Response to reviewer comments on "Characterisation of low-base and mid-base clouds and their thermodynamic phase over the Southern and Arctic Ocean" by B. Dietel, O. Sourdeval, C. Hoose

We thank the anonymous reviewer for their recommendations and comments on the manuscript. Please find the detailed responses below in blue.

Reply to reviewer 2 comments:

This study presents a thorough characterization of low-base and mid-base clouds in the Polar regions, including their cloud phase and cloud radiative effect (CRE) decomposed by different cloud types. The authors use 2 years of satellite data (CloudSat and CALIPSO) to investigate the influence of aerosols, surface type (ocean/sea ice) and cloud type on the cloud phase and CRE, respectively. This characterization based on observational data provides an important tool to validate model simulations in the future, as models currently struggle to simulate cloud phase in the high latitudes correctly. The study uses a consistent definition of cloud types, which is very important based on the presented results and needs to be considered when comparing to other studies.

The manuscript is extremely well structured and is well written, so it is easy for the reader to follow the storyline. The methods are clear and described in a concise way. The figures are generally of very good quality. Some figures display rather complex content to decompose the relationships with respect to the different cloud types. However, the authors made a good job in choosing different ways to visualize this. I would like to mention that I find the introduction and the discussion of the results with respect to other studies outstanding. This makes it much easier to put the findings into context. I do not have any major comments, but please find some specific comments and technical corrections below.

Specific comments

Line 24: Could you specify 'complex microphysics' a bit more?

We slightly changed the sentence in L24 to: "Models with more complex microphysics than only temperature dependent liquid and ice partitioning tend to show a better representation of the liquid phase fraction, but all models struggle to generate the correct shortwave reflection south of 55 °S (Cesana et al., 2022)." The more complex microphysics refers to the partitioning between liquid and ice, which is not just based on temperature as it is for simple microphysics schemes. More complex microphysics include more processes influencing this partitioning. In the Supplementary Information of the cited paper of Cesana et al. (2022), Table S1 shows an overview of the different CMIP5 models, and if they use only a temperature dependent liquid/ice partitioning or a more complex one, where further literature for each model is also provided.

L44: specify where this underestimation occurs – at the surface?

Yes, we added "at the surface" at the end of the sentence.

L124: It would be helpful to mention that you are investigating the CRE at the TOA already earlier in the paragraph (closer to the equation).

Yes, we changed the first sentence of the paragraph to make it clear that we only focus on the CRE at TOA. As we changed the first sentence to "We analyse the cloud radiative effect (CRE) of various cloud types at the top of the atmosphere (TOA) using the version ...", we then remove the last sentence of the paragraph (only stating that we investigate CRE at TOA).

L144: I think you could build a bit upon how you include Fig. 2 in the manuscript. This seems to me like a very nice justification of the introduction of Zmax for cloud classification based on atmospheric temperatures, however, so far you only introduce Fig. 2 with regards to the dashed lines. Please elaborate a bit here.

We added the following sentence in L151(revised version), to connect the threshold Zmax to the temperature distribution shown in Fig. 2. "Regarding the vertical distribution of the annual mean temperatures in Fig. 2, the threshold Zmax is also mostly parallel to the isotherms, which shows one of the reasons for the chosen threshold decreasing polewards. Furthermore, the threshold Zmax is in the upper part of the mixed-phase temperature regime."

L148: You are giving estimates about how often different cloud types occur over the different surface types, and also that you reduce the number of profiles by 50% by excluding multi-layer cloud scenes. Another helpful estimate would be how many clouds actually have CBH between the lower CloudSat detection limit of about 1 km and your lower threshold of 2 km? What is the exact reason that you are limiting yourself to clouds with CBH above 2 km instead of 1 km?
The threshold of 2 km is based on the definitions of the World Meteorological Organisation for low clouds, which is why we use this threshold for distinguishing cloud types. But we also include clouds with CBH lower than 2km, as illustrated in Fig. 1. The two figures below show 2-dimensional histograms of cloud base heights and cloud top heights for single-layer clouds (Fig. R1) and low-level clouds (Fig. R2).

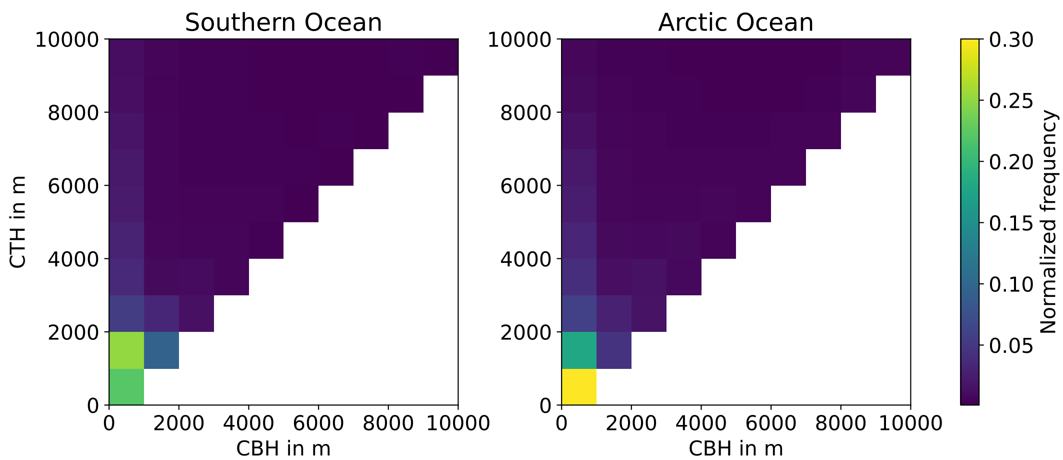

Figure R1: 2-dimensional histograms of the cloud base height and cloud top height of single-layer clouds.

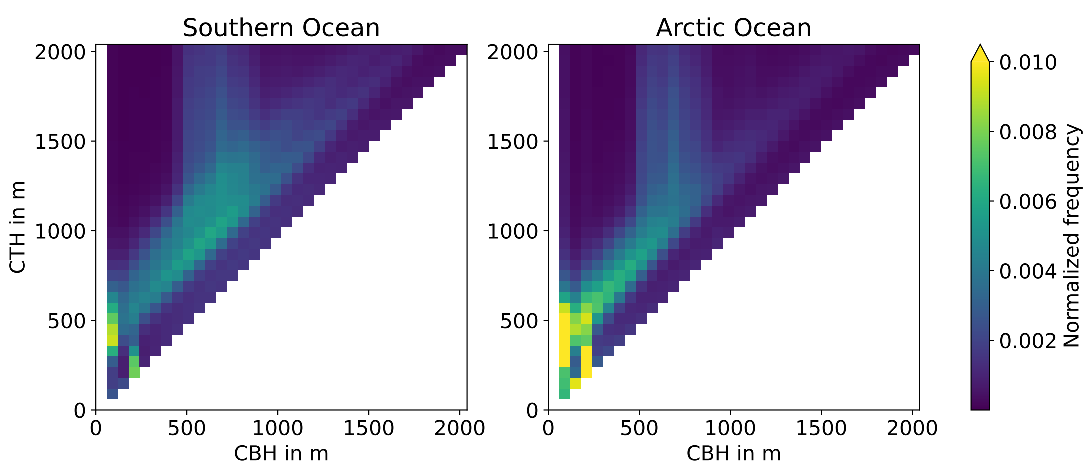

Figure R2: 2-dimensional histograms of the cloud base height and cloud top height of low-level clouds.

L167: What are the ranges in occurrences referring to? It seems like the calculation of fraction of cloudy profiles over e.g. open ocean would yield one value only.
Yes, the ranges of values refers to the different cloud types. We changed the sentence (L179-181 revised version) to make that more clear: "Over the Southern Ocean 72 % to 82 % of the cloud profiles occur over open ocean, 10 % to 16 % of the cloud profiles are over closed sea ice with the interval referring to the fraction for different cloud types."

Methodology: I suggest clarifying/summarizing at the beginning the two different approaches: (1) cloud object analysis of horizontally connected clouds, (2) individual cloud profile analysis. Please also specify that you are calculating the statistics over all profiles that are e.g. over open ocean, and that no spatial analysis is done. The use of the word 'pixel' in the vertical dimension for the liquid fraction calculation is a bit misleading, at least for me. I relate 'pixel' to something in the horizontal dimension. Maybe you could instead use vertical bin to clearly distinguish the two dimensions?
We added the following two sentences about the two approaches after the description of the cloud type classification: "We generally use two approaches, (1) the statistical analysis of individual cloud profiles, and (2) the analysis of cloud objects, which are horizontally connected cloud profiles. In most parts of the paper approach (1) is used, while in Sec. 5.2.1 approach (2) is used." We changed the word pixel to vertical bin or cloud top bin. We also clarified in L195-196, that for the comparison between ocean-sea ice and low-high aerosol concentration no spatial analysis is done: "These analysis are based on the statistics of individual profiles and no spatial analysis is done for this part." Most parts of the paper are based on the statistical analysis of individual cloud profiles, and only Sec. 5.2.1 (4.2.1 in preprint) is based on connected cloud profiles.

L221: Could you give numbers for that? Are these clouds more frequent in the Arctic with regard to the relative frequency, or in absolute numbers? (as the overall relative frequency of low-level clouds in the Southern Ocean is higher).
It is with regard to the relative frequency with respect to all single-layer clouds, which is shown in Fig. 4 (5 in revised version). It is not in absolute numbers. We add below a figure (Fig. R3) showing the absolute numbers of cloud type profiles as a function of the cloud top temperatures. We also add below a different visualization of Fig. 4 in the paper (Fig. R4) to clearly show the differences. Nevertheless, we think that the figure with stacked frequencies (shown in the preprint) shows a nicer overview of the most frequent cloud types in the mixed-phase temperature regime with better readability. We slightly changed the sentence in L221 (L274-275 revised version) to make it more clear that it refers to the relative frequency and not absolute numbers of occurrence: "The relative frequency of low-level clouds is slightly higher over the Arctic Ocean compared to the Southern Ocean for CTT colder than -13 °C."

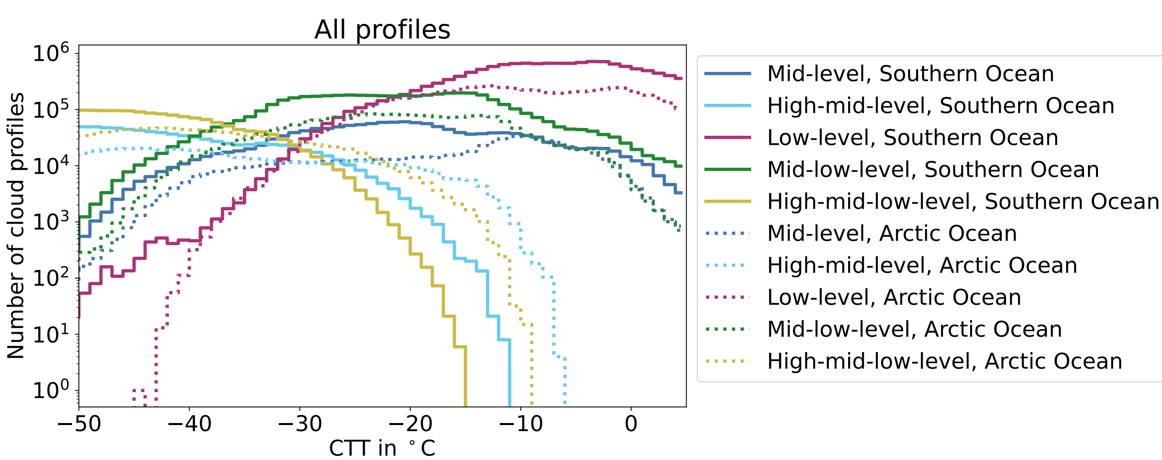

Figure R3: Histogram of the absolute numbers of observed cloud types in two years with respect to their cloud top temperature (CTT).

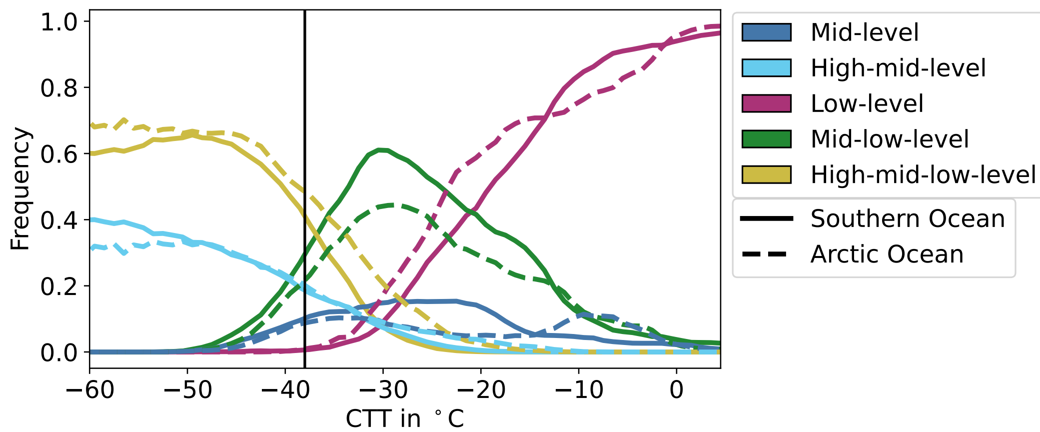

Figure R4: Relative fraction (not stacked) of different cloud types with respect to single-layer clouds as a function of cloud top temperatures (CTTs). The black line shows the lower temperature boundary of the mixed-phase temperature regime at -38 °C.

L227: The paragraph where you compare the cloud type occurrences to Sassen and Wang (2008) seems very relevant, however it seems like you are comparing it to your frequency values based on Fig. 3. Moving this paragraph before you start discussing the dependence on CTT (Fig. 4) would make a bit more sense to me.
Yes, that is a good point and we changed the order and moved the paragraph with Sassen and Wang before the discussion of CTT dependence.

L254: I find it a bit counter-intuitive that you get more low-level liquid clouds if you only consider profiles where the lidar is not fully attenuated as compared to all cloudy profiles. Your 'phase flag' approach basically assigns a liquid/mixed/ice flag based on your calculated liquid fraction. This should not lead to a higher frequency of liquid clouds because you can detect more liquid (as you say on L243), as your phase flag is not necessarily sensitive to the total amount of liquid water. The lidar gets mainly attenuated by the liquid part of the profile, so most often you should have the case where you miss ice in the lower parts of the cloud as the lidar is already attenuated by liquid above (e.g., in the very abundant case of liquid-topped mixed-phase clouds in the high-latitudes). Is this due to the fact that these are only relative frequencies here, and due to the larger vertical extent of mixed-phase clouds you actually filter out more mixed-phase clouds than liquid-only clouds when accounting for only not fully attenuated profiles?

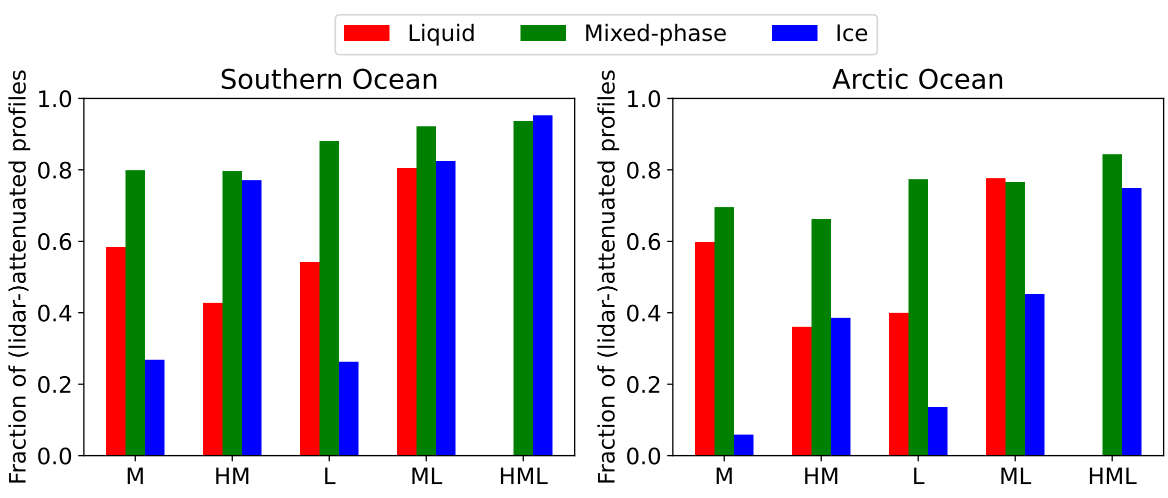

Figure R5: Fraction of the number of cloud type profiles, where the lidar signal is fully attenuated.

The increase of the fraction of liquid clouds is mainly based on the relative fraction and not on an increased detection of the liquid phase. We changed some sentences in this paragraph (also L296 ff.). Indeed, accounting for only not fully attenuated profiles reduces the absolute number of all liquid, mixed-phase, and ice clouds (see Fig. R5), but the strongest decrease can be seen in mixed-phase clouds, which is why this also shows a decrease in the relative frequency, while the relative frequency of liquid and ice clouds correspondingly increases.

L295: Could you state the extensions (horizontal/vertical) from your analysis here as well to compare the values? As the horizontal extent is given in number of profiles and not in km.
We added the numbers of the horizontal extent of mid-level clouds which are between 3.89 km to 6.24 km. We also changed the unit of the horizontal extent in the figure from number of profiles to km assuming a horizontal distance of 1.1 km.

L335: Very nice job in putting the results into perspective to other studies. Regarding one point you are mentioning briefly I was wondering whether you have looked into Fig. 7 on a seasonal basis? I am wondering whether sea ice leads to the fact that supercooled liquid clouds can get maintained at much colder temperatures without the open ocean as a potential source of INPs? A seasonal look into this very interesting data set could potentially disentangle some of the reasons the authors mention.
We did an analysis for another study for two seasons shown in Fig. R6. We saw an expected different coverage of cloud top temperatures in the different seasons, but the local minima are visible in both seasons. The argument that sea ice leads to the maintained supercooled liquid water at cold cloud top temperatures due to less INPs is discussed in Chapter 4.2.4, where we directly analyze cloud phase as a function of sea ice coverage and analyze aerosol reanalysis data.

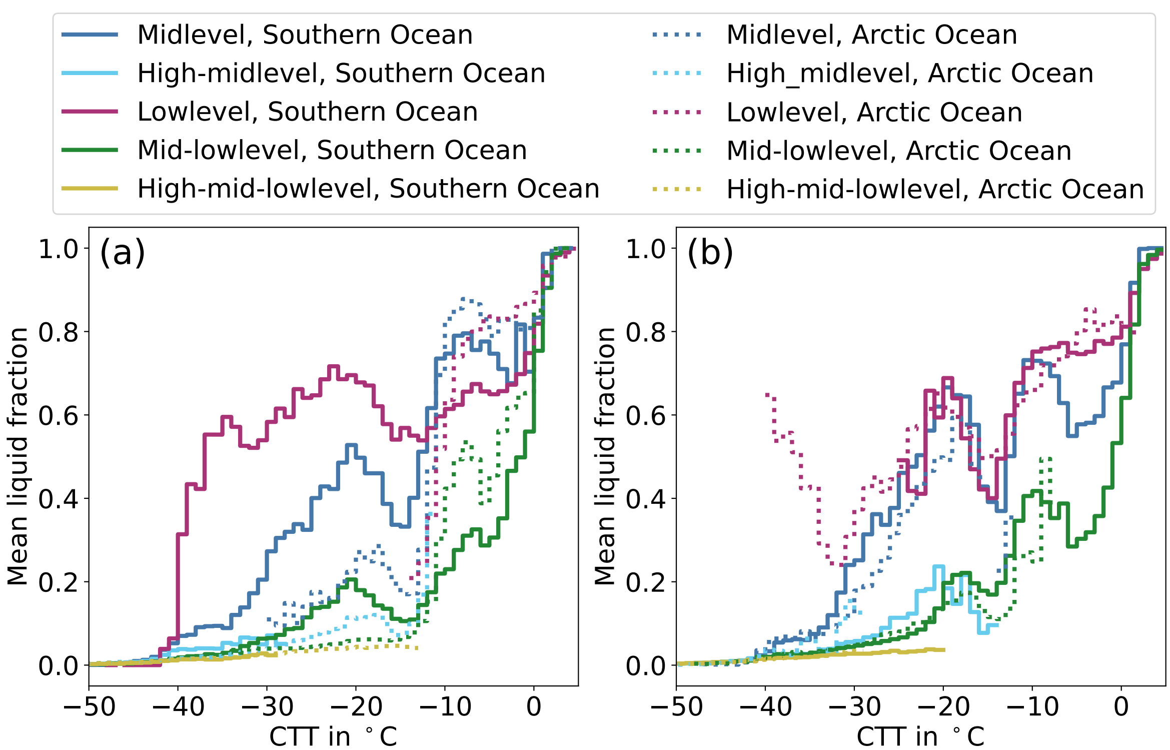

Figure R6: Mean liquid fraction of the period from 11 August - 09 September in panel (a) and of the period from 31 January - 28/29 February in panel (b) both of the years 2007 and 2008.

L404: In addition, as Papakonstantinou-Presvelou et al. (2022) investigate ice-only clouds, they might look into former mixed-phase clouds at a different stage in their lifecycle. These might already be completely glaciated clouds, so a comparison of the ice crystal number with the liquid fraction presented in this study is not easy.

We agree. We already state in L399-400 (L444 revised version) that "[...] Papakonstantinou-Presvelou et al. (2022) investigate only ice clouds, while our study investigates the general cloud phase." When describing their results, we also clearly state that they investigate ice crystal number concentrations, while we investigate cloud phase/liquid fraction. Although a direct comparison is not easy, we still think that the result of Papakonstantinou-Presvelou et al. (2022) should be part of the discussion as both studies investigate differences of low cloud properties over sea ice and ocean.

Fig. 11: Have you performed a similar significance test as in Fig. 9? Maybe the plot is getting quite busy with all the symbols then, but mentioning in the text whether these differences are significant or not would be helpful.
We did a similar significance test now for Fig. 11 (Fig. 12 in revised version) and show the results in the figure. Most differences are significant because of the large number of data points.

L492: do you mean larger optical thickness due to a larger vertical extent?
Yes, we added an information that due to the larger vertical extent the optical thickness is also increased.

Technical corrections
L20: I suggest citing a specific chapter (e.g. Chapter 7, Forster and Storelvmo et al. 2021) instead of the entire WGI report.
L22: showed
L36: delete 'differ'
L46: shows
L49: underestimated
L50: showed as well
L51: single-column model simulations
L60: delete 'a'
L79: split into
L108: provides
L111: IFS has been introduced earlier
L180: comma after percentile
L188: separate clouds
L209: delete 'further'
L219: single-layer, as a function single-layer cloud profiles, as a function
L236: also showed
Figure 5: Please increase the size of the figure a bit.
L243+245+250+Fig. 5 caption+...: I would use attenuated instead of extinguished
L263: such as the cloud phase as a function of...
Figure 6 caption: with one vertical profile having a horizontal... (instead of one vertical profiles)
L284: result
L286: ground-based
L303: CTT has been introduced before
L328: temperatures
Fig. 7 caption: the liquid fraction of each profile (not profiles)
Fig. 8: I suggest labelling the x axes 'Fraction of liquid/mixed-phase pixels' to clearly distinguish it from the liquid fraction that has been used up to now.
L357: further research is needed
L361: ground-based
Fig. 9 caption: clouds over sea ice
Fig. 12 caption: left panel shows
Fig. 12: could you increase the size of the figure a bit?
L420: seem to play
L465: further analysis shows
L539: compared to considering all cloud profiles
L540: and not tropical
L553: and 2B-FLXHR-LIDAR for CRE?

L588: in lower parts of the cloud
Thanks for the careful reading. We changed the technical corrections as suggested.

References

Grégory V. Cesana, Théodore Khadir, Hélène Chepfer, and Marjolaine Chiriaco. Southern Ocean Solar Reflection Biases in CMIP6 Models Linked to Cloud Phase and Vertical Structure Representations. *Geophysical Research Letters*, 49(22):e2022GL099777, 2022. ISSN 1944-8007. doi: 10.1029/2022GL099777. https://onlinelibrary.wiley.com/doi/abs/10.1029/2022GL099777.