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

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As lot of changes have been made in the revised manuscript, it would not be very convenient to upload a marked-up manuscript. So, to complement the revised manuscript, we propose here is a summary of the relevant changes we made, according to the reviewers' comments (followed by the complete replies to the reviewers' comments).

SUMMARY OF RELEVANT CHANGES:

- The title has been modified. It is now "Variability of mixed-phase clouds in the Arctic with a focus on the Svalbard region: a study based on spaceborne active remote sensing".

- In the introduction, the previous airborne experiments (and their associated references) have been listed chronologically to improve the readability.

- The "uncertainties and limitations" section has been moved to the "data and method" section (it is now section 2.3., as suggested by reviewer #3). This section includes now 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

  In this section, many changes have been made in order to take into account comments of the three reviewers regarding the quantification of uncertainties of DARDAR retrievals based on comparisons with ground based measurements (in particular in section 2.3.1.2., and figures 2 and 3).

- All the results and figures featuring F_{MPC} and $F_{MPC}(z)$ have been remade taking into account warm clouds in the determination of MPC occurrence.

- In the figure 6 of the revised manuscript, the seasonal total cloud occurrence (F_{CLOUD}) has been added, as suggested by reviewer #2.

- The section 4.2 concerning the single layer MPC characteristics has been shortened and included in the section 4 concerning MPC, and the corresponding figures have been removed, as suggested by reviewer #1.

- As suggested by reviewer #1, figures 3b, 5a and 5b have been combined (now figure 7 in the revised manuscript), to improve the organization of the paper.
- First paragraphs of sections 3 and 4 have been shortened and moved to the introduction.
- As suggested by reviewer #1, the two first paragraphs of the discussion have been removed since they repeated the results already presented.
- Discussion about the link between clouds and MPC occurrence and sea ice melting have been improved by the analysis of sea ice data in the discussion, including a new figure (section 5, figure 10 in the revised manuscript).
- In the conclusion (section 6), the main results are listed with bullets to improve the readability.
- Seasonal occurrences above open water and above sea ice have been determined and have been added in figure 8b (instead of occurrence over water which included both open water and sea ice in the original version of the paper).
- The revised paper has been reviewed by Professor Andrea Flossmann to ensure proper writing, sentence structure, and clarity.

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 #1

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, this study needs to do a better job of providing a full analysis of the uncertainties/limitations of the satellite measurements through detailed comparisons with ground-based measurements (especially targeting the biases related to clouds below 500m)

Authors' Reply (AR) :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 and suggests a full analysis of them, as well as comparisons with ground-based measurements. Obviously, we have in mind that space active remote sensing instruments have their own uncertainties and limitations, in particular for detecting low-level clouds. As suggested by the reviewer, we have emphasized these limitations at the beginning of the revised manuscript.

We agree with this main major comment which argues that the combination of ground-based and spatial observations is the unique way to accurately quantify these limitations. 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 quantifying 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.*

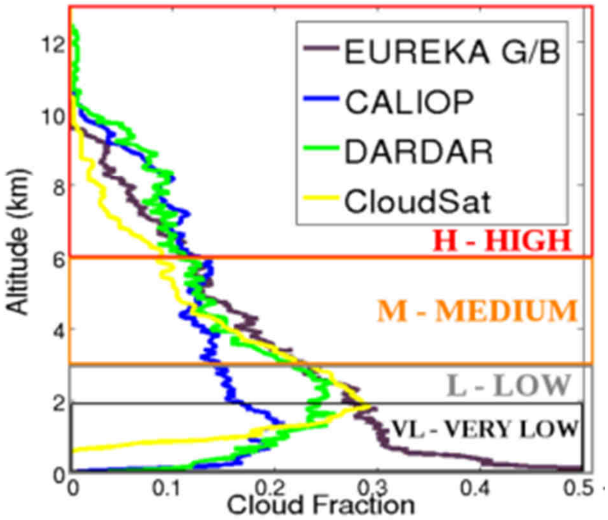

Figure A: Vertical profiles of cloud occurrence over Eureka station from CALIOP, CLOUDSAT, DARDAR and ground based observations. From Blanchard et al., 2014.

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 by reviewer #3. 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)

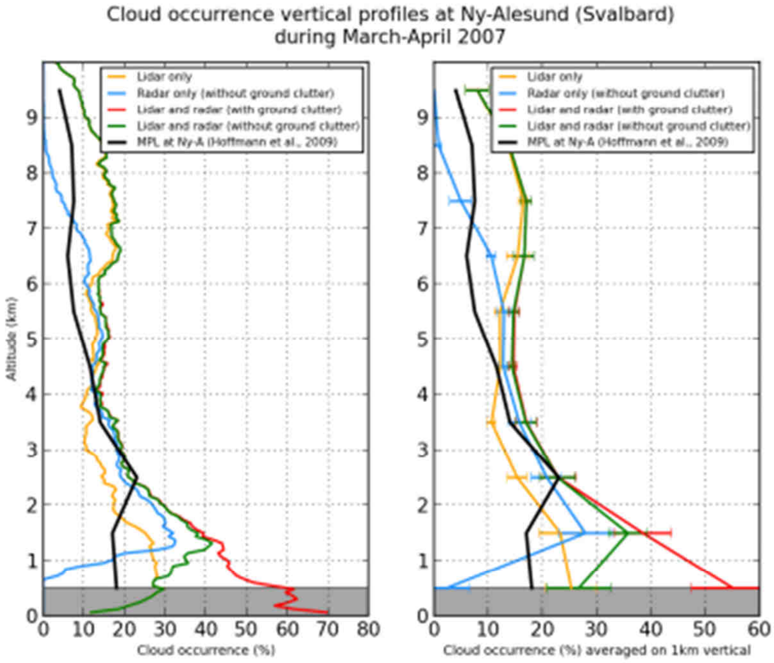

Figure B : Comparison of cloud occurrence vertical profiles from different DARDAR products and from Ny-Alesund ground based observations (Hoffmann et al, 2009) for the March-April 2007 period. Yellow lines corresponds to lidar alone, blue lines correspond to radar alone excluding pixels contaminated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

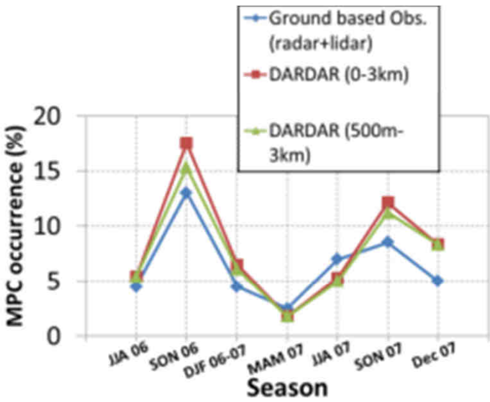

Figure C: Comparison of single layer MPC occurrence from DARDAR product and from Eureka ground based observations (De Boer et al, 2009) from June 2006 to December 2007.

RC : Second, the paper itself evaluates a version 2 data product and shows that it is better. The product is clearly available and was produced by a co-author on this paper. Thus, it is absolutely unacceptable to publish this paper without conducting the analysis with the clearly superior data product.

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: *Regarding limitations to the A-Train sensors, I do not recall reading anywhere about the latitudinal limitation to this constellation. They do not go north of 82 degrees. This is implied in the spatial map figure, but it would be a very good point to specifically mention in the text. This is particularly important because the Arctic domain north of 82 degrees is largely dominated by sea-ice, which is of clear importance to the Arctic system. Unfortunately A-train measurements can provide little information on the clouds in this important region.

AR : We forgot to mention the latitudinal limitation (82°N).

It is now mentioned in the dataset description (section 2.2) as follow:

"In this study the Arctic region is defined by all latitudes between 60°N (Liu et al., 2012) and 82°N (upper limit of CALIPSO/CLOUDSAT measurements)…."

RC : *P23464, lines 20-30: Yes, but there are serious limitations regarding low clouds and multi-layered clouds that should be mentioned out front. Don't hide these limitations towards the back of the paper. Also, just because the different ways of processing the same satellite data set agree does not mean that the data set / methods are correct!

AR : We took into account this comment and mentioned in the introduction the limitations of space observations regarding low clouds and multi-layers clouds as follow:

"Since 2006, they perform lidar (532 nm and 1064 nm) and radar (94 GHz) measurements, and provide an unprecedented dataset of the vertical structure of clouds, continuously in time and space (up to latitude 82°N), even if these instruments have serious limitations regarding low clouds and multi-layered clouds, as will be discussed below."

RC: *P23465, line 5-8: ISCCP has been shown to be inconsistent with ground-based observations at specific sites. While spatially confined, ground-based observations are relatively robust at getting cloud occurrence.

AR : Yes, and figure 2 also confirms that ISCCP is inconsistent with ground based observations.

The following sentence has been removed:

"However, annual variability from DARDAR may be considered as consistent with that from ISCCP over the same area i.e. over ocean on the west coast of Svalbard, even if ISCCP observations seem to show a notable and expected underestimation."

RC : *P23470: In the Arctic, many clouds occur at heights <500m. You avoid the issue altogether of clouds below 500m, which is perhaps the largest issue with using the satellite sensors in this study. The errors related to missing low-level clouds (<500m) can be evaluated using ground-based observations at a few locations. This should be done in order to provide much more robust occurrence statistics. Otherwise, it is unclear how the provided results actually relate to actual cloud occurrence fractions.

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

"Uncertainties in cloud or MPC occurrence is up to 20% between 500m and 2km, and up to 25% below 500m."

RC : *P23470, line 14-16, and also P23477, line 3-5: Just because contamination of the signal at 500-1000m is less than at 0-500m does not, by itself, justify using the 500-1000m data. You instead need to understand and demonstrating the accuracy of the 500-1000m data!

AR : To classify pixels as clouds, DARDAR MASK algorithm is based on the CloudSat cloud mask and the CALIPSO lidar mask (Delanoë and Hogan, 2010)*. Regarding CloudSat measurements, a pixel is considered as cloud if*

value of CloudSat cloud mask is greater than 30 (according to Mace (2007)). Values smaller than this CLOUDSAT mask threshold are considered inaccurate and possibly contaminated by ground echoes. So, CloudSat radar mask values greater than 30 definitely exclude ground contamination and are referred as reliable data. So, we are positive that pixels used for cloud and MPC fraction are not contaminated by ground echoes.
For additional information, we have investigated the reliability of DARDAR data in the 500-1000m altitude domain to give an insight on how ground contamination may affect the observations. Between 500m and 1000m, 40% of the DARDAR data are reliable (they correspond to clear sky or atmospheric features). The remaining 60% correspond to bad data and could be assigned to ground contamination on radar data (70%) and lidar total attenuation (30%). This result gives an insight on how ground contamination affects the observations and reduces the dataset in the 500m-1km altitude range.

These results have been added to the revised manuscript as follow:

"The fraction of reliable data (clear sky or atmospheric features) has been determined and represents about 40% of the total data in this altitude range. The remaining 60% correspond to data assigned either to ground contamination on radar data (70%) or to lidar total attenuation (30%). This result gives an insight on how ground contamination affects the observations and reduces the dataset in the 500m-1km altitude range."

AC : *P23475, line 17: Yes the satellite observations presented here are "uniform" however they are also biased. Ground based observations are not biased in the same way, but due to different instruments at different locations they are not so uniform. Likely the best approach to get at a true cloud fraction (or MPC fraction) is to use a combination of these approaches. But little work has been done here to really evaluate the satellite retrievals within the context of the ground-based measurements.

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

RC : *P23463, first paragraph: Why are only cold clouds considered in the determination of MPC occurrence? The way (I think) you define the MPC occurrence is the portion of clouds below the freezing point. But this inflates the MPC occurrence because there are also clouds warmer than this temperature that occur at times. I see no reason to add this constraint and it is not that useful for people unless they also know the fractional occurrence of T<0C. Without further justification, you should just use the total cloud occurrence at all temperatures.

AR : We reprocessed MPC occurrence taking into account all cloud as reference, instead of cold clouds. Warm clouds are mostly present during summer (occurring up to 10% of time). During the others seasons, $F_{WARM\ CLOUD}$ is very low (between 0 and 2% of time in average over the entire Arctic). So, when we include warm clouds for F_{MPC} calculation, F_{MPC} decreases during summer, but is almost unchanged during the rest of the year.

In the revised manuscript, all the figures featuring F_{MPC} and $F_{MPC}(z)$ have been remade (figures 6, 7, 8 and 9 in the revised manuscript)

RC : *Section 4.2: I don't think that this section (nor the figures that go with it) is needed. The whole thing can be summarized in a couple of sentences that basically say MPC-IB follow similar patterns to MPC and represent X% of the MPC population. Furthermore, at P23470, lines 24-26 it is stated that due to detection issues MPC-IB could be overestimated.

AR : We have shortened this section as suggested (it is now included in the section 4) and removed the corresponding figures in order to improve the readability of the paper.

RC : *P23471, line 4: The fact that a "second version" exists, that it was produced by a coauthor on this paper, that it was published in 2013, and that part of it was used in this paper to compare with the first version all suggest to me that better data is available for the present study. If it is better, then it should be used. There is no reason to publish this paper with the present results when it is clear that better data are easily available. This paper absolutely cannot be published without redoing the analysis with the better data set. This whole section on comparing the two versions can then be removed from the paper.

AR : The reasons why we used V1 version (and kept comparisons between V1 and V2) have been explained above.

RC :*P23473-23474: I have some difficulties with the interpretations on these pages. Lines 24-26: I don't get the connection here. Sure moisture is important for cloud formation, but the linkage to ice-liquid equilibrium takes a few more details!

AR : Moisture is important for cloud formation by initiating cloud liquid droplets. It is well established that within MPC, ice crystals can grow at the expense of liquid droplets (Wegener-Bergeron-Findeisein process). Such a microphysical process should produce rapid glaciation of MPC. However, Arctic MPC are known to be very persistent, with lifetime up to several weeks. Additional processes are thus needed to maintain equilibrium between ice and liquid, and in particular to initiate liquid droplets in order to balance the loss due to WBF process. We suggested that among the numerous additional processes involved in MPC lifecycle, the contribution of a larger amount of moisture is one that might promote the liquid droplets formation and so contribute to maintain the mixed phase within Arctic clouds. Of course, moisture is not sufficient by itself to maintain of the ice-liquid equilibrium, as shown by Korolev (2007), Korolev and Isaac (2003) or Korolev et al. (2003). *It has to be coupled with dynamics processes, such as updraft from cloud base or turbulence entrainment at cloud top.*

In the revised manuscript, we mentioned all these details as follow:

"Thus cloud formation and its development can be amplified, since the supply of moisture by the North Atlantic Ocean is favorable for the nucleation of liquid droplets. The initiation of new supercooled liquid droplets will balance the loss due to the WBF process within the MPCs, and therefore participate to maintain the equilibrium between ice and supercooled droplets. However, moisture is not sufficient by itself to maintain the ice-liquid equilibrium. As shown in Korolev (2007), Korolev et al. (2003) and Morrison et al. (2012), it has to be coupled with dynamics processes, such as updraft from cloud base, or turbulence and entrainment at cloud top."

RC : Line 29>line3: No, the inversions can contribute to the longevity of clouds simply because they are a moisture source, but preventing clouds at higher altitudes has little to do with persistence at lower altitudes.

AR: It was a misunderstanding: we wanted to say that inversions contribute to limit the vertical extension of MPC. Of course, clouds at higher altitudes could be present, but they will have no link with low-level MPC.

We rephrased the sentence in the revised manuscript as follow:

"These conditions associated with temperature and eventually humidity inversions at cloud top, which frequently occur in these seasons (Nygård et al., 2014; Sedlar et al., 2012), can contribute to the containment of Arctic clouds and MPCs at low altitudes by limiting their vertical extension."

RC :Line 3-4: Not really. The reason for transition season prevalence is to first order a product of the annual temperature cycle. Transition seasons have temperatures in the range were mixed-phase conditions are more probable from a microphysics perspective.

AR : Moisture is effectively not the main but an additional factor, coupling to the temperature conditions, which may promote the MPC formation during these transitions seasons.

It has been specified in the revised manuscript as follow:

"Moreover, winter and transition seasons are characterized most of the time by stable atmospheric conditions (Orbaek et al., 1999), coupled with a temperature range favorable for mixed phase conditions."

RC : Line 11-15: Mixture of concepts here is done inconsistently.
Also, this study has not demonstrated any links like this. That would require some analysis of sea-ice data, which has not been done.

AR: Our conclusions should have been considered as perspectives and suggestions for future works. For instance the investigation of the link between MPC and sea-ice coverage is beyond the scope of the paper. However, to strengthen this conclusion and the perspectives of this work, we propose to briefly look at the seasonal variability of sea ice and humidity over the Arctic region.

To do that, we processed CALIOP L1 data to extract sea ice concentration (%) (data from National Snow and Ice Data Center (NSIDC) projected on the CALIPSO track). Figure D represents the seasonal variability of the sea ice concentration. Then, two specific areas in the Arctic region are selected:

- *Zone A: over the Greenland sea: 70°N to 80°N and 10°W to 20°E*
- *Zone B: over the Western Arctic (Chukchi and Beaufort seas): 70°N to 80°N and 150°W to 180°W.*

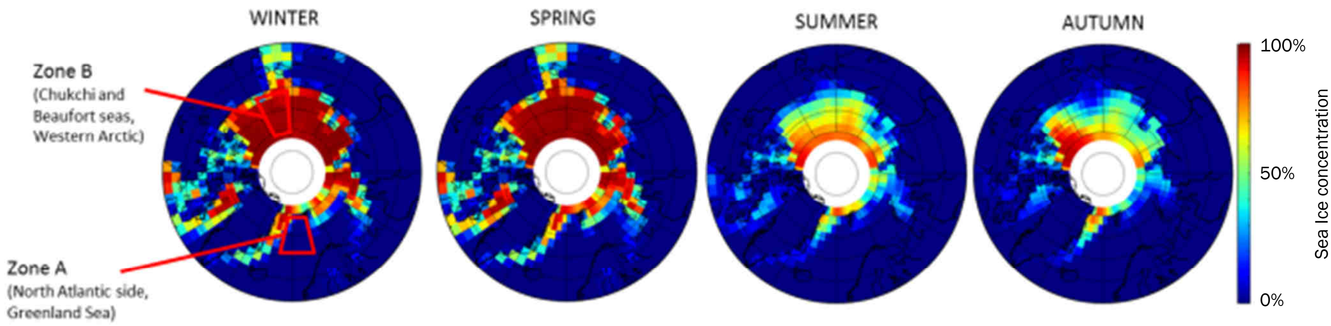

Figure D: Seasonal sea ice concentration (%) between 2007 and 2010. Data are from NSIDC.

Figure E illustrates the annual variability of specific humidity (top panel) and 2m temperature (bottom panel), from ECMWF (solid lines), between 2007 and 2010 for the whole Arctic region (black), over the Greenland sea (zone A, blue) and over the western Arctic (zone B, orange). On both figures, dashed lines represent the sea ice concentration (in %).
Sea ice concentration variability is very pronounced in the western Arctic with a large decrease from late spring/beginning of summer to late autumn (values larger than 90% in April fall down to less than 10% in September). Over the Greenland sea (Zone A), sea ice variability is rather constant, with low values between 5 and 20%. A small decrease is still observed from spring to autumn. 2m temperature and specific humidity are from ECMWF and they are interpolated onto the DARDAR grid. Note that specific humidity is averaged over the 0-500m altitude domain. Note also that the accuracy of these ECMWF retrievals is not discussed here, since we use them only to give an insight of their variability. From figure E, sea ice concentration is clearly inversely correlated with humidity and temperature. However, a delay is observed between the sea ice concentration minimum (September) and the humidity and temperature maxima (July).

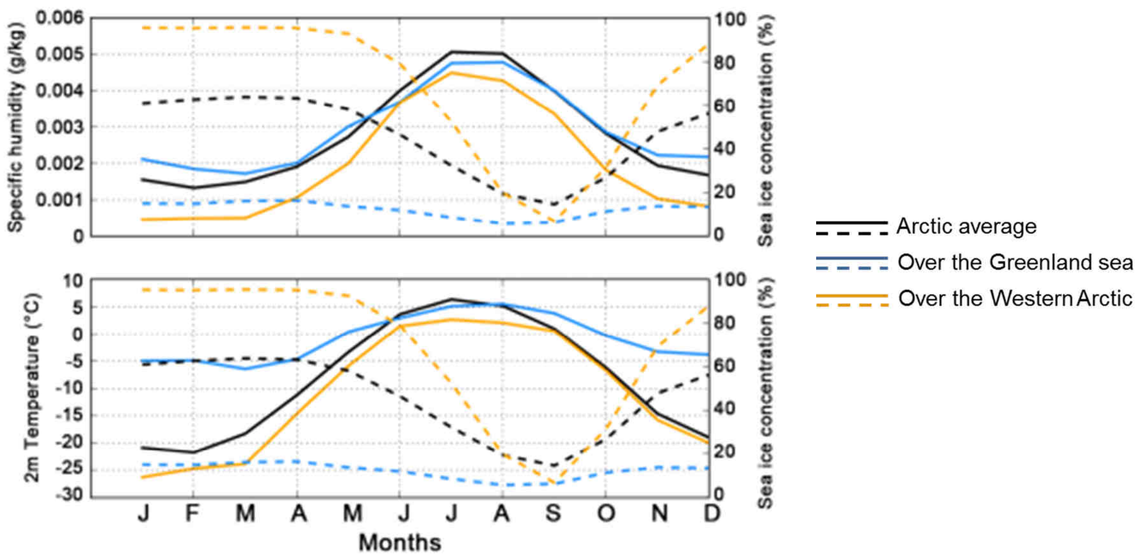

Figure E: Annual variability of specific humidity (top panel) and 2m temperature (bottom panel) for the whole Arctic region (black), the Greenland sea region (blue) and the Western Arctic (orange). Corresponding sea ice concentration is superimposed in dashed lines.

Figure F below represents the monthly cloud (circle symbols) and MPC (triangle symbols) occurrences as a function of monthly sea ice concentration for the whole Arctic (black), the Greenland sea (blue, zone A) and the Western Arctic (orange, zone B). Cloud and MPC occurrences clearly decrease when sea ice concentration increases (slope around -0,30, with correlation coefficient rather representative (0.7), for information purposes only). Figure F shows the same trend both for all clouds or MPC.
Note that the results over the Greenland sea (blue dots in the Figure F) do not point out a significant trend because of the small variability of the sea ice concentration throughout the year in this region. This is in agreement with the high cloud occurrence observed all along the year in this region.

From these results, it seems that cloud and MPC cover are linked to the sea ice melting. However, more investigation are needed to confirm this assumption, such as the study of cloud and sea ice over the whole Arctic region since our study is limited to the region below 82°N.

These results (including figures E and F) have been added to the discussion in the revised manuscript to strengthen the conclusions and perspectives to our work.

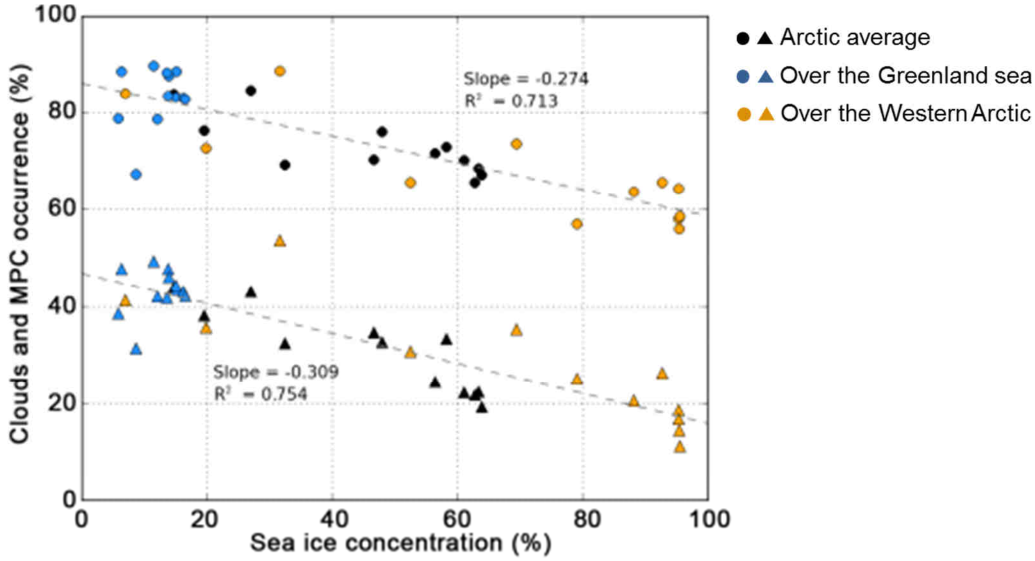

Figure F: Cloud and MPC monthly occurrences as a function of sea ice concentration.

RC : *P23477, line 9-18: A couple pages ago it is argued that ground observatory climatologies are NOT representative but then here it is argued that in situ measurements at Svalbard are! In situ measurements easily have as many issues as ground-based observations AND Svalbard is a single location that does not represent the full Arctic. A few case studies of mixed-phase clouds can be useful for understanding processes, however, multiple year's worth of cases above ground-based observatories provides a much more generalized understanding of cloud processes than a couple of cases.

AR : There is a misunderstanding concerning this conclusion. Of course, in situ measurements could not be more representative than ground-based observations. It is a question of observation scale. In situ observations are valuable to understand processes involved in MPC at the microphysical scale, which is not accurately possible from remote sensing measurements only. We showed in our study that the occurrence of mixed phase clouds over the Svalbard region was important. This particularity is largely due to the proximity of the North Atlantic Ocean, providing more favorable conditions for MPC formation throughout the year than over the mean Arctic. In situ observations of MPC made in this area could be very useful to study in details microphysical properties and processes governing ice and liquid particles within MPC. Indeed, we have to keep in mind the peculiarity of the study region, such as the geographical location and the influence of environment.

The present results could help us understand in which regional frame such kind of in situ measurements have been performed. This will also highlight the regional context of the small scale studies made from these in situ observations.

The section concerned has been rewritten as follow:

"Thus, the present study contributes to understand in which regional frame airborne campaigns and ground based observations have been performed. However, space remote sensing observations present well-known uncertainties near the surface which may have an important impact on low-level cloud amount determination. Therefore, airborne campaigns will provide a more thorough characterization of MPC properties at small scale. In particular, in situ measurements will help to understand microphysical processes involved in MPCs."

MINOR COMMENTS

As recommended by the reviewer, the re-worked manuscript has been reviewed by Professor Andrea Flossmann to ensure a proper writing.

RC: *P23454, line 19-20: What does this sentence mean? "Prevail" over what? Do you mean that they are the most common cloud type over sea?

AR: That means MPC are more frequent over sea (more precisely open sea) than over ice.

This sentence has been changed as follow:

"Moreover, results highlight that MPC are statistically more frequent above open sea than land or sea ice"

***P23455, line 12: "global" should be removed**

AR: It has been done.

***P23456, 1st paragraph. A couple of the sentences in this paragraph are not very clear. Should do some careful re-writing for clarity.**

AR: This paragraph has been rewritten as follow:

"This implies that our understanding of all steps of the MPC life cycle needs to be improved. Indeed, formation, development, persistence and dissipation of MPC are governed by a combination of local and large-scale processes (Morrison et al., 2012). At the small scale, the Wegener-Bergeron-Findeisen (WBF) process is one of the main mechanisms responsible for ice crystals growth at the expense of supercooled water droplets (Bergeron, 1935; Findeisen, 1938; Wegener, 1911). Such mechanism leads to a rapid glaciation of the MPC. On the other hand, dynamical processes, such as turbulence or entrainment may facilitate the formation of 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. Local and long-range dynamic processes are also involved in aerosol, heat and moisture transport which have a significant impact on Arctic MPC formation and properties (Cesana et al., 2012; Morrison et al., 2012; Shupe and Intrieri, 2004). It remains, therefore, difficult to fully understand the complexity of interactions between all these processes and to assert which of them play a key role in the MPC evolution (Harrington et al., 1999; Morrison et al., 2012)."

***P23456, line 28: Mixed-phase clouds are often simply referred to as "mixed phase" as is done here. This does not make sense. Should instead refer consistently to mixed phase clouds or MPC.**

AR: It has been corrected.

***P23457, line 10: "unique"? This should be clarified, does it mean "single" or "distinct" or something else?**

AR: "Unique" has been replaced by "single"

***P23457, line 12: "peculiar" should be "particular"**

AR: "Peculiar" has been replaced by "particular"

***P23457, lines 12-20. You are missing many of the earlier aircraft campaigns that were really formative in the understanding of MPC, and upon which many of these other campaigns were built. i.e., BASE, FIRE-ACE (1998), MPACE (2004), etc.**

AR: We added earlier aircraft campaigns and improved the readability with a bullet list as follow:

"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)."*

***P23458, line 9: A-train doesn't go north of 82 degrees. This should be mentioned explicitly.**

AR: "almost the entire Artic" has been replaced by "up to latitude 82°N"

***P23458, lines 10-13: Need to reword this for clarity.**

AR: This sentence has been rewritten as follow:

"This is the case for the new generation of spaceborne instrumentation onboard CALIPSO (Winker et al., 2003) and CLOUDSAT (Stephens et al., 2002) satellites. Since 2006, they perform lidar (532 nm and 1064 nm) and radar (94 GHz) measurements, and provide an unprecedented dataset of the vertical structure of clouds, continuously in time and space (up to latitude 82°N), even if these instruments have serious limitations regarding low clouds and multi-layered clouds, as will be discussed below."

***P23459: What is the pixel size used? i.e.., across and along track dimensions.**

AR: Pixel size along the track is 60 m vertically and 1.7 km horizontally. It is 1.4 km m across the track.

***P23460, line 14: greater than 30 what?**

AR: Values of the CLOUDSAT cloud mask are unitless (Mace, 2007).

***P23460, line 25: What does "in the vicinity" mean? Is this horizontal, vertical? How far?**

AR: It means vertically. The sentence has been changed as follow:

"…associated with the presence of ice or ice and supercooled water mixing in the 3 vertical adjacent pixels".

***P23461-23462: There is a lot of redundancy with the 2 degree latitude and 5 degree longitude statements.**

AR: We removed some redundancies.

***P23462, line 15-16: So this means >180m total thickness?**

AR: Yes. **We added it as follow:**

"The presence of cloud (and MPC) is detected in each atmospheric column if at least 3 consecutive pixels (i.e. minimum thickness of 180m) are classified as cloud (MPC) by DARDAR."

***P23463, line 8 and P23464, line 5: Need to introduce acronyms.**

AR: It has been done.

***P23463, lines 18-24: Redundancy.**

AR: the 2 first paragraphs of section 3 have been shortened and moved to introduction (section 1)

***P23464, lines 20-22: This is info for the introduction that has already been stated.**

AR: see previous comment.

***P23465, line 22-24: SHEBA does not equal Barrow.**

AR: It was a mistake.

"over Barrow, Alaska" has been replaced by "over the Western Arctic Ocean".

Moreover, this paragraph regarding the previous studies trying to quantify MPC occurrence has been moved to introduction as follow:

"An assessment of the annual variability of MPC was performed during the Surface Heat Budget of the Arctic Ocean experiment (SHEBA, Uttal et al., (2002)), showing that MPC and liquid-containing clouds are prevalent over the Western Arctic Ocean. The SHEBA experiment highlighted that liquid containing clouds (i.e. including supercooled and warm liquid clouds) over the Beaufort sea represent about 40 % of the clouds during winter and reaches more than 90 % in summer (Intrieri et al. 2002). Additionally, Shupe et al. (2006) showed that nearly 60% of the clouds in Arctic are MPC".

***P23466, line 1: Need to be careful with definitions. Some of the numbers that are being presented from past studies are % of time, while those given in this study are % of the time that clouds occur.**

AR: it has been specified (see previous comment).

***P23466, line 5: The word "ubiquitous" is used a number of times in this document and I think it is incorrectly used. Ubiquitous might be appropriate for describing the general cloud occurrence in summer (i.e., upwards of 80-90%). But at times the word is used in this document for much smaller fractions.**

AR: The word "ubiquitous" has been removed. The sentence has been changed as follow:
"One can note that MPCs are encountered in all seasons in the Arctic region."

***P23466, line 22-23: I don't see anything special about 3000m. The same trend exists above 3000m**

AR: This is mainly observed over the Svalbard region.

***P23467: I'm getting a bit confused. Please make it very clear which results relate to the whole dataset versus those that relate to Svalbard region. This is not always clear.**

AR: The section 4 has been modified in this way.

***P23467, line 4-5: Relative to what?**

AR: Relative to the other seasons. The sentence has been changed as follow:
"However, in summer, the vertical profile FMPC(z) is characterized by a higher cloud amount above 3000 m and less clouds below 3000 m than during the other seasons."

***P23467, line 14-15: It might be easier to combine this information with Fig. 3b.**

AR: This has been done: Figure 7 in the revised manuscript combines timeseries of F_{MPC} (7a and 7b), $F_{low\text{-}level\ MPC}$ (7c and 7d) and the ratio of low-level MPC over total MPC (7e and 7f).

***P23469, line 1: "Global" scales are not studied here.**

AR: The sentence has been removed since section 4.1 has been shortened.

***Section 5.2: The first two paragraphs of this "discussion" section are not that effective in that they simply repeat results that have already been presented with little analysis or interpretation. Moreover, this is not presented in a clean way. The points are jumbled together. There are also missed opportunities for actually using surface type data to draw solid conclusions instead of just referring to other analyses that have unknown applicability to the data presented here.**

AR: The first two paragraphs of this discussion have been removed in the revised manuscript.
Moreover, in order to improve the readability, the conclusion (section 6) has been modified by listing the main results as follow:
"The main results are summarized below:
- *Based on comparisons with ground based observations, uncertainties in the determination of cloud and MPC occurrence from the DARDAR product below 2 km of altitude are estimated to up to 20% between 500m and 2km, and around 25% below 500m.*

- *Clouds are present in the Arctic throughout the year, with occurrences between 50 % and nearly 100 %, depending on the season and the location. Moreover, clouds are more frequent in the Svalbard region than in the rest of the Arctic by around 5-10 %.*

- *Over the whole Arctic region, MPCs represent around 30 % of the clouds during winter and around 50 % of the clouds the rest of the year. Over the Svalbard region, MPC occurrence is almost constant all along the year, with values around 55 %. MPCs are mainly present at low-altitudes as 70 % to 90 % of the MPCs are located below 3 km (both for the entire Arctic and the Svalbard region), especially in winter, spring and autumn. In summer the MPC occurrence becomes significant at mid-level altitudes (3-6 km). During spring, MPCs are located mainly over the Greenland, Barents and Norwegian seas. In autumn, large occurrences are observed in the western Arctic (over the Chucki and the Canadian seas). Moreover, MPCs are generally more frequently encountered over open sea than over land or sea ice.*

- *The particular Arctic MPCs composed of a single supercooled liquid layer at cloud top and ice in the lower part of the cloud (MPC-IB) represent between 55 % and 70 % of the MPCs over the whole Arctic and between 65 % and 80 % of the MPC over the Svalbard region. Spatial, seasonal and vertical variability of this cloud type have strong similarities with MPCs.*

- *Differences between MPC seasonality over the Svalbard region and over the entire Arctic region can be partly explained by the vicinity of the North Atlantic Ocean and the particular atmospheric conditions encountered around the Svalbard archipelago. The mixture of cold air and warm water from the North Atlantic Ocean seems to be responsible for the large MPC amount observed during spring over the Svalbard. In the western Arctic, the MPC maximum frequency occur later during summer and autumn when heat and moisture are released due to the melting of sea ice. A short analysis based on comparisons of sea ice concentration with temperature, humidity and clouds and MPC occurrences seems to establish a link between sea ice and cloud and MPC occurrences. Evidently, here a more detailed study is needed, as MPC variability is also dependent on the regional scale characteristics such as the oceanic circulation, and on more local conditions (such as the proportion of open water/sea ice which exhibits a seasonal variability)."*

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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 #2

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): Neglecting warm clouds:
At the end of section 2.2. the authors explicitly note that warm clouds are not considered in calculating the statistics although already in the next sentences F_{CLOUD} is named "total cloud occurrence". I think neglecting warm clouds is a big mistake as it limits the interpretation of the mixed-phase cloud occurrence presented in the manuscript.
Considering climate warming, there might be an increase of warm clouds at the expense of mixed-phase clouds, especially in Arctic summer. If you want to detect any trends in occurrence of mixed-phase clouds linked to climate warming you have to include warm clouds in your statistics. Otherwise you always normalize the number of mixed-phase clouds by all clouds < 0°C which might remain a stable fraction despite a general decrease of mixed-phase clouds.
Furthermore, not considering warm clouds also makes N_{CLOUD} as presented in Fig. 2 meaningless with regard to analysis of the cloud radiative forcing. For the Earth energy budget, all clouds including warm clouds are of importance. Especially warm clouds which are likely to have a cooling effect. So presenting a cloud occurrence without warm clouds may give a wrong impression to the reader. Some questions still remains here. How often warm clouds can be observed in Arctic at all? Do the ground based remote sensing observations presented in Fig. 2 do also neglect warm clouds? How the comparison would look like if warm clouds are included.

Authors' Reply (RC) : Warm clouds were only excluded when calculating MPC occurrence. So, in Figure 2, total cloud occurrence includes warm clouds.
As recommended by the reviewer, we reprocessed MPC occurrence taking into account all cloud as reference, instead of cold clouds. Figure A below presents warm clouds occurrence (referring to time) according to the seasons. Warm clouds are mostly present during summer (occurring up to 10% of time). During the others seasons, $F_{WARM\ CLOUD}$ is very low (between 0 and 2% of time in average over the entire Arctic). So, when we include warm clouds for F_{MPC} calculation, F_{MPC} decreases during summer, but is almost unchanged during the rest of the year.
In the revised manuscript, all the results and the figures (figures 6, 7, 8 and 9 in the revised manuscript) featuring F_{MPC} and $F_{MPC}(z)$ have been remade.

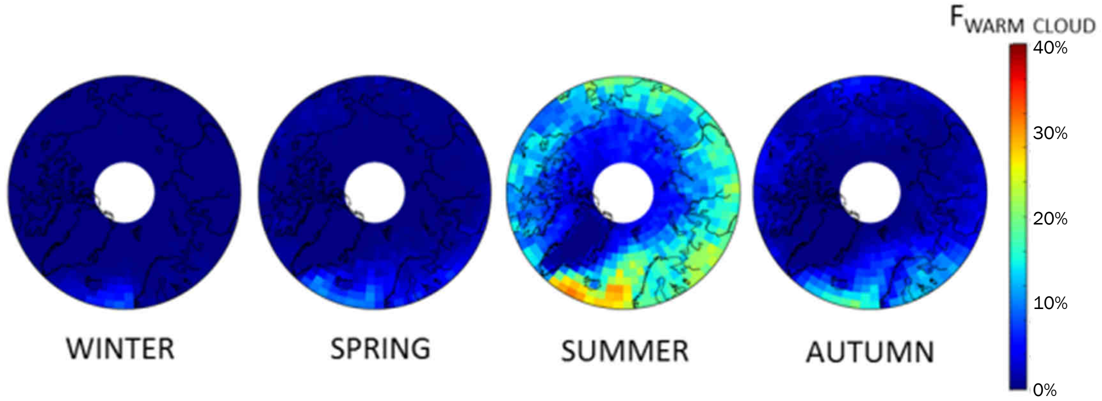

Figure A: Seasonal occurrence of warm clouds (referring to time).

RC: DARDAR product Version 2:
The authors present a section comparing DARDAR products from version 1 used in the manuscript and version 2 already published by Ceccaldi et al. (2013). Differences between both versions are quite significant ranging up to 15% for mixed-phase cloud occurrence. Although these differences are known, the presented climatology is calculated using the old version 1 of DARDAR. Having the new version 2 availably I highly recommend to reprocess the data using the version 2. There is no need to show outdated data and draw conclusions from an obviously biased data base. Using version 2 would also be more forward-looking in case the data set will be extended to more recent years. The comparison between V1 and V2 can still remain part of the manuscript. Just interpret differences as the improvements compared to literature using V1.

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".

MINOR COMMENTS

RC: *Title: "Variability of the mixed phase...". "The mixed phase" is somehow undefined and can also be related to subjects different than clouds. I suggest to reword "Variability of mixed-phase clouds...".*

AR: **The title has been modified in this way.**

RC: P23455, 12: "global net warming effect". Does that mean, that Arctic clouds warm so much, that globally all clouds are warming? Or do you refer to a "regional net warming effect"?

AR: We wanted to say that Arctic clouds tend to have a regional net warming effect. **It has been clarified in the revised manuscript as follow:**
"…tending to a regional net warming effect"

RC: P23456, 29: Discriminating ice and liquid (pure ice and pure liquid clouds) is not as difficult with current instrumentation. The statement of the authors is a little exaggerated. What is still limited and challenging is the discrimination of mixed-phase clouds from pure ice clouds. E.g. from remote sensing where even a small fraction of large ice crystals in mixed-phase clouds may cause similar radiative properties like pure ice clouds have.

AR: We mean that the discrimination of separate properties of liquid droplets and ice crystals within the same sample volume (both for in situ or remote sensing observations) remains challenging. Mixed phase depends also strongly on the observation scale. For example, it would be easier to measure a small volume of pure liquid embedded into an ice phase from in situ measurements, whereas remote sensing could miss it if liquid volume is too small. **The sentence has been modified as follow:**
"Moreover, the determination of separate properties of ice crystals and liquid droplets within the same sample volume remains challenging due to instrument limitations in both remote sensing and in-situ measurements."

RC: P23457, 12-20: This long sentence is very hard to read. Do the last references refer to SORPIC 2010? This can not be as publications are published earlier than the campaign.

AR: Of course not, it does not refer to SORPIC. It was referring to the in situ observations of the single layer MPC peculiar vertical structure. **We added earlier aircraft campaigns and improved the readability with a bullet list as follow:**

"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: P23460, 6: The criteria using the strong attenuation is not included in Fig. 1. Please add.

AR: The figure 1 has been modified and includes now this criteria.

RC: P23460, 11: "Physical thickness" I can not imagine that the lidar can penetrate all clouds entirely and give the cloud top and base altitude. That's why I would not call it "physical thickness". This is probably only the lidar penetration depth. Am I right? If so, this implies that there are certain limits in the cloud phase retrieval. Frequently low level clouds will be not classified. Please highlight at some point.

AR: We meant by physical thickness, the penetration depth. We can also call it the geometrical thickness.

It has been changed in the revised manuscript as follow:

"…and to have a penetration depth (detected by the lidar) thinner than 300 m".

Effectively, lidar will not go through cloud having an optical thickness greater than about 3. For these clouds, the penetration depth will be underestimated and cloud fraction may be underestimated too. However, even if lidar does not completely go through an optically thick liquid layer, the information of the presence of this layer is useful since we do not calculate cloud fraction according to the thickness of clouds but only their presence or not.

RC: P23460, 15: First reading it was not obvious that cloud classification by DARDAR provides vertical information and not only a single cloud class for each pixel. It would be helpful for the reader to highlight that more clearly at the begin of this section.

AR: It is now mentioned at the begin of this paragraph as follow:

"Active remote sensing observations are expected to provide a detailed characterization of the cloud vertical structure in the Arctic."

RC: P23460, Sec. 2.1: Overall there are a lot of assumptions and limitations in the cloud classification. To better understand the results please give a summary or definition what "Mixed-Phase Cloud" means in the context of the manuscript. What clouds are included, which potential mixed-phase clouds are not?

AR: This is done in section 2.2.:

"2.2 Dataset and methodology

In this study, mixed phase clouds are defined based on DARDAR classification. All DARDAR pixels satisfying one of the following two conditions are assumed to belong to MPC:

- *they are classified as a mixing of ice and supercooled water (class 2, see Table 1)*
- *they are classified as supercooled only (class 4, see Table 1) associated with the presence of ice or ice and supercooled water mixing in the 3 vertical adjacent pixels.*

Note that "isolated" supercooled water pixels are not classified as mixed phase clouds."

RC: P23461, 4: Is there a justification why this area was chosen? Comparison with ground based measurements at Ny Alesund? What I'm not sure is, if choosing such an area with a mixture of open water and land is a good choice. My first idea would have been to pick an open water and an ice or land covered area for comparison. Based on the
theoretical processed behind the dynamics of mixed-phase clouds which are different for clouds above land compared to clouds above open water.

AR: We chose to focus on the Svalbard region because this region benefits from particular meteorological conditions due to its location and the proximity of the North Atlantic ocean compared to the rest of the Arctic. So one interest was to look at the MPC variability in this region compared to the whole Arctic.
Secondly, and from a more technical field of view, many in situ measurements have been made in this area for several years. We think this study could help to understand in which regional frame such kind of in situ measurements have been performed. This will also highlight the regional context of the small scale studies made from these in situ observations.
There is no particular reason in the choice of the limits of this area. However, this zone contains effectively both sea ice, open water and land, but the frequencies of occurrence according to these surface types are determined further in the study.

RC: P23462, 15: Why 3 pixel were chosen as criteria? How many meters in vertical thickness are 3 pixel? The 3 pixel have to be consecutive or randomly distributed? What is the typical total number of all altitudes? (to have an impression what fraction mixed phase clouds have to cover)

AR: This threshold was chosen to avoid the isolated pixel to be counted in. The number of 3 is arbitrary, and pixels have to be vertically consecutive. Since vertical pixel size is 60m, this corresponds to a physical thickness of 180m. For information, the typical total number of pixels belonging to MPC class over all altitudes is around 6. **The sentence has been completed as follow:**
"The presence of cloud (and MPC) is detected in each atmospheric column if at least 3 consecutive pixels (i.e. minimum thickness of 180m) are classified as cloud (MPC) by DARDAR".

RC: P23463, 5-23: This part reads like an introduction text and causes a break in reading fluency. Some parts are even repeated from section 1. I suggest to shorten and move sentences into section 1.

AR: These two paragraphs have been removed from this section. They have been shortened and included in the introduction.

RC: P23464, 9: DARDAR has a 500m threshold? What about the ground based observations? Are they also limited below 500m altitude? Please give the vertical range of the ground based observations at all sites. That is important to draw any conclusions from the comparison in Fig. 2.

AR: DARDAR has not a 500m threshold, but it is well known that data below this altitude are contaminated by radar ground echoes. The ground observations have no minimum altitude limit and they are not limited below 500m. **It has been specified in the figure 5 in the revised manuscript**.

RC: P23464, 26: The authors present a similar cloud classification by NASA and show that there are only small differences. Why then using your own product when there is already another similar available? Differences and a justification to apply a new own algorithm should be given in Section 2.

AR: The comparison of DARDAR product with NASA cloud occurrence allow to assess the methodology presented in this study. DARDAR algorithm presents the advantage to merge the CALIPSO and CLOUDSAT observations on the same resolution grid (60m). Also, DARDAR allows for cloud phase discrimination, using combined information from radar and lidar.

RC: P23465, 16-26: Again this part reads like a kind of introduction and partly repeats what was written earlier in the manuscript. I suggest to shorten and move sentences into section 1.

AR: **This paragraph has been removed from this section and partly included in the introduction.**

RC: P23466, 20: Summarizing open water and sea ice into one category can be a good but also a bad choice. Consider climate change and sea ice retreat this is a good choice as I would assume to find a signal of ice retreat in the cloud statistics. Otherwise cloud formation above open water and sea ice can be very different. These differences will be

hidden when averaging over both surface types. Think about adding single statistics for sea ice and open water surfaces. Cloud formation above sea ice areas is much closer related to land surfaces. So land and sea ice might also be one combined category.

AR: We reprocessed cloud and MPC occurrences taking into account sea ice and open water surface types. Figures B below shows F_{CLOUD}, F_{MPC} and $F_{MPC\text{-}IB}$ according to these different surface types.
As mentioned by the reviewer, and clearly shown in figure B, cloud and MPC occurrences above sea ice is generally close to that over land, even lower. Occurrence over open water is almost always larger than over land or sea ice, except during summer.

Figures Bb and Bc replaced the old ones concerning MPC occurrences according to the surface type in the revised manuscript (now Figure 8b).

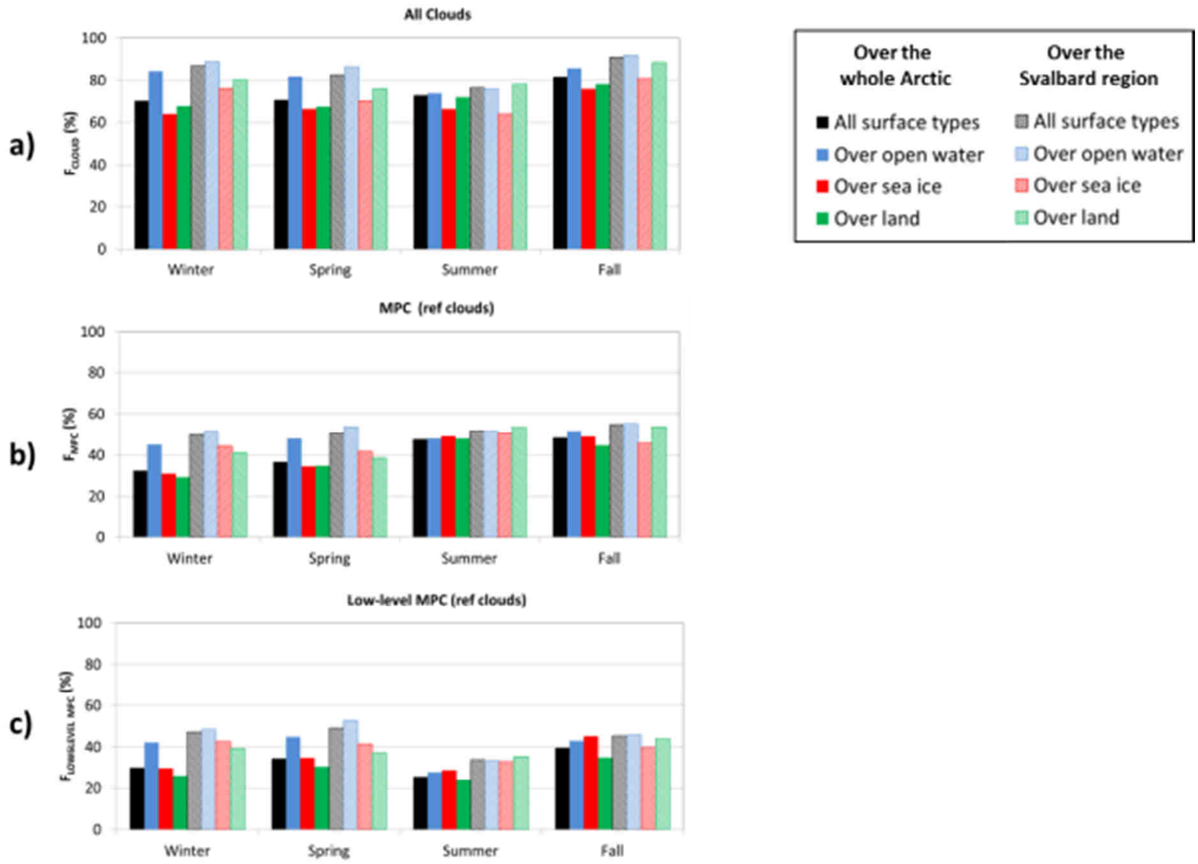

Figure B: a) F_{CLOUD}, b) F_{MPC} and c) $F_{LOW\text{-}LEVEL\ MPC}$ according to surface types over the whole Arctic region and over the Svalbard region.

Furthermore, to give an insight on the potential link assumed (in the discussion) between cloud and MPC occurrence and sea ice melting, we processed CALIOP L1 data to extract sea ice concentration (%) (data from National Snow and Ice Data Center (NSIDC) projected on the CALIPSO track). Figure C represents the seasonal variability of the sea ice concentration. Then, two specific areas in the Arctic region are selected:

- *Zone A: over the Greenland sea: 70°N to 80°N and 10°W to 20°E*
- *Zone B: over the Western Arctic (Chukchi and Beaufort seas): 70°N to 80°N and 150°W to 180°W.*

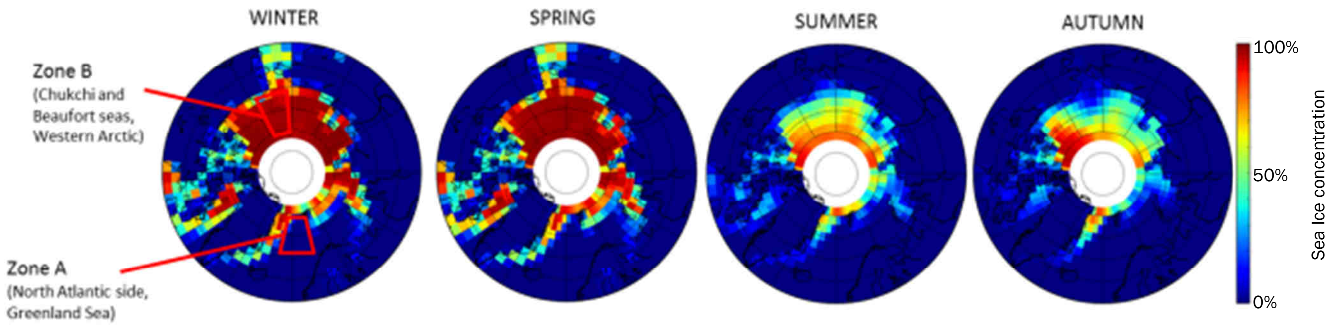

Figure C: Seasonal sea ice concentration (%) between 2007 and 2010. Data are from NSIDC.

Figure D illustrates the annual variability of specific humidity (top panel) and 2m temperature (bottom panel), from ECMWF (solid lines), between 2007 and 2010 for the whole Arctic region (black), over the Greenland sea (zone A, blue) and over the western Arctic (zone B, orange). On both figures, dashed lines represent the sea ice concentration (in %).

Sea ice concentration variability is very pronounced in the western Arctic with a large decrease from late spring/beginning of summer to late autumn (values larger than 90% in April fall down to less than 10% in September). Over the Greenland sea (Zone A), sea ice variability is rather constant, with low values between 5 and 20%. A small decrease is still observed from spring to autumn. 2m temperature and specific humidity are from ECMWF and they are interpolated onto the DARDAR grid. Note that specific humidity is averaged over the 0-500m altitude domain. Note also that the accuracy of these ECMWF retrievals is not discussed here, since we use them only to give an insight of their variability. From figure E, sea ice concentration is clearly inversely correlated with humidity and temperature. However, a delay is observed between the sea ice concentration minimum (September) and the humidity and temperature maxima (July).

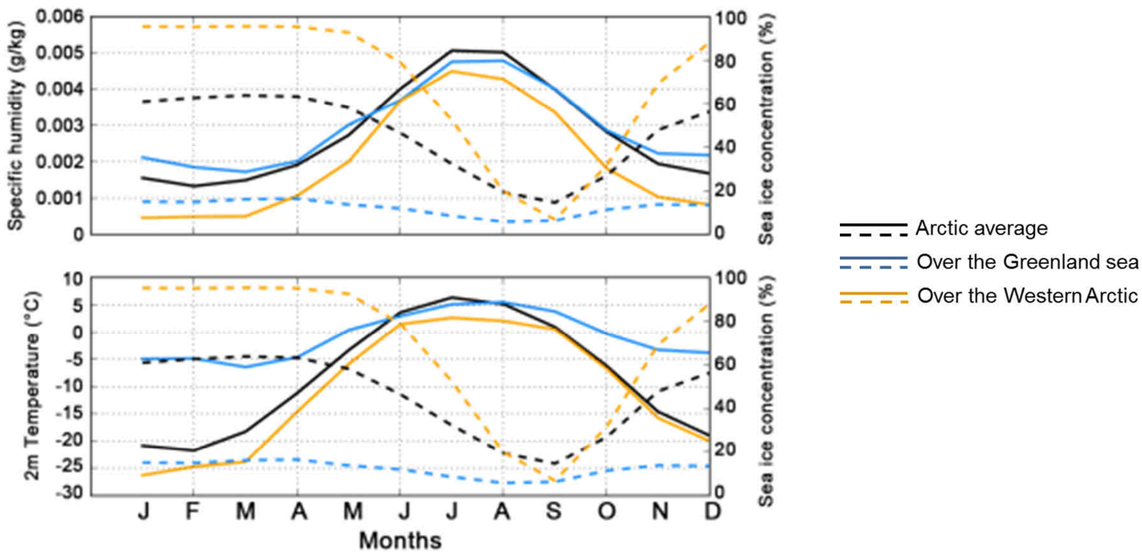

Figure D: Annual variability of specific humidity (top panel) and 2m temperature (bottom panel) for the whole Arctic region (black), the Greenland sea region (blue) and the Western Arctic (orange). Corresponding sea ice concentration is superimposed in dashed lines.

Figure E below represents the monthly cloud (circle symbols) and MPC (triangle symbols) occurrences as a function of monthly sea ice concentration for the whole Arctic (black), the Greenland sea (blue, zone A) and the Western Arctic (orange, zone B). Cloud and MPC occurrences clearly decrease when sea ice concentration increases (slope around -0,30, with correlation coefficient rather representative (0.7), for information purposes only). Figure E shows the same trend both for all clouds or MPC.

Note that the results over the Greenland sea (blue dots in the Figure E) do not point out a significant trend because of the small variability of the sea ice concentration throughout the year in this region. This is in agreement with the high cloud occurrence observed all along the year in this region.

From these results, it seems that cloud and MPC cover are linked to the sea ice melting. However, more investigation are needed to confirm this assumption, such as the study of cloud and sea ice over the whole Arctic region since our study is limited to the region below 82°N.

These results (including figures D and E) have been added to the discussion in the revised manuscript to strengthen the conclusions and perspectives to our work.

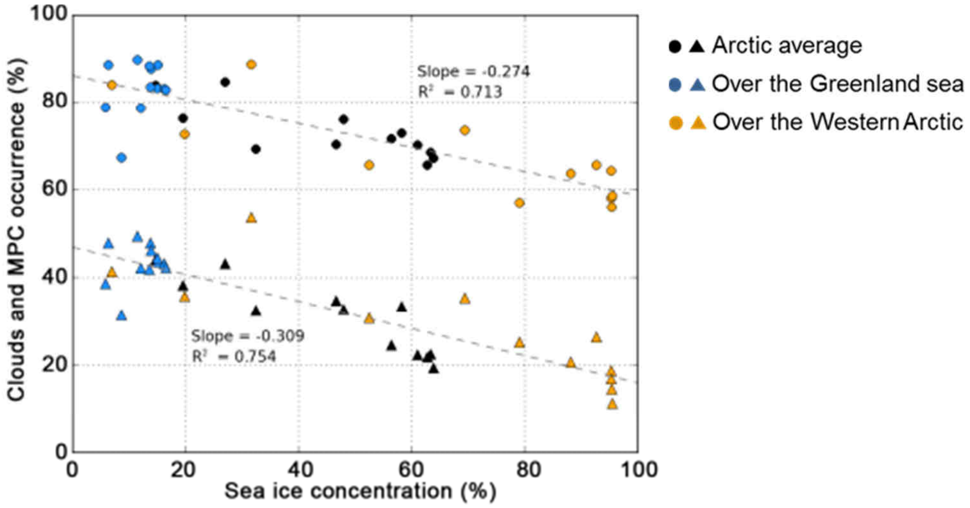

Figure E: Cloud and MPC monthly occurrences as a function of sea ice concentration.

RC: P23467, 5: "cloud" change to "clouds"

AR: It has been modified in the revised manuscript

RC: P23467, 16: Is the decrease in summer due to less low level MPC or an increase of mid-level MPCs?

AR: It is due to an increase in the mid-level MPCs

RC: P23469, 19: May a digital elevation model help to identify ground returns?

AR: A digital elevation model (GTOPO30) is already used in the CALIPSO surface detection routine. However, this model is known to be rather inaccurate over rugged terrains such as mountains or polar regions.

RC: P23471, 20: Results for altitudes below 500m have been considered to by contaminated by ground returns anyway and were before rejected from the data analysis. So I see no reason why data below 500m is shown here. The discussion is meaningless if the data below 500m is bad.

AR: **As recommended by the reviewer, data below 500m are now not shown in the revised manuscript.**

RC: P23474, 15-18: This decrease of low-level clouds might also be observed in the data because warm clouds are neglected at all.

AR: Decrease of low level clouds is still observed when including warm clouds, as shown in figure F below.

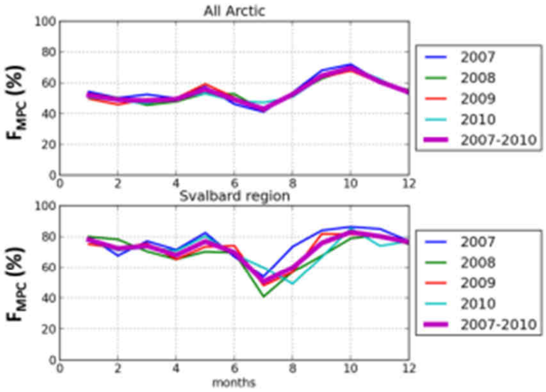

Figure F: Annual variability of cloud occurrence (including warm clouds) over the whole Arctic (top panel) and over the Svalbard region (bottom panel)

RC: P23476, 22: Isn't it the mixture of cold (not warm) air and warm water over the North Atlantic which causes many of the low-level MPC?

AR: Yes, and it has been corrected as follow in the revised manuscript:
"The mixture of cold air and warm water from the North Atlantic Ocean seems to be responsible for the large MPC amount observed during spring over the Svalbard"

RC: P23477, 9: I would not agree to this conclusion! Only because there are similar occurrence patterns it does not mean, that the clouds are similar. Therefore the definition of mixed-phase applied in this study is to general.
MPC can form under quite different dynamic conditions and thus may have completely different microphysical and optical properties. The definition of MPC in this paper is just based on the coexistence of ice and liquid water and does not tell anything about the formation mechanisms of the clouds and their detailed microphysical and optical
properties. Only because clouds have in average the same phase it does not mean, they are similar. E.g. mixed-phase clouds above ice and above open water have completely different dynamics!
So in-situ measurements of clouds above open water close to Svalbard can not be related to mixed-phase clouds above sea ice in any other Arctic area.

AR: There is a misunderstanding concerning this conclusion. Of course, MPC have different occurrence properties according to the location or the surface type. We showed in our study that the occurrence of mixed phase clouds over the Svalbard region was important. This particularity is largely due to the proximity of the North Atlantic Ocean, providing more favorable conditions for MPC formation throughout the year than over the mean Arctic.
So, in situ measurements made in the Svalbard region will help to understand microphysical processes involved in MPC occurring this region above open water. They will be very useful to study in details microphysical properties and processes governing ice and liquid particles.
The section concerned has been rewritten as follow:
"…the present study contributes to understand in which regional frame airborne campaigns and ground based observations have been performed. However, space remote sensing observations present well-known uncertainties near the surface which may have an important impact on low-level cloud amount determination. Therefore, airborne campaigns will provide a more thorough characterization of MPC properties at small scale. In particular, in situ measurements will help to understand microphysical processes involved in MPCs."

RC: Figure 1: Decision on the very left side (Layer thickness). I would have assumed that it is the other way around. Thin clouds in my view are more likely to be pure ice clouds and mixed-phase clouds are in general thicker.
Figure 1: How vertically extended clouds are treated here? When the lidar signal is attenuated, all cloud parts below can not be classified anymore. How this is accounted for?

AR: Yes, thin ice clouds could be thick, but they will not have a high backscatter and/or the signal will not be strongly attenuated through the layer.

When lidar is totally attenuated by a thick layer, no phase classification could be made below. In the 500-1000m altitude range for example, it represents around 18% of the data.

RC: Figure 2: Legend of the plot is quite small and hard to read.

AR: It has been improved in the revised manuscript.

RC: Figure 3: A similar projection for total cloud amount is needed for the interpretation. As F_{MPC} is only a relative number, figure 3 does not tell about the total number of occurrence. A higher fraction of MPC does not necessarily mean a higher total number of occurrence.

AR: Seasonal projections for F_{CLOUD} have been added in this figure in the revised manuscript (it is now figure 6)

RC: Figure 4: Single lines are very hard to distinguish.
RC: Figure 4: If the retrieval at altitudes below 500m is not trusted, you can't show results here.

AR: This figure has been modified in the revised manuscript (it is now figure 8)

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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 quantifying 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.*

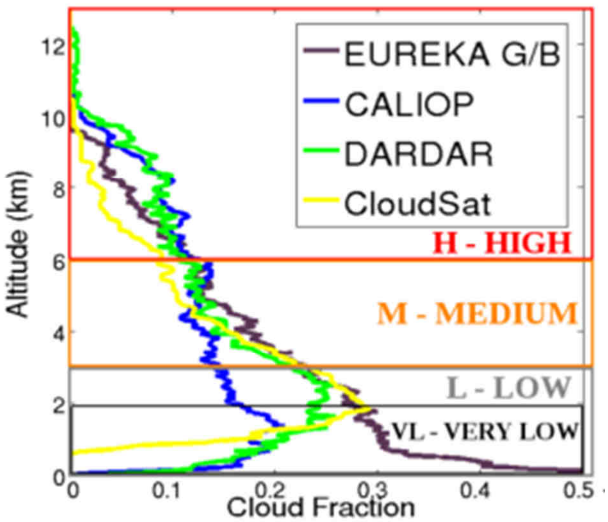

Figure A: Vertical profiles of cloud occurrence over Eureka station from CALIOP, CLOUDSAT, DARDAR and ground based observations. From Blanchard et al., 2014.

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)

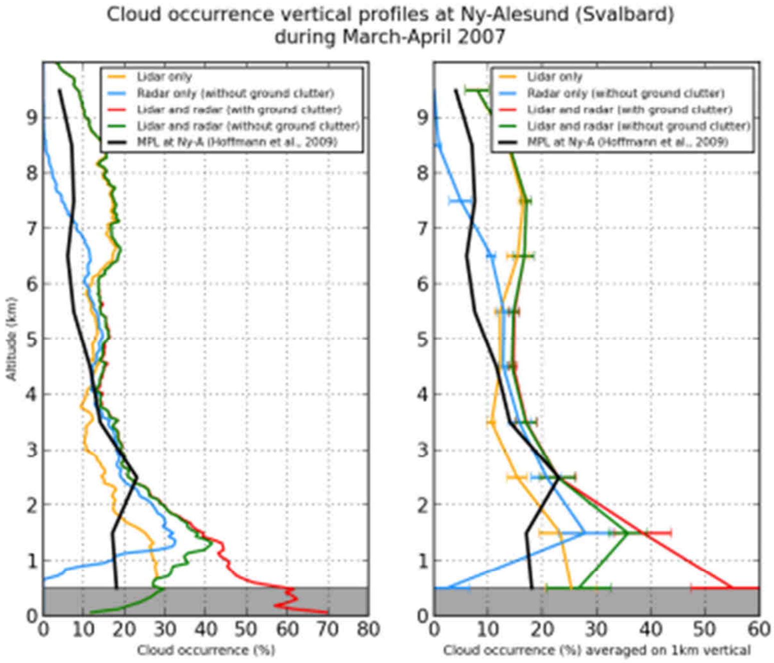

Figure B: Comparison of cloud occurrence vertical profiles from different DARDAR products and from Ny-Alesund ground based observations (Hoffmann et al, 2009) for the March-April 2007 period. Yellow lines corresponds to lidar alone, blue lines correspond to radar alone excluding pixels contaminated by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

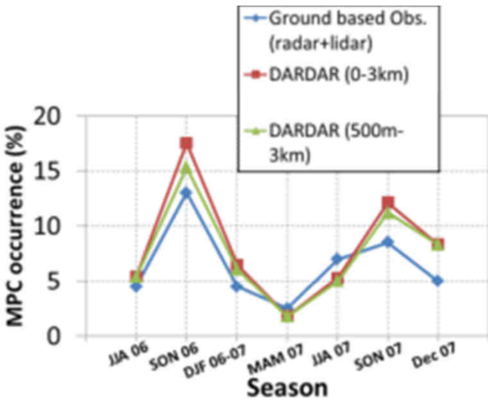

Figure C: Comparison of single layer MPC occurrence from DARDAR product and from Eureka ground based observations (De Boer et al, 2009) from June 2006 to December 2007.

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 mixed-phase 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 ground-based 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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