Understanding the drivers of marine liquid-water cloud occurrence and properties with global observations using neural networks

— RESPONSE TO REFEREE 3 —

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We would like to thank referee 3 for her/his review of the manuscript and her/his constructive criticism. Comments by the referee are colored in blue, our replies are colored in black.

This paper pursues a promising approach to study the sensitivity of marine liquid-water cloud properties on a set of meteorological and aerosol predictors, using an artificial neural network approach. It steers clear of correlative approaches for studying aerosol-cloud interactions and instead considers the meteorological context, segregated by region / meteorological regime. In essence, this amounts to a multi-variate analysis based on an optimal combination of satellite and re-analysis data. The paper is very well written, clearly represents new ideas, and has the potential to lead to major improvements in our assessment of ACI, regionally and globally. It is rare to see such a high-quality paper. I only have minor comments, which don't necessarily have to be addressed in this manuscript, but could be considered in future work. The most important ones are probably #1 regarding scale, and regarding the quality (reliability) of the data. Also, follow-up papers might consider using the co-sensitivity of some predictors (details below).

In a separate comment to the editor, I recommended that the paper be highlighted because it seems highly innovative in its approach and deviates from the traditional correlative aerosol-cloud interaction studies. I believe that it has potential to change the direction of this field of research.

Thank you very much for this kind assessment. We respond to each point individually below.

General comments:

p5,L18: In the spirit of the McComiskey and Feingold ACI papers, it would have been interesting to also consider the impact of scale on ACI relationships. Here, one specific scale has been used (dictated by the analysis grid) - but it may not be straightforward to generalize these relationships.

This is a good point and we agree that the scale of the data sets used to study aerosol-cloud interactions influences the derived sensitivities (McComiskey et al., 2009; McComiskey and Feingold, 2012). Here, we use temporally and spatially highly aggregated data sets (monthly means in the defined equal-area regions), as with this study, we are specifically interested in the very large scale mechanisms and patterns of the aerosol-cloud-climate system. This is certainly not the scale at which the processes occur, so that our derived sensitivities may not match the magnitude of the sensitivities at the process scale. An analysis of the impact of the extent of spatial aggregation of the 1°x1° data on the derived sensitivities would be interesting; however, the spatial aggregation we chose was needed for sampling reasons (sufficient number of observations for the statistical model). In the revised version of the manuscript, we discuss this on P6L1–3. ("*As the temporal and spatial scales considered in this study are not on the same scale as the actual processes, so that the calculated sensitivities may not match the magnitude of the sensitivities at the process scale (McComiskey et al., 2009; McComiskey and Feingold, 2012).*")

p6,L4: "skill of simple correlation between AOD & cloud properties": It is a bit unclear, which "simple correlations" specifically have been used for this study. This statement calls for elaboration. The statement on p6,L6/7 shows the intent - the "simple correlations" are used as a baseline to show the improved predictive skill of ANN. The quantitative results would be more useful by including more information about that baseline.

Here, with "simple correlation" we referred to a "simple" Pearson correlation between AOD and either CLF/CDR/LWP/COT in each equal area region. In the revised version of the manuscript, we describe this at P6L8, however, in the current version of the manuscript, the results of Pearson correlations between log(AI) and the respective cloud properties is illustrated in figure 2.

p6,L11 (fig 4): How/where are the equal-area regions defined? Are those just pixel aggregated that meet the selection criteria for the sensitivity analysis?

This is explained in the manuscript on P4L33-P5L3. The equal-area regions are defined by dividing the space between 60°N and 60°S (and all longitudes) into 20x40 equally sized areas. The original 1°x1° data is aggregated in these regions at their original spatial resolution. The selection criteria for the sensitivity analysis is checked for each equal-area region (but only for the sensitivity analysis - in figure 4, all equal-area regions are shown). In the revised version of the manuscript, we added some information to the caption of figure 4 for clarity.

p9, Fig 5. How is the CF and LWP sensitivity to AOD compatible? Is it a fair statement to say that we get more clouds with lower LWP for higher aerosol loading, while COD stays the same (perhaps because the "classical" indirect effect kicks in) - or can we not make such a blanket statement?

The CLF sensitivity to AOD/AI is probably the sensitivity that is the most uncertain, due to cloud contamination of the satellite aerosol retrievals and the influence of confounding variables on both CLF and the satellite retrieved aerosol quantity. While we weaken the influence of confounding variables by including them in the ANN, we are not able to reduce effects related to data quality (this is discussed on P13L4–6 in the revised version of the manuscript:

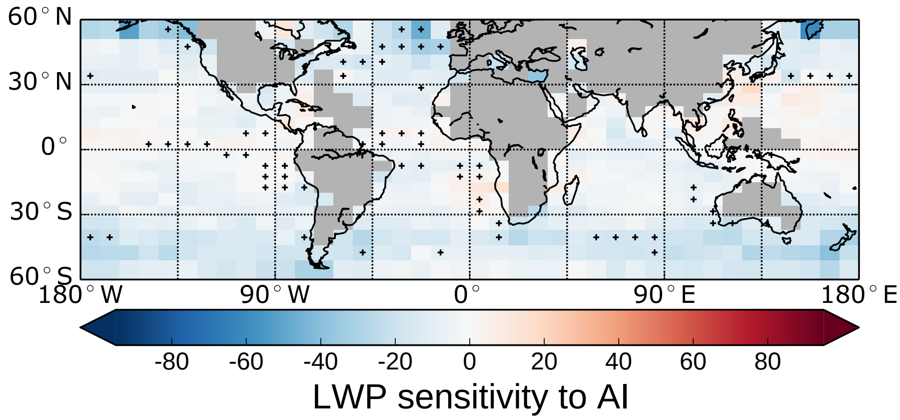

Figure 1: Global map of LWP sensitivity to AI: The globally averaged sensitivities are based on the regions marked with a '+'.

"*While the influence of confounding factors is limited by the multivariate approach, effects concerning data quality (e.g. cloud contamination) are not accounted for and need to be considered when interpreting the CLF sensitivity to AI.*"). One should also note that the averaged LWP sensitivities rely on very few regions (due to the selection criteria) and should thus not be considered global. In most regions, the sensitivity of LWP to AI is relatively low.

While it makes sense to combine the sensitivities as proposed by you, one needs to remember that these are derived from separate ANNs. While LWP and CLF in the respective ANNs respond to AI/AOD in the way that you point out, changes in LWP might also affect CLF and vice versa, which would not be accounted for. Therefore, we are somewhat cautious in the interpretation of combined sensitivities.

p10, L5: Would it make sense to plot co-sensitivity maps, considering that many predictands co-vary with predictors. In the inverse theory equivalent, one would consider the off-diagonal elements of the covariance matrices. After all, one of the attractive features of this analysis is that it allows multi-variate analysis of ACI, fully considering the meteorologic conditions - but then the plots / analysis do not reap the full benefits of this approach. The authors do explain some of the co-variabilities/co-sensitivities, but then again it would be even better to have some graphical representation for some of these connections.

Yes, this is a good idea - and an idea which we discussed internally, as well. Ultimately, this level of detail exceeds the scope of this study, as one would have to create co-sensitivity plots for each grid-cell-specific ANN individually and would thus not be able to produce summarized global co-sensitivities easily. This is an idea we are currently pursuing in a more detailed regional study.

p10,L28: Does the CDR - AOD relationship for the SE Atlantic region make sense? For the outflow from the Arabian peninsula and the Sahara, it does, and the manuscript explains this with dust - but on the West coast of Namibia and Angola the dust is confined to the coast. It is possible that the identified relationships here points to limitations of the data set(s) that serve as the basis. Perhaps dust is overrepresented in the data? Overall, it would be good to see a discussion in which regions we would trust the correlations (given the uncertainties in the data).

This is a good question - in a regional study some years ago, we found that in certain conditions (stable/humid), AI and CDR are positively related in the Southeast Atlantic (Andersen and Cermak, 2015). However, in most cases, the AI-CDR relationship was found to be negative as in (e.g. Costantino and Bréon, 2013). This specific regional sensitivity may be affected by retrieval or sampling issues, as now discussed in the revised version of the manuscript on P10L5–8 ("*Issues of sampling (few aerosol retrievals in high CLF-regions) or scale (highly aggregated data) or their combination might affect the observed CDR sensitivity to AI in this region.*").

p12, L15: So, cloud radiative effect sensitivities are actually not (yet) addressed in the manuscript. Instead, cloud properties are analyzed. Earlier in the manuscript (p4,L24), it is stated that cloud radiative effects are analyzed. This should be fixed (minor comment).

Yes, you are correct. We have deleted the mentioned text passage in the revised manuscript.

References

Andersen, H. and Cermak, J. (2015). How thermodynamic environments control stratocumulus microphysics and interactions with aerosols. *Environmental Research Letters*, 10(2):24004.

Costantino, L. and Bréon, F.-M. (2013). Aerosol indirect effect on warm clouds over South-East Atlantic, from co-located MODIS and CALIPSO observations. *Atmospheric Chemistry and Physics*, 13(1):69–88.

McComiskey, A. and Feingold, G. (2012). The scale problem in quantifying aerosol indirect effects. *Atmospheric Chemistry and Physics*, 12(2):1031–1049.

McComiskey, A., Feingold, G., Frisch, a. S., Turner, D. D., Miller, M. a., Chiu, J. C., Min, Q., and Ogren, J. a. (2009). An assessment of aerosol-cloud interactions in marine stratus clouds based on surface remote sensing. *Journal of Geophysical Research: Atmospheres*, 114(D9):D09203.