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 #3

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The manuscript presents an interesting study of aerosol-cloud-closure in terms of cloud CDNC and shortwave radiative flux using ground-based and UAV platform measurements, satellite retrievals at Mace Head, Ireland during summer 2015, as well as a 1-D aerosol-cloud parcel model simulations. The authors look at CDNC closure between Hoppel CDNC, satellite retrievals, and ACPM simulations, and cloud-top extinction and shortwave radiative flux closure between UAV measurements and ACPM simulations. The authors find that clouds in decoupled boundary layer have larger shortwave radiative flux differences between observations and simulations. More interestingly, the authors find that accounting for cloud-top entrainment in simulations greatly reduces the radiative flux differences. The manuscript is well written and organized. Overall, the article is suitable for publication in the ACP with some revisions. Below are some specific comments.

We thank the reviewer for their comments. 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.

Specific comments:

L77 and 86: the sentences are repeating.

Referenced text:

> **“Marine boundary layer decoupling is often seen in the tropics and has been attributed to processes that involve cloud heating and surface cooling as cloud warming can result from cloud-top entrainment, leading to decoupling of the boundary layer [*Albrecht et al.*, 1995; *Bates et al.*, 1998; *Bretherton et al.*, 1997]. In addition, Bretherton and Wyant [1997] have suggested that the decoupling structure is mainly driven by an increasing ratio of the surface latent heat flux, (i.e., evaporative cooling at the surface) to the net radiative cooling within the cloud, while other factors, such as drizzle, 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. Nicholls and Leighton [1986] suggested decoupling results from cloud-top**

radiative cooling and the resulting eddies do not mix down to the surface. Zhou et al. [2015] showed that the entrainment of the dry warm air above the inversion could also be the cause. Marine boundary layer decoupling is often seen in the tropics and has been attributed to easterlies bringing air over increasing SST, which increases latent cooling and adds negative buoyancy below the cloud layer [*Albrecht et al.*, 1995]."

The text has been modified to the following based on responses from reviewers 1-3 and previously restated in responses to reviewer 1 and 2:

> **"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)."**

Section "UAV vertical profiles": How cloud-top radiative fluxes are measured? It is not illustrated in the manuscript.

There were no airborne direct measurements of cloud-top radiative flux. Cloud-top radiative flux is calculated using extinction measurements from the cloud droplet sensor measurements and from ACPM simulations. The cloud albedo is calculated from extinction (equations 1-3) and the albedo is used to calculate the cloud-top radiative flux. The following text in section 2.4 explains how the cloud-top shortwave radiative flux is calculated: "the shortwave radiative flux (RF) is calculated as RF = αQ, where Q is the daily-average insolation at Mace Head and α is the cloud albedo."

In the "UAV vertical profiles" section the last sentence of the following text was added for clarity: "In-cloud extinction was measured in-situ using a miniature optical cloud droplet sensor developed at the University of Reading [Harrison and Nicoll, 2014]. The sensor operates by a backscatter principle using modulated LED light which is backscattered into a central photodiode. Comparison

of the sensor with a Cloud Droplet Probe (DMT) demonstrate good agreement for cloud droplet diameters >5μm [Nicoll et al., 2016]. The extinction measurements were used to calculate cloud-top shortwave radiative flux and is further discussed in section 2.4."

L205: need a reference here.

A reference is included at the end of the sentence: "The model employs a dual moment (number and mass) algorithm to calculate particle growth from one size section to the next for non-evaporating compounds (namely, all components other than water) using an accommodation coefficient of 1.0 [Raatikainen et al., 2013]."

L260: Reference to Hoppel 1979 is not listed. I would suggest giving more details of using Dmin to estimate CDNC. How accurate is the estimation?

The Hoppel reference has been added.

The last sentence in the following text has been added to explicitly explain how to calculate the Hoppel CDNC: "The dry aerosol particles with diameters greater than the Hoppel Dmin have undergone cloud processing and are used here to estimate the CDNC. For each of the case study days, Figure 5 demonstrates the aerosol size distribution measurements, from the SMPS and APS, that are used to find the Hoppel Dmin, Hoppel CDNC and used to initialize the ACPM. The Hoppel CDNC is calculated by integrating the SMPS and APS combined size distributions for aerosol sizes greater than Hoppel Dmin."

The Hoppel CDNC is within 30% of both the simulated CDNC and the satellite estimated CDNC.

Figure 6: It is better to add variations of measured and satellite-retrieved CDNC. For comparisons between Dmin-estimated CDNC and simulated CDNC, they both use ground-based aerosol distribution measurements as input, therefore, these two are not independent.

We do not have measured CDNC, but instead are using the CDNC calculated by the aerosol-cloud parcel model (ACPM). Even though the Dmin-estimated CDNC and simulated CDNC both use ground-based measurements of the aerosol distributions, the ACPM simulates the supersaturation to determine the critical diameter based on the size and chemical composition of the particles. The critical diameter is not necessarily the same as the Dmin diameter. The ACPM is the main link between observations and the satellite measurement, which is why both the satellite CDNC and Dmin-estimated CDNC are compared to the ACPM CDNC. The main purpose of the figure was to show that the satellite CDNC are within 30% of the ACPM CDNC because the error associated with the satellite retrieval method is 30% (Rosenfeld et al., 2016).

L308: 0.3 or 0.5?

The minimum diameter of the OPC is 0.3 microns. This has been corrected in the manuscript.

L326: Even for simulations with 50% decreased cloud-base aerosol, decoupled cases still have greater radiative differences than the coupled cases. Does that mean there are other factors other than aerosol between decoupled and coupled cases that contribute to the radiative differences?

The main reason the radiative flux difference is large is simply because the cloud (D05Sc) is the thinnest cloud, and therefore error's in extinction (from measurement error or error in simulated) have a larger influence on the radiative differences. From equation 2, a small change in a cloud with low optical thickness (thin cloud) has a greater effect on the albedo than a small change in a

high optical thickness (thick cloud). Notice the error in extinction for the D05Sc case in table 2 is similar to the C11Sc case even though the error in RF is lower for C11Sc.