Variability of mixed phase clouds in the Arctic with a focus on the Svalbard region: a study based on spaceborne active remote sensing"

by G. Mioche et al.

Answer to reviewer #3

The authors would like to thank the reviewer for his/her helpful comments and suggestions, which hopefully will help us to greatly improve the quality of our paper. Below you will find detailed answers to the reviewer's comments.

The reviewer's comments are reported in bold, the authors' answers are reported in italic, and the changes in the revised manuscript are indicated in red color.

MAJOR COMMENTS

Reviewer's Comment (RC): First, I found the organization of the manuscript peculiar. Typically, I would expect discussions of the quality control and uncertainty associated with the analysis to be presented before the results of the analysis are shown. The opposite seems to be done in this paper, with Section 5 discussing the limitation of the data after the results have already been presented. It would be much easier to have this discussion up front so that one could be interpreting the results with these limitations in mind.

Authors' Reply (AR): The section concerning the uncertainties has been moved to the end of the "Data and method" section (section 2), in the new sub-section: 2.3, including the following sub-sections:

2.3.1. Limitations of observations near the surface

- 2.3.1.1. Ground contamination on CloudSat data
- 2.3.1.2. Comparisons with ground based observations
- 2.3.2. Multiple layers clouds
- 2.3.3. DARDAR algorithm and assumptions

RC: Second, I find it curious that the authors use Version 1 of DARDAR given that Version 2 is available, and given their suggestion that there are some rather large discrepancies between the two versions. Although I am entirely sympathetic with the desire to publish analysis that has already been performed without doing extra work, given the rather

large differences I would encourage the authors to replace the Version 1 results with the Version 2 results. Presumably the codes for doing the analysis and for plotting the figures have already been written, so it would not be that much extra work to repeat the analysis. I think the end product that would come out would be that much better.

AR : This main comment concerns the use of V1 version of DARDAR products for cloud and MPC occurrence determination, instead of V2.

Even though the V2 DARDAR algorithm has been published recently, the V2 DARDAR product is not yet available for the whole CALIPSO/CLOUDSAT dataset. The second version of the DARDAR algorithm highlighted some improvements, notably concerning the cloud phase classification (Ceccaldi et al, 2013), but it has been evaluated by comparisons with V1 product on one case study (26 may 2007) and over 3 months of data only (January, February and March 2010). The complete processing of CALIPSO/CLOUDSAT dataset with V2 DARDAR algorithm is a very long production process. The co-authors in charge of the DARDAR algorithm are currently taking care about the production line of V2 DARDAR product, but it will take a very long time before the new product will be released (at least one year or more). This is the reason why we used V1 version in our study.

Furthermore, knowing that V2 version will be released in the future, we thought it made sense to make comparisons between V1 and V2 in order to give an insight about the impact on MPC occurrence.

So, we made the choice to compare V1 and V2 on a reduced, but statistically representative, dataset. This comparison permits to quantify differences between V1 and V2, eventhough a more detailed study will be necessary in the future when complete V2 will be available.

We hope that this information will help the reviewer to understand why we used V1 DARDAR product. We propose thus to keep our results from V1 product, as well as the section concerning the comparisons with V2 to assess the differences between the two versions, since V2 product is not available. In addition, the reason why V2 version is not used has been added in the revised manuscript as follow:

"However, DARDAR V2 product is currently not available for the entire CALIPSO/CLOUDSAT dataset, and the results from Ceccaldi et al. (2013) are based on one case study and 3 months of data only".

RC: Third, I am a bit concerned about how the omission of clouds with z < 500 m is affecting the statistics. Past ground-based and in-situ observations have suggested that in some regions of the arctic mixed-phase clouds can be frequently occurring within 500 m of the surface. Hence, omission of these clouds would be biasing the statistics. Although data to evaluate whether clouds are present throughout the Arctic at z < 500 m, presumably this could be done for a few of the stations in the Arctic where ground-based remote sensing data are available. It would be nice if some quantitative estimate of the uncertainty could be made due to the omission of these clouds.

The main goal of our study is the characterization of the vertical and spatial variability of mixed-phase clouds over the Arctic region from space observations based on lidar and radar measurements onboard CALIPSO and CloudSat satellites. The reviewer points out the uncertainties and limitations of spatial observations below 500 m and suggests a comparisons with ground-based measurements. Nevertheless, a detailed study including direct comparisons between ground-based and spatial observations in order to quantify with accuracy the uncertainties and limitations of spaceborne measurements is beyond the scope of the present study. Moreover, such a work has been recently done by Blanchard et al. (2014). They directly compared ground-based observations at the Eureka Arctic station (cf. Figure A below), located in the Canadian archipelago of Nunavut (80°N, 87°W, Nunavut, Canada), with collocated A-Train observations and DARDAR products (V1 version). They made a fully detailed study on cloud fraction and vertical distribution over the Eureka station, identifying and auantifying uncertainties and limitations of A-Train observations and DARDAR products. The larger differences occur at the very-low altitude level below 2km of altitude. Cloud fraction observed from spaceborne observations is lower than that from ground based observations by 10% in the 500-1000m altitude domain and up to 25% at the 0-500m altitude domain. These differences are mainly attributed to undetected low-level clouds due to sensitivity loss of the CALIOP lidar and the surface proximity for CLOUDSAT radar, but also to the distance between satellites tracks and the ground station. Moreover, near the surface, ground-based measurements may be affected by local effects and cloud fraction may be overestimated by presence of ice crystals close to the ground (diamond dust, blowing snow, precipitation) which are classified as clouds, as also shown in Shupe et al. (2011) and Bourdages et al. (2009).

Furthermore, to complement the study of Blanchard et al. and to go deeper in the analysis of limitations and uncertainties of the DARDAR products, we propose a comparison between the occurrence of low-level clouds using DARDAR and that from ground-based locations available in previous studies:

- First, it is Hoffmann et al. (2009) study, in which vertical profile of cloud fraction is determined from MPL lidar at Ny-Alesund station (Svalbard, 78.9°N, 11.9°E) in March and April 2007.
- Secondly, it is De Boer et al. (2009) study, in which Single layer MPC occurrence is calculated from ground based radar and lidar at Eureka station (80.2°N, 86.2°W) between June 2006 and December 2007.



Figure A: Vertical profiles of cloud occurrence over Eureka station from CALIOP, CLOUDSAT, DARDAR and ground based observations. From Blanchard et al., 2014.

Figure B shows the comparison of the vertical profile of cloud occurrence from DARDAR products (with different configurations and different settings, see the legend of the figure) with that from Ny-Alesund ground based observations for the March-April 2007 period (from Hoffmann et al. (2009) work). The left panel displays DARDAR profiles at the original vertical resolution (60m), and the right panel displays DARDAR profiles averaged on a 1km vertical grid, as it is done in Hoffmann et al. (2009).

Above 5km, more clouds from DARDAR observations than ground based are observed. This is due to the attenuation of ground based observations at high altitude levels. Moreover, radar alone misses some high clouds as they are optically too thin. These results are in agreement with those from Blanchard et al. (2014). Between 2 and 5 km, space and ground based observations agree very well. This corroborates the results of Blanchard et al. (2014). Below 2km, cloud occurrence from space observations are larger than from ground based by 20% between 1km and 2km, and by about 10% below 1km.

One can note also that taking into account ground clutter (red curve) greatly overestimates cloud occurrence by up to 40%.

Figure C displays the single layer MPC seasonal occurrence from Eureka ground based observations (from De Boer et al (2009), blue line) and from DARDAR product (red and green lines). There is a general good agreement between DARDAR and ground based observations. In particular, annual variability agrees very well. Space observations present larger occurrence than ground observations by only 5%, and only in autumn. But no systematic bias can be observed. Note that the choice of a 500m or 0m minimum altitude threshold on DARDAR data does not significantly impact the cloud occurrence.

These results show that variability of F_{CLOUD} or F_{MPC} , determined from space observations, agree well with that from ground based observations. However, and contrary to the results of Blanchard et al. (2014), our results do not highlight a systematic bias in low-level cloud amount retrieved from space observations. It may be due to the small data set used for the comparisons (2 months and several seasons), the accuracy of the collocalisation in space, or also to differences in the cloud and MPC occurrence determination method.

It is obvious that a more detailed study based on comparisons of space and ground based observations aiming the quantification of uncertainties in low-level cloud/MPC amount is needed and would be very useful, but it is beyond the scope of this paper.

From all these results, and considering ground-based measurements as reference, we can first conclude that DARDAR product is reliable above 2km. Secondly, below this altitude, uncertainties in cloud or MPC occurrence is up to 20% between 500m and 2km, and up to 25% below 500m.

These information are useful for discussing the results about the cloud and MPC occurrences later in the paper.

These results have been added to the revised manuscript in the "Uncertainties and limitations" section in order to evaluate the uncertainties and limitations of DARDAR product below 1km. This section has been moved in the "Data and method" section to improve the organization of the paper (as suggested in the first comment). It is now the section 2.3 in the revised manuscript. Accordingly, Figures B and C have been included in section 2.3. (Figures 2 and 3 in the revised manuscript)



Cloud occurrence vertical profiles at Ny-Alesund (Svalbard) during March-April 2007

Figure B: Comparison of cloud occurrence vertical profiles from different DARDAR products and from Ny-Alesund ground based observations (Hoffmann et al, 2009) for the March-April 2007 period. Yellow lines corresponds to lidar alone, blue lines correspond to radar alone excluding pixels contaminated by ground, red lines correspond to lidar and radar including pixels contaminated by ground clutter, and green lines corresponds to lidar and radar merged (excluding pixels contaminated by ground clutter).



Figure C: Comparison of single layer MPC occurrence from DARDAR product and from Eureka ground based observations (De Boer et al, 2009) from June 2006 to December 2007.

RC: Fourth, I am left wondering about whether variations in aerosol concentrations or compositions could be responsible for some of the variations that are seen in the characteristics of the clouds. Whereas I don't think that the authors need to do any analysis with regards to this because the paper is already quite complete, I think that at least some comments should be made.

AR: Variations in aerosols concentrations or compositions could be one more hypothesis to explain variations in MPC occurrence throughout the Arctic. However, transport of these aerosols throughout the Arctic region should be studied at the same time.

Comments about this have been added in the discussion as follow:

"The link between the variations of aerosol concentrations or compositions and the MPC characteristics should be investigated as it might partially explain some variations in the cloud and MPC occurrences. It would improve our understanding in the aerosol-cloud interactions in the Arctic, like the studies performed by Avramov et al. (2011), Jackson et al. (2012) or Tjernström et al. (2014)." RC: Fifth, the paper needs to be carefully inspected for grammatical and spelling errors that are pervasive throughout the manuscript and can be a little distracting.

AR: As it is also recommended by reviewer #1, the re-worked manuscript has been reviewed by Professor Andrea Flossmann to ensure a proper writing.

SPECIFIC COMMENTS

RC: Page 23455, line 11: Reference Vogelmann and Lubin study for dominance of longwave effect

AR: This reference has been added:

Lubin, D., and A. M. Vogelmann (2006), A climatologically significant aerosol longwave indirect effect in the Arctic, Nature, 439, 453-456.

RC: Page 23456: Korolev has published a number of studies on causes of persistence of mixed-phase clouds and has developed conceptual models that explain their persistence. Some of his papers should be referenced here. Also, on line 10 the authors talk about the persistence of supercooled water droplets. I don't think it is the supercooled water droplets that are persisting, but rather the supercooled or mixedphase clouds themselves. The water is being continually cycled through the cloud, with formation of new supercooled drops and glaciation or falling out of others. The discussion as written makes it sound like one cloud is being maintained for several days or weeks, rather than a recycling of the water in the ubiquitous mixed-phase clouds.

AR: We totally agree with this comment. We meant that clouds persist, not the supercooled droplets inside. These droplets are generally consumed by ice crystals (Bergeron process), and new droplets are initiated to maintain the equilibrium between ice crystals and supercooled droplets.

It has been corrected and some previous studies from Korolev are referenced as follow:

"On the other hand, dynamical processes, such as turbulence or entrainment may facilitate the formation of new supercooled water droplets. For example, resupply of water vapor from the surface or from entrainment of moisture above the clouds may contribute to the continuous formation of liquid droplets within MPC. The coupling of such various processes is, thus, necessary to maintain the unstable equilibrium between liquid droplets and ice crystals within MPC. This may explain the longevity of MPC up to several days or weeks as it has been frequently observed (Shupe, 2011; Verlinde et al., 2007, Morrison et al., 2012). Previous studies from Korolev et al., (2003), Korolev and Isaac, (2003) and Korolev (2007) also point out that the life time of MPC could not be simply reduced to the WBF process, but depends on numerous parameters such as local thermodynamical conditions or is linked to cloud dynamics."

RC: Page 23457, line 12: I don't think this structure is particularly peculiar and has been observed in many other locations in addition to the Arctic. See Fleishauer et al. (2002) and Plummer et al. (2014) as examples of mixed-phase clouds or clouds having supercooled water near the tops of clouds.

AR: The structure is not peculiar in itself since it is observed in Arctic as well as others regions in the world. But its continuous presence throughout the year in the Arctic region (with larger occurrence than others regions) is a particularity of the Arctic.

RC: Page 23457, lines 17-21: Check that references are referring to the right field experiments.

AR: References have been checked and the section has been rewritten *including a bullet list* to improve the readability:

"These particular clouds have been frequently observed in situ in the Arctic at small scales for several years in previous airborne experiments such as:

- in 1994 the Beaufort and Arctic Storms Experiment (BASE, Curry et al. (1997)),
- in 1998 the First ISCCP Regional Experiment Arctic Clouds Experiment (FIRE-ACE, Curry et al. (2000)),
- in 2004 the Mixed-Phase Arctic Cloud Experiment (M-PACE, Verlinde et al. (2007)),
- in 2004 and 2007 the Arctic Study of Tropospheric cloud, Aerosol and Radiation (ASTAR, Gayet et al. (2009); Jourdan et al. (2010)),
- in 2008 the Polar Study using Aircraft, Remote Sensing Surface Measurements and Models of Climate, Chemistry, Aerosols and Transport (POLARCAT, Delanoë et al. (2013)) and the Indirect and Semi-Direct Aerosol Campaign (ISDAC, McFarquhar et al. (2011)),

- in 2010 the Solar Radiation and Phase Discrimination of Arctic Clouds experiment (SORPIC, (Bierwirth et al. 2013)),
- in 2012 the study on the Vertical Distribution of Ice in Arctic clouds (VERDI, Klingebiel et al. (2014)),
- in 2014 the Radiation-Aerosol-Cloud Experiment in the Arctic Circle (RACEPAC)."

RC: Page 23459, line 1: Wouldn't it make sense to validate the methodology by comparing against groundbased remote sensing retrievals at some of the specific Arctic stations where such data are available? This is hinted at on page 23463 line 13 where it is stated satellite cloud fractions are smaller than surface observations by 3 to 35%, which seems like a very large amount!

AR: 5-35% is the difference observed between passive remote sensing spaceborne measurements (ISCCP and Nimbus-7) and ground-based observations. As previously shown (cf. reply to the third comment), active remote sensing spaceborne measurements from CALIPSO/CloudSat seem to present between 10% and 25% of uncertainty when comparing to ground based-observations, mostly below 2 km of altitude.

RC: Page 23460: See major comment above on difference between Version 1 and Version 2 of DARDAR. It almost reads that inclusion of Version 2 analysis was an afterthought in the paper.

AR: Answer to this comment is made previously in the major comments.

RC: Page 23462: The writing needs to be improved here. It seems that there are a number of disjoint sentences, each written as a separate paragraph.

AR: This section has been modified to avoid the disjoint sentences and improve the readability.

RC: Page 23463, line 27: I would like to see a bit more of a quantitative statement here rather than saying methodology is justified based on consistency: would also like to see comparison against ground-based retrievals.

AR: The answer to this comment is included in the answer to the third major comment concerning the uncertainties and limitations at the beginning of this document.

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