Version 02.R2, 5 March 2020

Manuscript Title: *Supercooled Liquid Water Clouds observed and analysed at the Top of the Planetary Boundary Layer above Dome C, Antarctica* **by Ricaud et al.**

RESPONSES TO THE EDITOR

→ One reviewer requested minor changes to the paper. Specific changes have been made in response to the reviewer's comments and are described below. The reviewer's comments are recalled in blue and changes in the revised version are highlighted in yellow.

As requested by the reviewer, we have modified the title into:

> `Supercooled Liquid Water Clouds observed, analysed and modelled at the Top of the Planetary Boundary Layer above Dome C, Antarctica`

Anonymous Referee

Review of the revised version of "Supercooled Liquid Water Clouds observed and analysed at the top of the Planetary Boundary Layer above Dome C, Antarctica" by Ricaud et al. (acp-2019-607)

----------------------- Main comment: -----------------------

I am very satisfied with the answers and improvements made by the authors to the manuscript. The two case studies are clearly put into context and the authors assess how representative they are. The discussion is definitely a plus and improves the paper. To me the essential aspects are addressed and the paper can be published almost as is, but I list a few points below that should be considered in my opinion.

→ Thank you

• Why not showing figures of the modeling experiments in the main text? This is important and interesting to show that the typical case can be simulated by changing microphysical parameters (the partition scheme), while this is not enough for the perturbed case. (please see also my comment of Lines 742-765).

→ Modified, see below.

• Please mitigate a bit the SLW cloud vs Mixed-Phase Cloud discussion (please see my comment of the section 7.1)

→ Modified, see below.

------------------------------------ Line by line comments: ------------------------------------

Title – Considering the substantial effort made by authors to include some modeling experiments by changing the ice/liquid partition scheme, I would tend to suggest this title:

"Supercooled Liquid Water Clouds observed, analysed and modeled at the top of the Planetary Boundary Layer above Dome C, Antarctica"

This is also a paper about modeling, particularly in its revised version.

→ The title has been modified accordingly.

> Supercooled Liquid Water Clouds observed, analysed and modelled at the Top of the Planetary Boundary Layer above Dome C, Antarctica

---------------------- Abstract ----------------------

L32 "…exhibited SLW clouds": please add "for at least one hour"

→ Done

---------------------- 1. Introduction ----------------------

L76: "…sea ice production of ice-condensation nuclei". This is more appropriate to say INPs for Ice Nucleating Particles. However, here, this is also sea ice as a source of CCN and not only INP, which is discussed in the papers. Sea ice could bring CCN in the form of sea salt. Moreover, you are citing Legrand et al. 2016's paper, which I think is about sea salt measurements coming from sea ice. Sea salt is a good CCN, not a good INP, at these temperatures.

→ We clarified this point and modified the incriminated sentence into:

> These studies also highlighted sea-ice production of Cloud-Condensation Nuclei and Ice Nucleating Particles, which is important in winter both coastally and at Dome C (see e.g. Legrand et al., 2016).

-- 4. Typical diurnal case of the PBL ---

L 322: you defined LT but are using LST here. Please define.

→ We changed LST into LT in all occurrences.

L353-361: you could also say that ARPEGE is missing the precipitating ice as well (comparing Figure 2 and 3) between 0 and 12UTC.

→ This is an interesting comment. Based simply on comparing Figs. 2 and 3, we cannot state any conclusions on the precipitating ice from ARPEGE-SH since only clouds (fraction, ice and liquid) are represented in Figure 3. The diurnal variation along the vertical of the Total Snow Flux (mm day^{-1}) calculated by ARPEGE-SH on 24 December 2018 and on 20 December 2018 is shown on Figures Supp2 and Supp3, respectively. Note that ARPEGE-SH computes only solid and liquid phases for precipitating water and cloud. There is no distinction between snow and graupel. On 24 December 2018 (Fig. Supp2), ARPEGE-SH forecasts some solid precipitation between 00:00 and 10:00 UTC from 500 m agl to the surface consistently with the LIDAR observations (Figs. 2a and b). On 20 December 2018 (Fig. Supp3), ARPEGE-SH calculates some traces of solid precipitation close to the surface around 16:00 UTC consistently with the LIDAR observations (Figs. 9a and b). In conclusion, ARPEGE-SH was able to forecast solid precipitation during the 2 case studies. We have inserted the 2 new Figures (Supp2 and Supp3) in the Supplementary Material document and have updated the Figure numbering. We have inserted a new paragraph in the main document.

> The diurnal variation along the vertical of the Total Snow Flux (mm day-1) calculated by ARPEGE-SH on 24 December 2018 and on 20 December 2018 is shown on Figures Supp2 and Supp3, respectively. On 24 December 2018 (Fig. Supp2), ARPEGE-SH forecasts some solid precipitation between 00:00 and 10:00 UTC from ~500 m agl to the surface consistently with the LIDAR observations (Figs. 2a and b). On 20 December 2018 (Fig. Supp3), ARPEGE-SH calculates trace amounts of solid precipitation close to the surface around 16:00 UTC consistently with the LIDAR observations (Figs. 9a and b).

ARPEGE-SH was thus able to forecast solid precipitation during the 2 case studies.

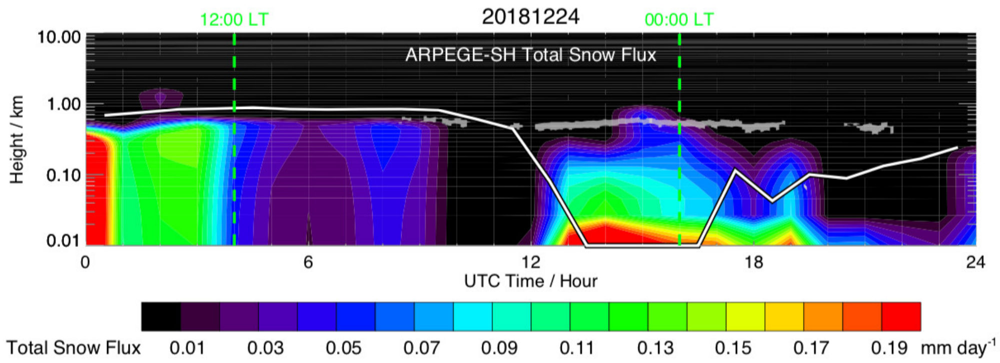

Figure Supp2: Time-height cross section on 24 December 2018 (UTC Time) of the Total Snow Flux (mm day^{-1}) calculated by the ARPEGE-SH model. Superimposed is the top of the Planetary Boundary Layer calculated by the ARPEGE-SH model (black-white thick line) and the SLW cloud (grey area) deduced from the LIDAR observations (see Fig. 1c). Two vertical green dashed lines indicate 12:00 and 00:00 LT.

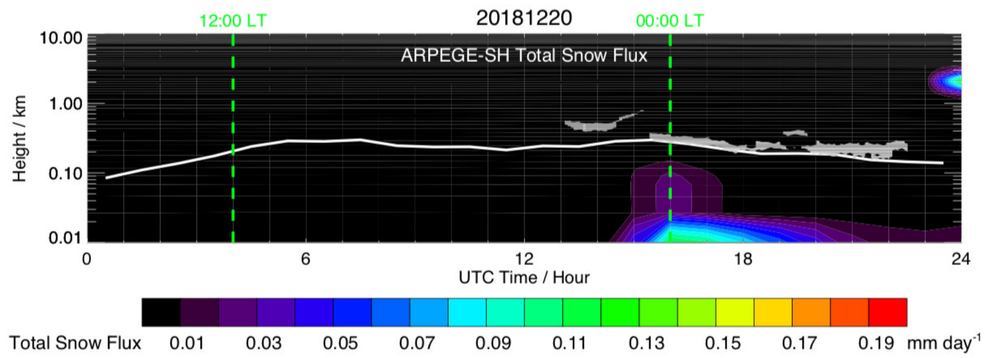

Figure Supp3: Same as Figure Supp2 but on 20 December 2018.

L452-465: Two almost identical paragraphs here. I guess you want to keep the second one only.

→ Yes, we have removed the first incriminated paragraph.

-- 7. Discussion --

-- 7.1 SLW Clouds vs Mixed-Phase Clouds --

I see your point. However, when we look at Figures 2a and 9a there is a clear sign – to me – of ice (the streaks) coming from the height where the SLW layer is. It is fine to say that the SLW layer is virtually only liquid but it is difficult to think that no process is taking place that depletes liquid and turns in into ice, hence giving the ice seen below the SLW layer. I think it is difficult to rule out the fact that the SLW layer is not a part from a – microphysically speaking – mixed-phase process. Where would the precipitation come from then? Small (undetected) crystals can be falling out of the SLW layer then grow while they fall so that the lidar detects them, eventually.

Put it more simply I can see why saying that the "ice component, even if present, is irrelevant from a radiative point of view" (Line 658-659). I think it is not from a microphysical point of view. The authors recognize themselves that there might by small crystals not seen by the lidar ("Some S signal is nevertheless present…" L644-645). How do you know the SLW layer is not slowly disappearing also because it is slowly converted into ice, which precipitates (see e.g the end of the day Figure 9a)? In which case the ice microphysics would also be important since it guides the termination of the SLW layer, hence impacting (also!) the radiative budget (indirectly).

Unless the authors have something against this argument, I would like to see something about this in the discussion to mitigate the "SLW cloud". To me you are investigating the SLW layer of an overall mixed-phase process (or say mixed-phase cloud).

More generally it is always difficult to say what is and what is not a mixed-phase cloud and definitions differ especially when observing with different instruments (space lidar vs. ground-based one, for instance).

I think here, it is not entirely fair to the complexity of mixed-phase microphysical processes to treat these SLW layers as "pure" SLW clouds. It just rules out the role ice might be playing in driving their lifetime (hence indirectly impacting the radiative budget).

→ We understand the reviewer's point of view. Other arguments for the presence of a mixed-phase cloud can be proposed when considering precipitating ice detected by the LIDAR and calculated by the model (Figures 2b and Supp2, respectively) on 24 December 2018 between 00:00 and 10:00 UTC (vertical stripes). We have suppressed the sentence that can be considered too much favourable to a pure SLW cloud layer (L. 658: "The layer is thus a truly SLW layer, being that its ice component, even if present, is irrelevant from a radiative point of view."). We have enlarged the discussion to state that the presence of mixed-phase clouds cannot be ruled out.

> On the other hand, when we consider the aerosol depolarization ratio measured by the LIDAR (Figure 2b) and the total snow flux calculated by ARPEGE-SH (Figure Supp2) on 24 December 2018, it is obvious that precipitating ice is present from 00:00 to 10:00 UTC in a layer from ~500 m to the surface (vertical stripes). Therefore, physical processes are supposed to take place within the cloud to deplete liquid and turn it into ice, giving the ice observed and calculated below the SLW layer. In which case, the ice microphysics would also be important since it guides the termination of the SLW layer, hence indirectly impacting the radiative budget. As a consequence, we cannot completely rule out we are investigating a SLW layer of an overall mixed-phase cloud.

-- 7.3 SLW Clouds in ARPEGE-SH --

L722:

-Then it would be interesting – if easily doable ? – to know how frequent SLW layer with a lifetime >12h (and not >1h) are, so that the first case's representativity (in terms of SLW layer lifetime) could also be assessed. What does Figure 17 with a 12h- and not 1h-criterium give? This would back up more the "may have a strong impact on the calculation of the radiation budget" (Line 723).

→ As requested by the reviewer, we have updated the Figure 17 by further considering the percentage of days per month that SLW clouds were detected within the LIDAR data for more than 12 hours per day. A day is flagged with a SLW cloud occurrence when a SLW cloud has been detected in the LIDAR observations for a period longer than 1 hour (orange/green) or 12 hours (blue). As expected, the occurrence of SLW clouds with a lifetime greater than 12 hours (blue) during SOP-SH is less than the occurrence of SLW clouds with a lifetime greater than 1 hour (green). But, whatever the criterium used (1 hour or 12 hours), the maxima of occurrences are shown to be in December and January during SOP-SH. SLW clouds with a lifetime greater than 12 hours occurred about a quarter of the days (20-25%) against about half of the days for SLW clouds with a lifetime greater than 1 hour (40-45%). The occurrence of SLW clouds above the Dome C station in summer is thus a significant phenomenon that may have a strong impact on the calculation of the radiation budget as stated farther in the manuscript. We have inserted a new paragraph.

> In Figure 17, we show the percentage of days per month that SLW clouds were detected within the LIDAR data for more than 12 hours per day (blue) during SOP-SH. As expected, SLW clouds occur less often when they last 12 hours (blue) than when they last 1 hour (green). But, whatever the criterium used (1 hour or 12 hours), the maxima of SLW cloud presence occur in December and January during SOP-SH. 12-h SLW clouds occurred about a quarter of the days (20-25%) compared to roughly half of the days for 1-h SLW clouds (40-45%). This reinforces the argument of the critical importance of well representing SLW clouds in models in order to better estimate radiation budget over Antarctica.

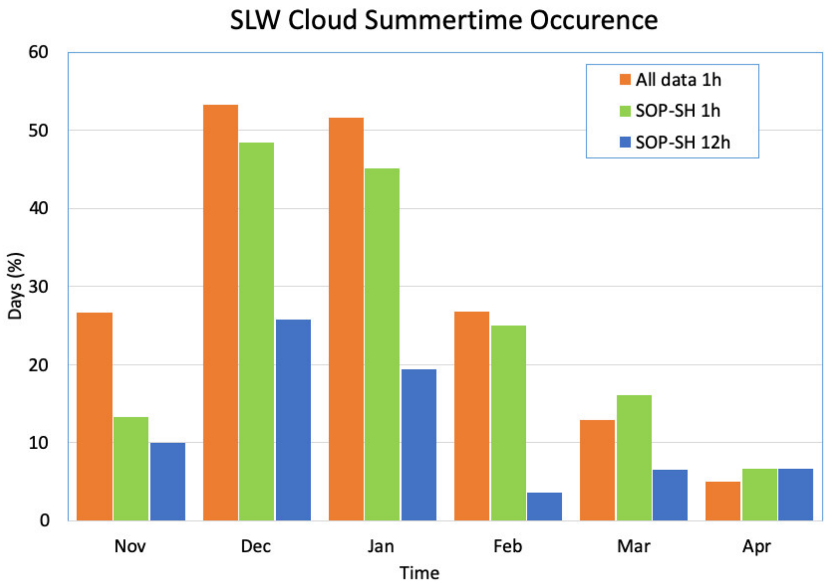

Figure 17: Percentage of days per month that SLW clouds were detected within the LIDAR data for more than 1 hour per day over different summer periods: "All data 1h" (orange) refer to November (2016-2018), December (2016-2018), January (2018-2019), February (2018-2019) and March (2018-2019); "SOP-SH 1h" (green) represents the YOPP campaign (November 2018 to April 2019). "SOP-SH 12h" (blue) represents the percentage of days per month that SLW clouds were detected during the YOPP campaign within the LIDAR data for more than 12 hours per day.

-There is not any section 3.1, only a section 3, now.

→ A careful examination of the paragraph shows that it should be referred not to subsection 3.1 but to subsection "4.1 Clouds" within the section "4. Typical diurnal cycle of the PBL". We have modified the subsection number accordingly.

But the incriminated sentence was mentioning a cloud extension not consistent with the revised version. It was previously written: "As the SLW cloud horizontal extent in the first case study is about 280 km and persists over more than 12 hours (section 3.1), (…)". We modified the sentence into:

> As the SLW cloud horizontal extent in the first case study is between ~450 and ~700 km and persists over more than 12 hours (section 4.1), (…)

For a sake of consistency, we have also updated the conclusion. Since there are no spaceborne LIDAR observations available on 24 December at the time SLW clouds are observed at Dome C, we changed the original sentence "Spaceborne lidar observations revealed horizontal extensions of these clouds as large as 280 and 550 km for the 24 and 20 December cases, respectively." into:

> Spaceborne LIDAR observations revealed horizontal extensions of these clouds as large as 700 km for the 24 December case study.

L733: "… since the cloud water is not a model control variable in the 4DVar scheme, it cannot be analysed"

I am not sure what is meant here by just "analysed": do you mean the analysis step of the data assimilation process? or just the fact of analysing an output? I suppose it is the former and then I would advise to say: "updated by the analysis step of the 4DVar data assimilation process".

→ As suggested by the reviewer, the incriminated sentence has been updated as follow:

> The underestimation of the SLW in ARPEGE-SH can be explained by the fact that: 1) the underestimation of liquid water is mainly a physical problem in the model related to the ice/liquid partition function vs temperature (see below) and 2), since the cloud water is not a model control variable in the 4DVar scheme, it cannot be updated by the analysis step of the 4DVar data assimilation process.

L742-765: I don't see why you would not show the figures with the modeling experiments here (Fig. Supp11 and Supp12), in the main text. You can very well leave the Figure showing the partition scheme in the Supp. Material, however. This is very interesting to see that you manage to find a partition scheme, which improves a lot the modeling for the first case at least, but also is not enough to solve the problem (2nd case). In the second case (Figure Supp 12), it clearly seems that the sudden increase of water vapour (advection?) is not reproduced in the model and should be the reason of the only slight improvement in the SLW modeling brought by the new partition scheme.

→ As suggested by the reviewer, we have inserted in the main manuscript the 2 Figures (Supp11 and 12) initially in the supplementary material. We have modified the text of the main manuscript and of the supplementary material in order to take into account the changes in the numbering of the Figures.

> For 24 December 2018, and consistently with Fig. 3, we have drawn on Fig. Supp9 the diurnal evolutions of different variables calculated by ARPEGE-SH-TEST: a) the Cloud Fraction, b) the Ice Water mixing ratio and c) the Liquid Water mixing ratio. Similarly, and consistently with Fig. 4, Figure 19 presents: a) the ARPEGE-SH-TEST TCI, b) the LWP measured by HAMSTRAD and calculated by ARPEGE-SH-TEST and c) the IWV measured by HAMSTRAD and calculated by ARPEGE-SH-TEST. Eventually, and consistently with Fig. 9, Figure Supp13 presents the net surface radiation observed by BSRN and calculated by ARPEGE-SH-TEST, and the difference between surface radiation of longwave downward, longwave upward, shortwave downward and shortwave upward components observed by BSRN and calculated by ARPEGE-SH-TEST. In the same manner, for the case of 20 December 2018, Figs. Supp12, 20 and Supp14 echo Figs. 11, 12 and 16, respectively.

-- **8. Conclusions** --

L779: recall here "for at least one hour".

→ Done