Zamora et al. ACPD Reviewer Responses

Response to reviewer #2

GENERAL COMMENTS:

This manuscript by Zamora et al. presents an extensive study of thin liquid clouds over the Arctic and how these are affected by aerosol loading. The study combines satellite data from CALIPSO and CloudSat with FLEXPART modeling and aircraft measurements to better distinguish to which degree that the clouds were affected by aerosols. The study is limited to nighttime thin clouds between 1 and 8 km height and an estimation of the radiative impact of these clouds is provided. The manuscript is well written and contains detailed discussions regarding the uncertainties in the method and results. I recommend that the manuscript be published after answers to the following comments have been provided.

We thank the reviewer for their helpful comments, which have improved the paper.

SPECIFIC COMMENTS:

1) The study only includes nighttime clouds that have a COD < 3 and that are liquid. For the clouds to be included in the study they also must have an altitude between 1 and 8 km. In the methods section there are detailed descriptions of removal of data due to several other criteria considering confidence in data etc. My question is how representative the clouds included in the study are for the general conditions in the Arctic. Could you provide an estimate of how common these liquid clouds are? If the clouds in this study represents the conditions during 80% of the time or 20% of the time makes a big difference. I believe that the second sentence in the abstract may be a bit bold if it turns out that these clouds are not very common in the Arctic.

This was actually a very helpful suggestion, and in combination with comments from the first reviewer, it has helped us reframe the discussion and estimate radiative impacts in a more useful way. As requested, we now provide more information on how common these kinds of clouds are in context of the general conditions in the Arctic. To estimate cloud coverage, we examined the relative fraction of profiles containing our cloud subset vs. any cloud, and vs. the total profile number over the Arctic. The following addition to the text was added to the new section 3.2 (formerly section 2.3):

"It is important to emphasize that the ONLi cloud group is not representative of all Arctic clouds. During our study period, ONLi clouds were present in only 5.28% of all total comparable nighttime cloudy profiles over the Arctic Ocean ("comparable clouds" defined as having a satisfactory in-cloud CAD score of 70-100 and with cloud bases > 200 m to exclude fog). Liquid-dominated clouds tend to be found at lower altitudes than thicker opaque clouds and thus may not always be identified in multi-layer clouds using CALIPSO. However, even though the actual prevalence of these clouds may be somewhat underestimated, it is clear that ONLi clouds represent just a small fraction of all Arctic clouds. Thus, we emphasize that the aerosol indirect responses described in this paper are not necessarily representative of general Arctic clouds."

The abstract has been re-written with this information being highlighted, and limitations on the analysis are now more fully discussed throughout the text (e.g., p. 20, l.1; p. 10, l. 10-18).

Another large change we made based on this comment was in how we estimated the radiative impacts to the surface. Before we had quantitative information on how common the clouds were, the maximum regional cloud longwave impacts were estimated by multiplying those expected in a 100% homogeneous cloud environment by the total cloud fraction of all clouds from a different study (Kay and L'Ecuyer, 2013). However, that was a very large over-estimate of the actual impacts since obviously (to us, in retrospect) our cloud subset is only a small portion of all clouds. Now with much more accurate information on the actual coverage of these specific clouds, we have provided a much reduced, and more precise and useful maximum regional impact. Thanks for getting us thinking about this! For more information on how these changes were implemented in the paper, please see section 3.6 (especially the first 2 paragraphs).

The reviewer also said, "The description of the data selections is very well written and detailed. However, it would be nice to know approximately how much data are lost at each step in the selection process."

At the suggestion of reviewer #1, we expanded the dataset to include many more types of optically thin, liquid clouds so that many of the previous steps in the selection process are no longer relevant (please see the new Table 1, for these changes). However, we still do refer to the previous MOONLiT cloud subset for reference, because this subset still has the highest certainty in aerosol classifications. Thus, for the reviewer's reference, we have added the following information in the Supplementary material:

"If the MOONLiT criteria were changed to include a) clouds with bases that were 200 m instead of 1 km above the surface, b) clouds above a separate ice cloud, or c) clouds below other non-opaque cloud layers (icy or otherwise), the MOONLiT cloud sample size would respectively have increased by 107 (121), 16 (28), and 303 (617)% over sea ice (open ocean). Any other differences between the MOONLiT cloud subset and the ONLi cloud subset was due to cases where uncertain aerosol CAD scores (<70) existed above or beneath cloud layer of interest. These clouds were allowed in the ONLi cloud subset, but not in the MOONLiT cloud subset."

Page 4, line 11: There are large land areas in parts of the described regions. Were these removed from the dataset?

Yes. That we focus only on clouds over the Arctic Ocean has now been clarified in the title, abstract, and throughout the text.

Page 4, line 22: Were all the cases averaged to 80km resolution or do the different cases have different resolutions?

Yes, for a cloud to have been present in a clean background air mass, the CALIPSO transect in which that cloud had been found had to have been horizontally averaged across 80-km with no evidence of an aerosol layer. The CALIPSO aerosol layer algorithm works by first looking for evidence of an aerosol layer at 5-km resolution (where the strongest aerosol layers would be observed). If there is a weak aerosol signal, it might not be identifiable from the noise present at a 5-km resolution. Thus, if evidence of an aerosol signal is not found at 5-km resolution, the algorithm progressively lowers background noise by averaging over a larger area until a maximum of 80-km. Please see the first paragraph of section 2.1.1 for further information. To clarify this better in the text, we have changed the referred-to sentence as follows:

"The "clean, background" cloud subset met the above criteria, but no aerosol features were permitted above or below cloud **even when air masses had been** horizontal**ly** averaged **across** 80-km **in the CALIPSO aerosol detection algorithm, which is the resolution that detects weak aerosol layers with highest confidence**."

Page 7, line 9: Why is data 10 degrees further south than the satellite data included in the comparison?

To better answer this, we have changed the line in question as follows:

"**The aircraft data with highest aerosol particle concentrations were clustered between 50-60^o N during this campaign. Thus, we included** aircraft data **from** between 50-82^o N (subarctic + Arctic) **in order to assess comparable ranges of dilute and concentrated aerosols expected to be present over the greater Arctic.**"

Page 15, line 12: In the calculations of the indirect radiative effect of aerosols on MOONLiT clouds you write that you use the clean background cloud subset. Previously in the method you write that the parameters used in the calculations are cloud base height, cloud thickness and COD. For the cases over sea ice the COD is the same for the clean background and all cases datasets which means that the differences in the radiative effects is due to the difference in cloud base height (1.8 km vs. 1.9 km) and the difference in the cloud thickness (0.9 km vs. 1.2 km). Did I understand this correctly? Could you comment on this?

This is mostly correct, except that observed cloud droplet effective radius was also used as a variable input parameter from the cloud dataset for the radiative impact calculations. To make it clearer to the reader which parameters were used in the calculations, the below information has now been re-arranged as follows:

"**Variable input parameters for the radiative impact calculations included** cloud base height, cloud thickness, COD, **and r_{el} for** clouds over sea ice and open ocean**. Parameter values were taken from Table 2 median values, except for r_{el}, where the** interquartile range was used to reflect the larger uncertainty in that parameter."

For the reviewer's reference, in this instance, holding all other variables equal, aerosol-related changes in cloud optical depth were an order of magnitude more important for radiative effects than the changes in cloud droplet effective radius, and the changes in geometric thickness had nearly no impact, as now discussed in the text (p. 17, l.11-14).

Figure text figure 3: "where a value of 0 indicates that the ocean surface was the next lowest feature". Does ocean surface here also mean sea ice?

Yes, this is what we meant, as average Arctic sea ice is generally less than 3 m thick (e.g.

Zhang and Rothrock (2003)). To clarify, the text has been revised as follows:

"Figure 3: The data shown in a) and b) are weighted-average gridded maps of features below individual cloud points from Figure 1a for a) sea ice fraction, and b) height of the next lowest feature associated with individual cloud profiles, where a value of 0 indicates that the ocean surface **or sea ice** was the next lowest feature. Over open ocean, multi-layer clouds were much more common than over sea ice. Shown in c) is a boxplot indicating the cloud base heights (km) for single layer clouds over sea ice (grey) and open ocean (blue)."

TECHNICAL CORRECTIONS:

Page 12, line 7: optical thickness should be changed to COD.

Edited as recommended.

References

Amante, C. and Eakins, B. W.: ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA., , doi:10.7289/V5C8276M, 2009.

Zhang, J. and Rothrock, D. A.: Modeling Global Sea Ice with a Thickness and Enthalpy Distribution Model in Generalized Curvilinear Coordinates, Mon. Weather Rev., 131(5), 845–861, doi:10.1175/1520-0493(2003)131<0845:MGSIWA>2.0.CO;2, 2003.