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 comments:

I was somewhat disappointed in reading the response to my main comments and the revised manuscript. Only one major revision was done in response to this; the inclusion of a more significant uncertainty section. Unfortunately this section is rather superficial and reads like “OK, we'll include some text on uncertainty to please the reviewer” but nothing else in the study has changed much to alleviate my concerns in this respect.

Thank you for the critical, yet constructive feedback. We have revised our analysis and the manuscript significantly in response to the criticism. In particular, we have now removed all clouds below 500m from the analysis. We have also repeated the analyses with different latitude ranges for the Arctic and Southern Ocean regions and present the results here in the replies.

I still contend that the fact that CloudSat can't be used below 500 m combined with the fact that CALIPSO becomes attenuated for optically thick clouds means that a large part of the low clouds will be misrepresented. In the Arctic, clouds are dominated by low clouds with cloud tops below 1 km and cloud bases below a few hundred meters. Other studies indicate these are often mixed phase; in this case a liquid layer at the cloud top that precipitates ice. In that case the cloud top will be easily picked up by the radar but not the cloud interior and therefore the cloud base can often not be detected. This I believe is also reflected in low clouds being liquid more often than mix-phase which is contrary to many studies showing that liquid-only clouds are relatively few. Another effect is that the liquid fraction decreases with height into the cloud, which is just unphysical. There is nothing one can do; what is not observed is just not observed. Consequently, there are also large differences between the results for when the lidar is attenuated or not. But the results for the attenuated cases is a mix of clouds where the radar could be used (CBH $> \sim$500 m) and where the radar cannot be used. The proper comparison should therefore be only cases where you know the CBH is higher than 500 m. When I read the text, there is actually a lot of speculation on this topic, but it never floats to the top; this needs to be handled up front. I therefore think that the uncertainty analysis is kind of useless as it doesn't contain any analysis of what the effect of these uncertainties mean for the results in this study. There is just a list of uncertain things; the study then proceeds ignoring most of them.

In the revised version of the manuscript, a threshold for the CBH of 500 m has been applied as suggested. To explain why we have not done this before despite the known problems with the radar ground clutter, a drawback is that we also loose information which would be available from the lidar for very thin low clouds, which is the advantage of the the combined usage of radar and lidar information. The lidar extinguishes within about 300 m (Danker et al., 2022), which means there would still be some information for very thin low clouds from the lidar. But we also see the point that especially for the lowest 500 m the uncertainty of the cloud phase is very high due to the missing information from CloudSat . We therefore applied a filter to the entire analysis and repeated all calculations only considering clouds with a cloud base height larger than 500 m to reduce uncertainties introduced by ground clutter from the CloudSat signal, as suggested by the reviewer.

We replaced the figures and adapted the numbers within the text accordingly. We will not list each line where numbers have changed, but instead list here the main changes in the results and figures. The exact changes of all numbers can be found in the marked-up manuscript (latexdiff) version.

- The largest changes from not considering cloud profiles with CBH $\leq$ 500 m can be found in Fig.

4 and Fig. 6. Fig. 4 shows the fraction of cloud type profiles, and we can see a strong decrease in the relative frequency of low-level clouds from 25.6% (21.5%) to 15.8% (8.6%) for the Southern Ocean (Arctic Ocean) while other cloud types with low CBH (HML, ML) only show a slight decrease in the relative occurrence. Fig. 6 shows the relative occurrence frequencies of the cloud phases for different cloud types. The strongest difference can be seen in the reduced fraction of liquid low-level clouds from 63% (62%) to 40% (53%) over the Southern Ocean (Arctic Ocean) and a corresponding increase of the relative mixed-phase fraction. Mid-low-level and high-mid-low-level clouds affected by the CBH threshold only show small changes in the results. Regarding the results when only profiles are considered where the lidar is not extinguished, we still see an increase of the relative fraction of liquid clouds, which is expected, as the analysis is then more focused on thin clouds which can be penetrated by the lidar.

- The analysis of the horizontal and the vertical extent of clouds (Fig. 7) mainly shows a decreased horizontal extent of low-level clouds which is expected, as less cloud profiles are considered as low-level clouds, and therefore more gaps between profiles considered as the same cloud type along the satellite track occur reducing the calculated horizontal extent of "connected" cloud profiles.
- Regarding the liquid fraction as a function of CTT in Fig. 8 we see a small decrease of the liquid fraction of low-level clouds compared to the previous analysis, so that the liquid fraction of low-level clouds and mid-level clouds are more similar for some CTTs. But all our main points of the discussion are still valid and have not changed. The minima around -15°C and -5°C show up even more clearly.
- In Fig. 9 the vertical phase distribution is shown. We can see that the increased liquid fraction at cloud base is reduced, but is still clearly visible for low-level clouds. Uncertainties due to attenuation or multiple scattering may play a role, but on the other hand for shallow clouds, it is also not unphysical that the first ice forms at cloud top in liquid clouds, where the temperature is coldest, while only at a second step the ice grows strongly at the expense of the liquid droplets, leading to the sedimentation of ice crystals and the typically know mixed-phase cloud structure with liquid at cloud top and large ice crystals below.
- The analysis of the liquid fraction over open ocean and sea ice (Fig. 10) shows slightly lower absolute values, but still higher liquid fractions in clouds over sea ice than in clouds over open ocean for mid-level and mid-low-level clouds over the Southern Ocean and low-level clouds over both regions.
- Fig. 11 and Fig. 13 show almost no differences compared to the previous analysis.
- Fig. 12 shows as well similar results as before and the strange positive values for low CTTs in low-level clouds over the Arctic Ocean regarding sea salt concentration disappeared.
- The cloud radiative effects in Fig. 14 show similar results with the only difference that liquid low-level clouds over the Southern Ocean show now a higher SWCRE than mixed-phase low-level clouds over the Southern Ocean, while it was lower in the previous analysis. Our assumptions is that the exclusion of very thin low layers with a low SWCRE led to an increased SWCRE.
- The changes of the contribution of the cloud types to the SWCRE and LWCRE (Fig. 15) are in line with the changes of the cloud type frequency shown in Fig. 4 leading to a reduced contribution of low-level clouds, but they still show the largest contribution compared to other cloud types in the SWCRE at TOA.

In summary, we can see that most of our results of this study don't change, but reducing the uncertainties introduced by ground clutter strengthens our findings.

My second main objection on comparing Arctic and Southern Oceans with the definitions used here, did not lead to any significant revision; the authors just state that because models are crappy at both it is relevant to compare. I disagree. First, the Arctic Ocean does not extend to 60N; using that definition you also include a fair proportion of the Atlantic and Pacific Oceans. You also include the tail ends of the extratropical storm tracks, while for the Southern Ocean you include the entire midlatitudes. But clouds in polar regions are dominated by other clouds than clouds in the midlatitudes. The midlatitudes are affected by convection, deep and shallow, whereas the largest proportion of the Arctic has almost no convection at all and frontal clouds prevail in the midlatitudes; not so much in the polar regions. Finally, a large part of the Arctic remains ice covered even in summer whereas the Antarctic is essentially ice free in summer; in fact the largest part of the Southern Ocean, as defined here, never has any sea ice ever, not even in winter. These differences affect the boundary layer and especially the low clouds; it also affects affects the aerosols, as sea ice essentially cuts off sea spray, and the CRE, since surface albedo is a factor. In summary, this makes the comparison almost impossible interpret. Apples against oranges as it were...

We fully agree that the meteorology and the surface conditions are different between the Northern and Southern high latitudes, but the cloud physics appear to be very similar despite these differences. Therefore, we uphold that not only regions with the exact same conditions can be compared, but that universal relationships can be found from their manifestation in different cloud regimes. In addition, while many studies investigate cloud phase by averaging over all clouds all over the world without further distinction, we categorize cloud types based on their base and top height, which for example can be seen as an indirect way of distinguishing between deep convection and more shallow clouds. Finally, many of the mentioned differences between the Northern and Southern regions (like sea ice coverage or aerosols) are directly analyzed as part of the study within subchapters (see Chap.5.2.4).

Specifically, both of the regions contain:

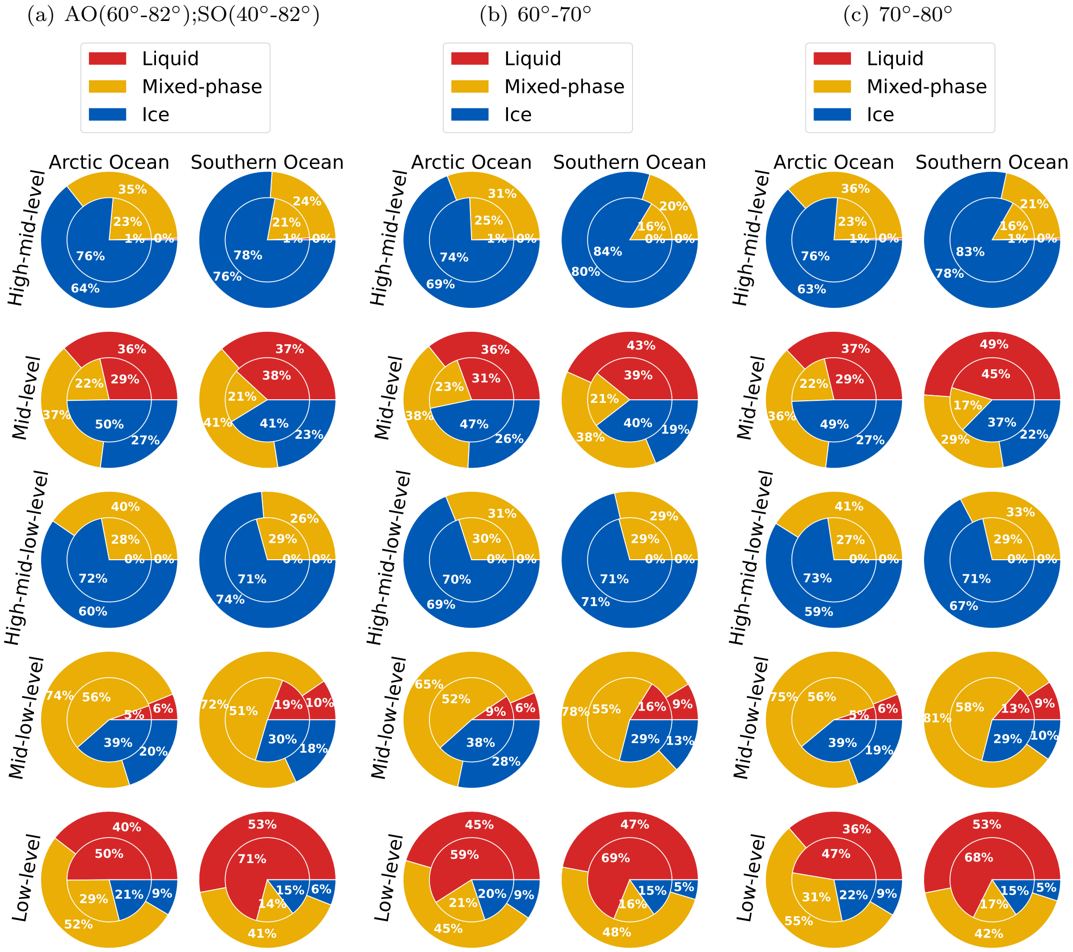
- areas covered by sea ice,
- areas with open ocean with varying SST,
- cloud profiles with low and high aerosol content,
- areas where convection can occur, and areas where more stratiform clouds can occur,
- and areas of extratropical cyclones.

Contrary to point observations or case studies, we analyze highly resolved vertical cloud profiles over rather large regions using data of two full years, leading to a large dataset covering various conditions withing a parameter space spanned by various variables. This enables a statistical analysis including the investigation of varying conditions like sea ice or aerosols.

We partly agree with the criticism regarding the denomination of the analyzed regions. The reviewer is correct that the "Arctic Ocean" is usually defined as a nearly landlocked ocean consisting of a deep central basin surrounded by seven epicontinental seas, i.e. the Barents, Kara, Laptev, East Siberian, Chukchi, Beaufort, and Lincoln Seas (Jakobsson et al., 2004) and does not extend to 60°N. Nevertheless, the International Hydrographic Organization also includes the Greenland, Norwegian, Iceland, and White Seas; Baffin and Hudson Bays; Davis and Hudson Straits; and the waterways of the Canadian Arctic Archipelago (Jakobsson et al., 2004). We have explained the definition more clearly in the manuscript and now used the term "Arctic marine regions". Meanwhile, we have not changed our definition of the Southern Ocean because it is in agreement with the majority of related literature, as shown below. We changed our title from "[...] Southern and Arctic Ocean" to "[...] Southern Ocean and Arctic marine regions" to clarify that we investigate all seas over the Arctic region including parts of the northern Atlantic and northern Pacific besides the Arctic Ocean. The "Arctic region" is often defined as a region north of 60 °as e.g. in Cesana et al. (2023); Wendisch et al. (2023); Lawrence et al. (2019); Schacht et al. (2019); Comiso (2003). Table 1 lists the analyzed latitudes of several studies investigating cloud over the Southern Ocean, which mostly begin at latitudes of 40°S.
To investigate whether the selection of the latitude range has an impact on the results, we have repeated key parts of the analysis for different latitude ranges (60-82°N and 40-82°S as previously chosen versus 60-70 and 70-80 degrees in both hemispheres). The results of these analyses are included in the following. The cloud phase distribution (Fig. R1) only varies slightly for different latitude bands. The vertical liquid fraction shows very similar results regarding different latitude bands over the Arctic, but shows differences over the Southern Ocean. Low-level, mid-level, and mid-low-level

Table 1: Definitions of the Southern Ocean in previous literature investigating clouds over the Southern Ocean.

Analysed region	Literature	Title
40°S - 60°S	Wall et al. (2022)	Observational Constraints on Southern Ocean Cloud-Phase Feedback
40°S - 72°S	Bodas-Salcedo et al. (2016)	Large Contribution of Supercooled Liquid Clouds to the Solar Radiation Budget of the Southern Ocean
40°S - 70°S	Cesana et al. (2023)	The correlation between Arctic sea ice, cloud phase and radiation using A-train satellites
40°S - 60°S	Coopman et al. (2021)	Analyzing the Thermodynamic Phase Partitioning of Mixed Phase Clouds Over the Southern Ocean Using Passive Satellite Observations
30°S - 75°S	D'Alessandro et al. (2019)	Cloud Phase and Relative Humidity Distributions over the Southern Ocean in Austral Summer Based on In Situ Observations and CAM5 Simulations
50°S - 80°S	D'Alessandro et al. (2021)	Characterizing the Occurrence and Spatial Heterogeneity of Liquid, Ice, and Mixed Phase Low-Level Clouds Over the Southern Ocean Using in Situ Observations Acquired During SOCRATES
40°S - 65°S	Danker et al. (2021)	Exploring Relations between Cloud Morphology, Cloud Phase, and Cloud Radiative Properties in Southern Ocean Stratocumulus Clouds
40°S - 65°S	Huang et al. (2012)	A study on the low-altitude clouds over the Southern Ocean using the DARDAR-MASK
40°S - 60°S	Huang et al. (2015)	A-Train Observations of Maritime Midlatitude Storm-Track Cloud Systems: Comparing the Southern Ocean against the North Atlantic
40°S - 70°S	Kay et al. (2016)	Global Climate Impacts of Fixing the Southern Ocean Shortwave Radiation Bias in the Community Earth System Model (CESM)



(a) AO(60°-82°);SO(40°-82°) (b) 60°-70° (c) 70°-80°

Figure R1: Cloud phase distributions of various cloud types (rows) over the Arctic ocean and the Southern Ocean. The outer pie charts include all cloud profiles of a cloud type, while the inner pie charts only consider cloud profiles, where the lidar signal is not fully attenuated by the cloud. The left panel shows the results for the definitions used in our manuscript. The middle panel shows the results only considering latitudes between 60°N/S and 70°N/S, while the right panel shows results for latitudes between 70°N/S and 80°N/S. All analyses exclude cloud profiles over land surfaces.

clouds show higher liquid fractions for higher latitudes regarding the same cloud top temperature. Nevertheless, Fig. R3 shows that the comparison between different cloud types over both regions looks very similar for different latitudes.

We also analyzed further aspects of different conditions influencing our results like sea ice cover on CRE (shown in Fig. R4). As expected we can see a reduced SWCRE over sea ice, but the relative behavior of the CRE does not change if we only consider clouds over open ocean (panel c,d) compared to the discussed results in the manuscripts, where cloud profiles over sea ice are included (panel a, b).

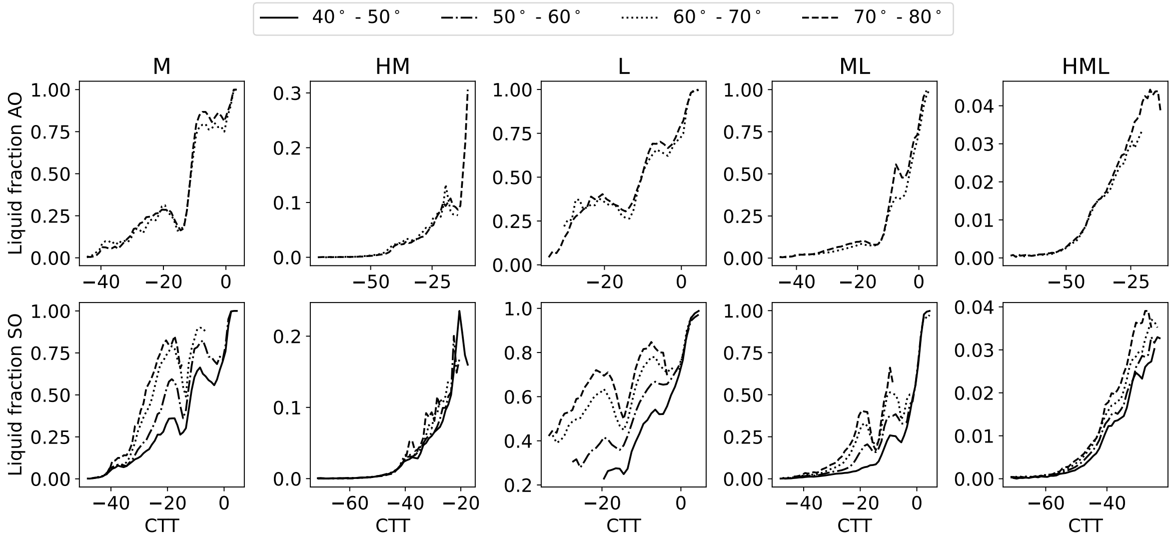


Figure R2: Comparison of the vertical liquid fraction as function of cloud top temperature (CTT) considering different latitude bands of our analyzed regions. The upper row refers northern latitudes, while the bottom row refer to southern latitudes.

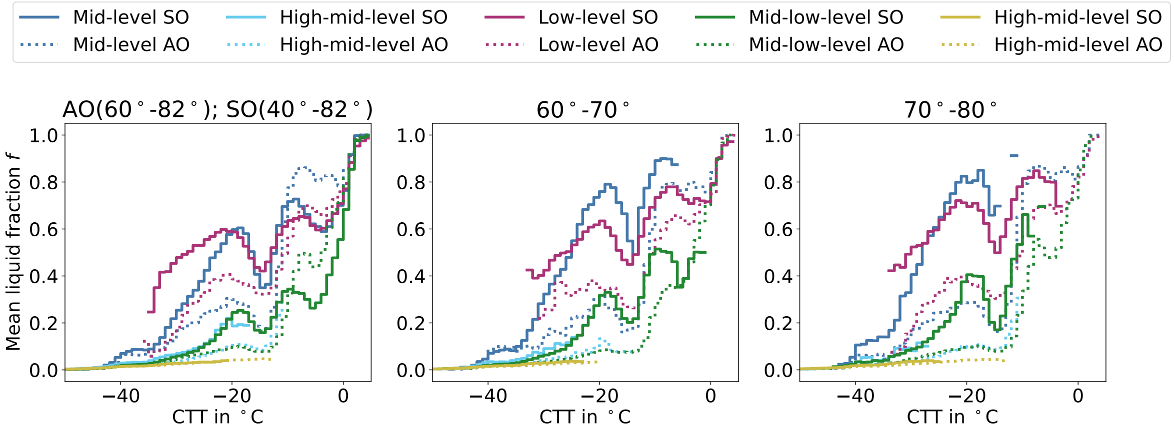


Figure R3: Comparison of the manuscript results regarding the liquid fraction considering different latitude bands.

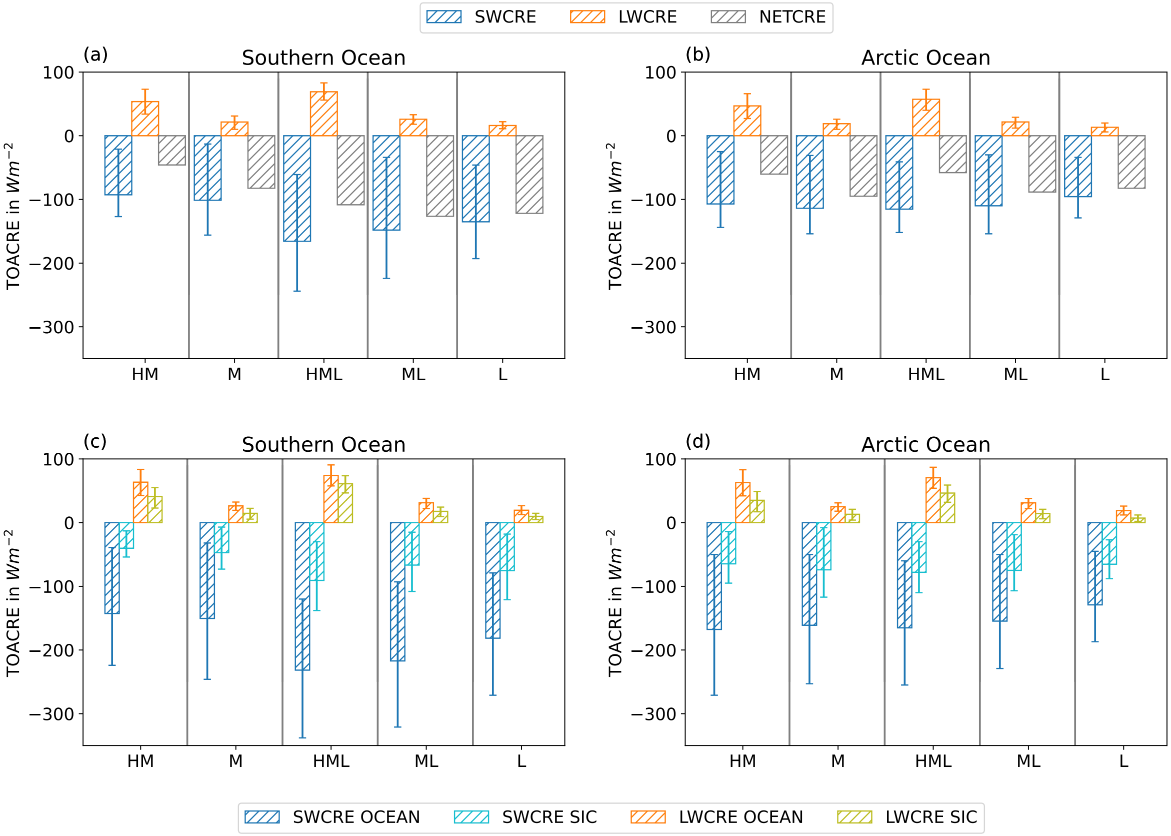


Figure R4: TOACRE for different cloud types. Panel (a) and (b) show the results shown in the paper considering profiles over ocean and sea ice, while panel (c) and (d) distinguish between open ocean and sea ice. Sea ice defined by a sea ice concentration equal or larger than 80%.

In summary, I must continue to insist on a major revision. I have numerous minor comments that I'm saving until I can review a manuscript that takes my objections above seriously.
We believe that our additional analyses and revisions address the major points listed above and are looking forward to the additional minor comments.

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