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.

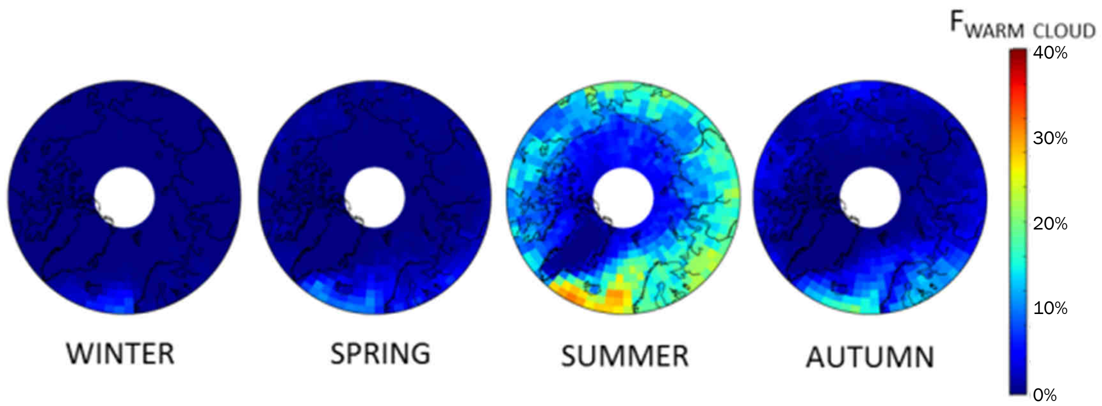

Figure A: Seasonal occurrence of warm clouds (referring to time).

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".

<u>*MINOR COMMENTS*</u>

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).

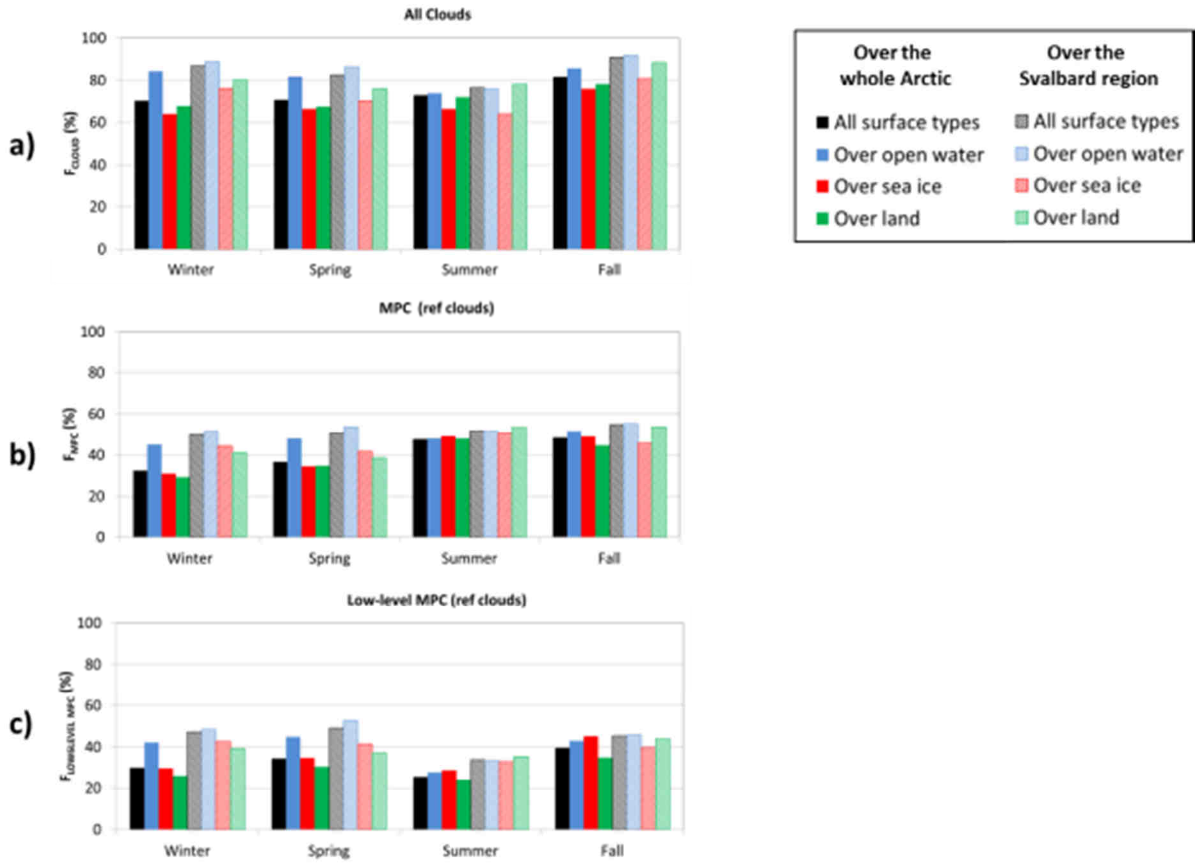

Figure B: a) F_{CLOUD}, b) F_{MPC} and c) $F_{LOW\text{-}LEVEL\ MPC}$ according to surface types over the whole Arctic region and over the Svalbard region.

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.*

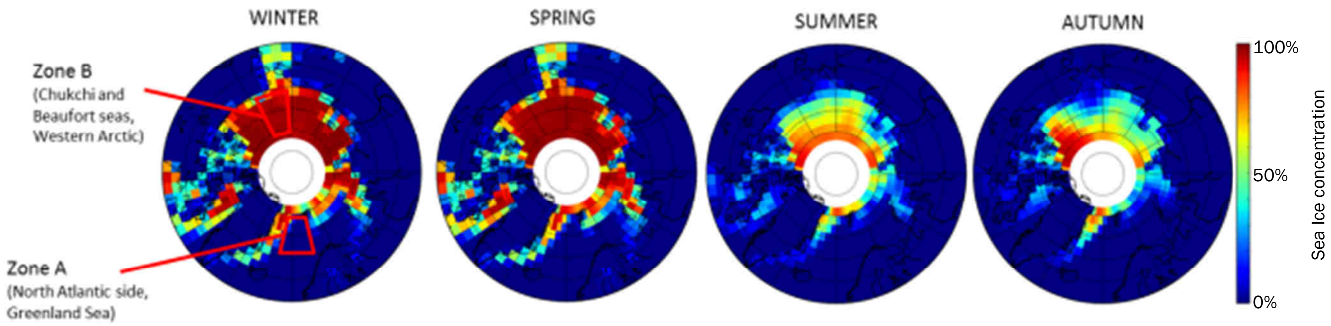

Figure C: Seasonal sea ice concentration (%) between 2007 and 2010. Data are from NSIDC.

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).

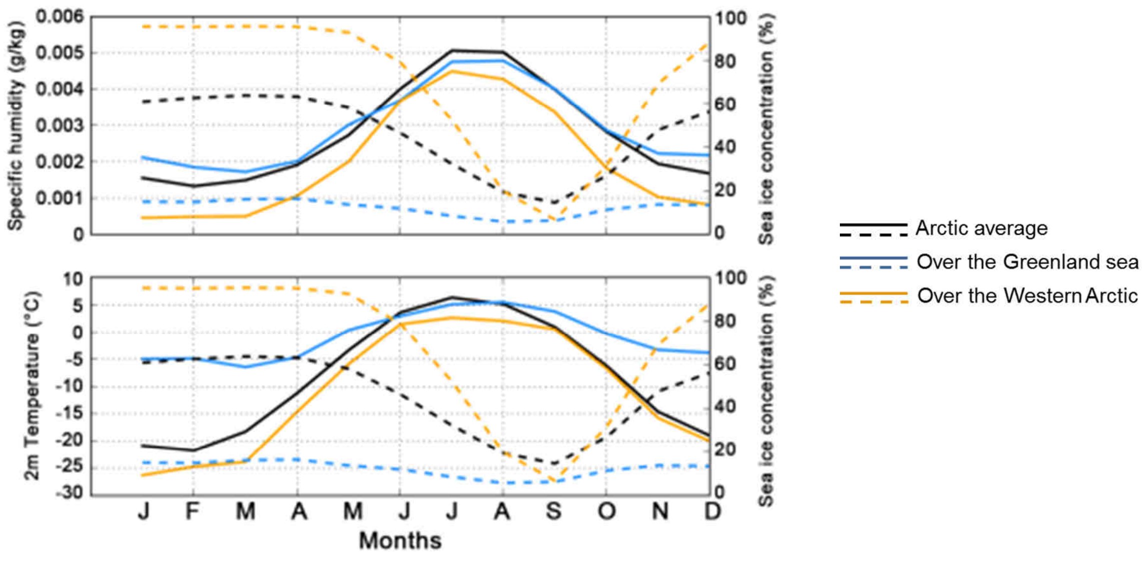

Figure D: Annual variability of specific humidity (top panel) and 2m temperature (bottom panel) for the whole Arctic region (black), the Greenland sea region (blue) and the Western Arctic (orange). Corresponding sea ice concentration is superimposed in dashed lines.

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.

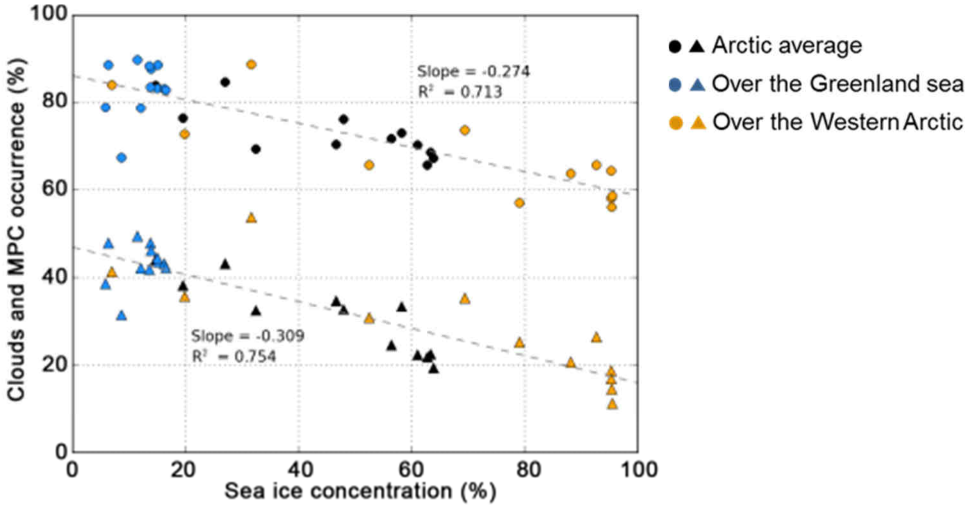

Figure E: Cloud and MPC monthly occurrences as a function of sea ice concentration.

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.

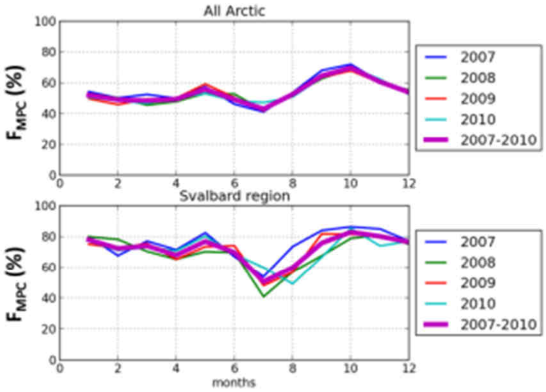

Figure F: Annual variability of cloud occurrence (including warm clouds) over the whole Arctic (top panel) and over the Svalbard region (bottom panel)

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)

REFERENCES

Ceccaldi, M., Delanoë, J., Hogan, R. J., Pounder, N. L., Protat, A. and Pelon, J.: From CloudSat-CALIPSO to EarthCare: Evolution of the DARDAR cloud classification and its comparison to airborne radar-lidar observations, J. Geophys. Res. Atmospheres, 118, 1–20, doi:10.1002/jgrd.50579, 2013.