Response to Anonymous Referee #1

This manuscript reported a positive correlation between LWP and aerosol number concentration for "dry" atmosphere condition observed during the recent CARDEX field campaign. This relationship was further explored for the low and high polluted cases separately that led to the discussion about the causal mechanisms. The analysis based on new data and the supplemental material made this manuscript valuable for the community. However, the presentation of the results was lack of coherence. A proper literature review was missing in the introduction; some figures were out of place; the key points were not presented clearly in the current manuscript, some of them were discussed back and forth with supporting material in different sections; the writing should be refined and improved. The manuscript should be accepted after some substantial revisions.

We thank the reviewer for their careful reading of our manuscript. We reproduce the reviewer comments in normal face text and respond to the each comment below in bold, with edits to passages within the text provided in *italics*.

1. In the introduction, there should be a review on the climatology and aerosol transport of this studied region. Current Figure 1 offers a big picture of the aerosol transport, but has not been discussed in details in the text. The discussion on large scale condition and aerosol origin in section 3 would have more theoretical support if the related information and previous studies were properly introduced first.

Thank you for this input. We address Comments 1 and 2 below Comment 2.

2. The introduction should also include a literature review about the past studies on aerosol to cloud properties relationship. Without literature review and comparison of this work to the previous studies, it is hard to see how this work contributes to the scientific understanding of the aerosol-cloud interaction.

We have added additional text to the introduction providing more background. New text has been added as follows:

> As nations in southeast Asia have increased bio- and fossil fuel combustion in recent decades, corresponding increases in atmospheric aerosol pollution have been seen over the region (e.g. Ramanathan et al, 2001). The high levels of anthropogenic emissions combine with the seasonal monsoon cycle (Lawrence and Lelieveld, 2010) to cause frequent episodes of heavy air pollution over the northern Indian Ocean, especially in the so-called winter monsoon season (November through March) when the low-level atmospheric flow is northerly/northeasterly, following the temperature gradient from the colder subcontinent to the warmer ocean (Figure 1).
>
> In addition to their direct effects on the climate (i.e. heating or cooling), aerosols are also known to affect clouds by three primary mechanisms: cloud brightening (e.g. Twomey, 1974, the first indirect effect); precipitation suppression (e.g. Albrecht, 1989, the second indirect effect); and radiative (the so-called semi-direct) effects, which may either enhance or diminish cloud cover based on the cloud type and relative position of the aerosol layer (e.g. Koch and Del Genio,

2010). It is important to note that in addition to the often opposing signs of each of these effects, aerosol-cloud interactions have been shown to be highly dependent on the regime (i.e. the typical meteorological conditions, cloud types, location) in which they are found (Stevens and Feingold, 2009). That is, the expression of any or multiple aerosol-cloud effects will be dependent on the conditions under which they are expressed, and thus may vary from one region to another even when considering physically similar clouds. In-situ observations of all types of clouds are thus critical to understanding the full range of indirect effects influencing the Earth's atmosphere.

3. Figures and tables from the appendix are frequently cited in the section 2 and 3, affecting the logical flow of the writing. It seems Figure A1,2,3,4,7,8,9,10, Table A1 are not cited in the appendix, but only in section 2 and 3. Appendix A may be consolidated into the method section, since it is only three paragraphs and they are closely related to the results being discussed later in the manuscript.

Thank you for this comment. We intend the appendix as a compilation of additional text as well as figures which may be of interest to those looking for more depth on our work, without being a primary result of the paper. The Appendix figures and the Appendix text are thus intended to be largely exclusive of one another. However, we have rewritten references in Sections 2 and 3 to highlight the figures of the main text while using the appendix as a supplement where appropriate, and have done some minor reorganizing within the figures (e.g. we have consolidated the original Fig. 7 and A5 into one, and moved Figure 7 after Figure 10 while removing Figure 8 as addressed in a later comment). We have rewritten the text referencing the appendix figures to make them more concise and stand-alone as a supplement. Regarding Appendix A, we have added some additional methods text in the revision and believe it remains long enough and specific enough to merit its own appendix. The revised intro text laying out the paper structure is copied below:

Here we present new observations of the dry season climatology of this trade cumulus regime, including cloud, aerosol, and meteorological properties, as observed during CARDEX. In Sect. 2, we *describe characteristics of the full CARDEX dataset* and two distinct *classes of* atmospheric properties ("wet" and "dry" regimes) *and examine* the differing *conditions which are responsible for each*. *Section 3 then focuses on cases within the latter regime to describe the systematic distinctions observed between low and high pollution cases, as well as observed aerosol–cloud correlations. These pollution case studies allow insight into the mechanisms governing the observed differences in cloud properties*. We then offer *a brief discussion of* some potential causal factors of the observed correlations, including the role of aerosol in modifying atmospheric humidity and the potential implications for the understanding of aerosol effects on clouds.

4. Since the moderately polluted cases contribute to nearly half of the total cases, the results from these cases should be at least discussed in the manuscript, and compared to the low- and high-polluted cases.

This was discussed in the original text (Page 29355, Lines 22-25; Table 4). As mentioned in the text, we wish to focus on the contrast between the two case studies; however, we have added brief additional text describing the characteristics of Case M as follows:

> The ``moderately polluted'' cases (1000<CPC<1500,cm^{-3}) are excluded from the figures in order to bring focus to the high/low pollution contrast; however, Table 4 shows that these observations consistently fall between Case L and Case H *(e.g. LWP, z_PBL, LEF),* and in many cases they are in fact closer to Case H values *(e.g. LCL, z_cb, humidity)*. *This holds true for the UAV vertical profiles (T, RH, aerosol) as well.*

5. Have the authors explored the reasons why the "wet" cases do not show a correlation between LWP and CPC? This seems to be an important piece of the puzzle, and could potentially help to explain the correlation shown in the "dry" cases.

Thank you for this comment. The main point of making this distinction is that LWP exhibits much greater variability during the "wet" periods, (evident in Figure 6 and Table 3); therefore a longer record of LWP data would be required to detect a statistically significant correlation for those cases. Thus while the focus of this paper is on the variability under the so-called dry cases, we have added additional text regarding our hypothesis as to the ''wet''/LWP correlations.

> This difference in origin corresponds to greater variability in the clouds formed during "wet" conditions. When considering only the "dry" cases *with a narrower range of variability in LWP*, we *are able to detect a statistically-significant correlation between aerosol and cloud variability*. *We hypothesize that the greater variability of LWP under high-humidity conditions is a result of unconstrained vertical development of the clouds which form under more humid conditions; greater humidity tends to increase cloud thickness, so greater upper-level humidity may feed cloud development that is decoupled from conditions within the boundary layer.*

6. Figure 8 seems redundant after Figure 7.

The original Figure 8 has been removed and the discussion has been consolidated around original Figure 7.

> Figure *9 [original Figure 7]* shows the observed Case L and Case H 5 flight profiles from the aerosol-radiation UAV. Note that Case H is uniformly more polluted (as measured by both the CPC and aethalometer) through the lower atmosphere up to about 2km, at which point average pollution decreases for both cases. This is true for all cases except for one Case L flight which sampled an elevated aerosol plume. Case H exhibits warmer temperatures throughout the atmospheric column, with the maximum mean difference between the two cases occurring around the temperature inversion/cloud layer altitude (due to systematic differences in inversion height for Case L vs. H*).* […] The more polluted cases rather uniformly have higher boundary-layer relative humidity, and substantially higher free troposphere relative humidity. *The brief exception to this is around 800m, where the humidity of Case L is greater than that of Case H; this* corresponds to differences in the average altitude of the sub-cloud mixed layer

> between the two cases, which is higher in altitude for Case L. Case H again has higher RH above the inversion, which may partly facilitate the correspondingly larger average cloud water content in this case, *similar to the hypothesized mechanism behind the variability in cloud liquid water for the "wet" versus "dry" cases as discussed in Section 2, though to a lesser degree.*

7. The air mass back trajectories are mentioned in section 2.2, and the air mass origin is again discussed in section 3.2.2. The authors should consider rearrange and consolidate the material.

Thank you for the comment. As also addressed under Comment #3, the structure of the paper was intended to first discuss the dataset as a whole in Section 2 (i.e. the wet/dry distinction), before focusing solely on the ''dry'' data in Section 3. Additionally, the discussion in Section 3 has been substantially rearranged for clarity. Specifically, Section 3.1 has been rearranged in itself; text from Section 3.3 has been moved up to 3.1; the remaining Section 3.3 has been rearranged. The difference in the context between the air mass trajectories in Section 2.2 and Section 3.2.2 has been clarified.

1. Page 29349, line 7, change to "INDOEX is the result of…"

This has been reworded to improve clarity. The sentence now reads:

> *INDOEX, a collaborative experiment between multiple international organizations and led by Scripps Institution of Oceanography,* made simultaneous multi-platform measurements in the Indian Ocean with the goal of observationally constraining direct and indirect effects of aerosols in the region, in particular the atmospheric heating and surface cooling caused by the presence of black carbon (BC) aerosols within the atmospheric column.

2. Page 29349, line 16, delete "would"

This has been changed for clarity.

> INDOEX *thus* set the stage for later work in the region investigating the effects of absorbing aerosols within the atmospheric column.

3. Page 29349, line 25, "CARDEX follows…" should be moved to the next paragraph

This sentence has been reworded as follows, however it should remain as the concluding sentence of the previous paragraph as it functions as a transitional concluding sentence.

> CARDEX follows from these previous studies using UAVs and ground measurements, and for the first time incorporates *measurements of turbulent kinetic energy and latent heat fluxes* for a greater focus on *how thermodynamic factors and atmospheric dynamics* may *influence aerosol effects on clouds*.

4. Page 29350, line 16, delete "a time"

We believe "a time" is necessary for grammatical clarity of this phrase (i.e. we are saying "the dry season is a time when…" rather than "CARDEX was designed when…").

5. Page 29350, line 17 to 20, “The atmospheric conditions…” please rephrase this sentence

The sentence has been reworded as follows

> *As the atmosphere is heavily influenced by anthropogenic pollution during this dry season, the data presented here are valuable to a broader understanding of potential aerosol effects on atmospheric conditions.*

6. Page 29350, line 28, “discussion” seems to be a more suitable word instead of “speculation”

This has been changed.

> We then offer *a* brief *discussion of* some potential causal factors of the observed correlations, including the role of aerosol in modifying atmospheric humidity and the potential implications for the understanding of aerosol effects on clouds.

7.Page 29353, line 14 to 19 need to be rephrased.

We have restructured this paragraph and reworded the sentences for clarity as follows:

> *Thus the most significant distinction in the atmospheric structure of the two populations is in the conditions above the boundary layer, especially the lack of temperature inversion and greater atmospheric humidity at higher elevations for the ``wet'' cases. This analysis is additionally supported by the ECMWF reanalysis over MCOH (Fig. A3a and b).*
>
> *Note that the atmospheric moisture described here is given as relative humidity (RH), as this is the metric directly measured by the aircraft. Although an increase in temperature would produce a decrease in RH for a fixed specific humidity (q), in our cases the measured RH is seen to be consistent with q calculated incorporating changes in temperature (e.g. Fig.A5).*

8. Page 29355, line16, change to “all available low/high pollution dry days”

This has been reworded for clarity.

> In this analysis, we use all low/high pollution dry days *with available reanalysis and satellite data (Table 1)*; observations from the UAVs are necessarily limited to the subset of these days when a UAV was flown (Table 2).

9. Page 29360, line 2, this sentence “The bottom: : :” is not necessary

This sentence has been removed.

10. Page 29361 line 26, delete one of the “in contrast to the”

Thank you for catching this typo! It has been removed.