Figure 12 where sigma_ext is more sensitive to lower entrained qt and θ values."

Page 12, line 407-419. Does Table 3 include the entrainment sensitivity results from Figure 12?

Yes, the errors given in Table 3 account for the range of $\boldsymbol{\theta_{e,ent}}$ and $\boldsymbol{q_{t,ent}}$ measured (red points in figure 10).