Dear reviewer,

thank you for careful reading and spending many hours to provide us with a long list of valuable suggestions and recommendations that helped a lot to improve the manuscript significantly.

We considered almost all points.

Our answers in blue in this reply letter. Significant changes are in deep blue in the revised manuscript.

General comments:

This paper summarises the new information added to the body of knowledge regarding mixed-phase clouds (MPCs) by analysis of the data collected from the research vessel *Polarstern*. The paper presents four case studies and a statistical analysis of all observations in support of some generalised conclusions about the behaviour and formation of MPCs. This is a worthwhile expansion of the current scientific understanding of MPCs, and my recommendation is for publication after the minor issues outlined below have been addressed.

Specific comments:

The main issue that stands out to me is the statement in lines 670–671 that 'The decreasing moisture content of an air mass, rather than empty CCN and INP reservoirs, is probably the reason for the dissolution of stratiform cloud layers in most cases'. While you do clearly establish that in your case studies you observed water droplets nucleating on a sufficient supply of background aerosol, that does not by itself conclusively answer the question of whether most MPCs dissipate because they exhaust their supply of water or because they exhaust their supply of aerosol (c.f. Sterzinger et al. [no affiliation] 2022, 'Do Arctic mixed-phase clouds sometimes dissipate due to insufficient aerosol?' or Loewe et al. [no affiliation] 2017, 'Modelling micro-and macrophysical contributors to the dissipation of an Arctic mixed-phase cloud during the Arctic Summer Cloud Ocean Study (ASCOS)'). Both are physically possible causes. If your argument is that throughout the full year of MOSAiC observations you never saw evidence of cloud dissipation as a result of low aerosol (and thus low CCN and INP), this point should be made more explicitly and in more detail.

We observed so many cloud layers and checked the water vapor conditions when the end of an extended cloud layer crossed the Polarstern, and we always found in the Raman lidar water vapor profile observations (possible during the winter half year) and in the year-round radiosonde humidity profile observations that the cloud layer dissolved because the humidity decreased in the air mass. We never had a case where the humidity remained at high level but the cloud dissolved.

However, we concentrated on the free troposphere, and the aerosol content in the free troposphere is widely linked to the aerosol conditions over the continents surrounding the Arctic via long-range transport. The situation may be very different for boundary layer clouds. Here, efficient washout processes may persistently remove aerosol particles from the boundary layer so that situations may occur where a cloud cannot form because the aerosol content is too low.

We mention our impression (dissipation of the cloud layers by decreasing water vapor in the air mass) only briefly in Section 6 (MPC conceptual model: an update).

I agree with RC1 (no known affiliation) that 'temporal evolution' would be preferable to 'lifecycle', especially in the context of observations taken from a drifting vessel under

advected cloud. Separately, referring to the cloud as 'alive' (e.g. line 35: 'keeps the MPC top layer alive, frequently for hours') is idiomatic and unclear. A description of the cloud processes would always be preferable to an analogy to biological life, e.g. 'The steady resupply of water droplets allows the MPC supercooled liquid top layer to persist despite the continuously forming ice below, frequently for hours'.

This sentence 'The steady resupply of water droplets…' is now included in the second paragraph of the introduction.

The existence of the gravity wave in the September case also seems to me inconclusive. In the first mention on line 249 it is understood to be the 'best guess' theoretical explanation for the upward motion: 'Gravity waves may have caused the perturbations.' Similarly line 431: 'probably the result of a gravity wave', and line 669: ' probably by gravity wave activity'. However, the caption for Figure 7 states definitively: 'Gravity waves crossed Polarstern between 12:00 and 14:00 UTC'. What evidence is there for this?

We removed all speculations about the reason for the perturbation. We leave it simply open. We no longer use 'gravity wave' in the manuscript.

Lines 8–9: 'We discuss two long-lasting Arctic MPC cases (one mid winter case and one late summer case) observed close to the North Pole in December 2019 and in September 2020.' This should be edited to include mention of the 18 June and 25–28 July cases.

We removed Section 4.3 (June-July 2020 MPC observations). Now, there is no discussion of additional two cases. However, we use the 17-18 June observations as an example for the statistical analysis. Therefore, the 17-18 June case is now part of the statistics section (Sect. 5). The discussion is kept short of 17-18 June observations is kept short.

Line 40: define 'fall strikes'.

We mean: fall streaks, and improved it.

Lines 98–101: Remove the sentence 'We even illuminated a potential role of stratospheric wildfire smoke on polar ozone depletion (Ohneiser et al., 2021; Ansmann et al., 2022) and the relationship between vertically integrated tropospheric water vapor and the downward, broadband thermal-infrared irradiance at the ground during the MOSAiC winter half year (Seidel et al., 2024).' These achievements are not directly relevant to the focus of this paper.

Done!

Lines 137–137: 'The basic lidar data analysis applied to obtain the geometrical and optical properties (backscatter, extinction, linear depolarization ratio) is outlined in Baars et al. and Hofer et al. (2017).' The placement of this parenthetical list suggests that all of these are both geometrical and optical properties. 'Geometrical' also does not occur in either of the sources cited, so the meaning is not immediately clear. I would suggest changing to e.g. 'The basic lidar data analysis applied to obtain the geometrical (cloud base and cloud top heights) and optical (backscatter, extinction, linear depolarization ratio) properties is outlined in Baars et al. and Hofer et al. (2017).'

We used this description now in Sect. 2.2. Note, Section 2 now has more subsections, Sect. 2.1 to 2.6 instead of 2.1 to 2.4 before. Each data analysis approach has its own subsection. The structure of this complex and busy section is now better visible, we think.

Lines 150–152: ‘The particle number concentration n50, considering all particles with radius >50 nm, is used as a proxy for the CCN concentrations, and n250, considering the large particle fraction (particles with radius >250 nm), is used to indicate the reservoir of INPs.’ Why is one a proxy and the other a reservoir? ‘Proxy for the INP concentrations’ would make more sense here, especially if you explained immediately thereafter that you are treating 1% of the n250 as ice-nucleating dust.

We included a new paragraph in Sect. 1 on time-dependent and time-independent parameterization of immersion freezing, and in this context, we introduce the ‘INP reservoir’.

We now use the wording ‘reservoir’ throughout the manuscript.

Note, Fig.1 of the submitted manuscript is now Fig.2 in the revised manuscript. In Fig. 2, we now show n50 for the height levels of 1 km, 3 km, and 5 km. In the old Fig. 1 we showed n50 for the height level of 2 km, only. This improvement was indirectly requested by the other reviewer.

Table 1: It would be very helpful to include a column for the abbreviations for each aerosol and cloud property e.g. $R_{e,liq}$ for cloud droplet effective radius.

We improved Table 1 accordingly. Note, Table 1 contains much more information now. On the other hand, we reduced the number of quantities. Listed are only parameters used in this article.

Lines 179–180: ‘Since lidar observation of pure ice crystal backscattering is only available for the virga zones’ – explain why in physical terms.

This is now explained in detail in Sect. 2.5. The main reason is that cloud droplets do not fall out of the liquid-bearing cloud layer, in contrast to ice crystals. Droplets are too small.

Lines 182–183: ‘the cloud base of the MPC top layer’ – unclear phrasing. I would suggest changing this to ‘base of the liquid-dominated cloud layer of the MPC’ as in line 170 and keeping this phrasing consistent throughout the text. A simple schematic diagram might also be helpful to the reader.

We followed both recommendations! We introduced a new Fig.1 (sketch). This will help to better understand our research strategy by combining lidar-radar observations at 250 m below the base of the liquid-containing cloud layer and dual FOV lidar observations 75 m above cloud base.

Lines 183–184 and 199–200: ‘these virga observations are well representative for the entire MPC height range, including the liquid-dominated cloud top layer’; ‘we use the virga IWC value at the top of the virga zone to be representative for the entire liquid-dominated cloud top layer as well’ – justify this briefly in-text as well as giving the Mioche et al. (2017) citation.

We try to explain that a bit better and write in Sect. 2.5: According to the airborne in situ MPC observations of \citet{Mioche2017}, the ice-phase retrieval products just below the main cloud deck, represent well the ice properties in the lower half of the liquid-bearing cloud layer. In the upper half, the ice crystal properties change much with height as function of the ice nucleation rate and growth of the crystals by water vapor deposition.

Line 210: ‘After applying several quality assurance procedures to the lidar observations’ – detail these.

We provide detailed information now in Sect. 2.6: The quality assurance procedure includes checks of the inter-channel constants between all four channels used to determine the two volume depolarisation ratios. Here, long data sets with clouds and cloud-free conditions are used to check the long-term stability of the counting efficiencies of the polarization sensitive channels. It was also checked that none of the lidar signal counts (in each channel) reached the saturation level of the detectors during cloud events.

Lines 222–223: ‘we counted a cloud field as one single cloud system if the detected cloud-free periods lasted for less than an hour’ – an hour seems like a very long gap. Explain the selection of this threshold.

We now write: In the case of a broken cloud fields (many cloud segments at the same height level), we counted a cloud field as one single cloud system if the detected cloud-free periods lasted for less than an hour. \citet{Shupe2006} counted individual cloud layers in the same way, i.e., cloud layers with gaps of < 1~h in duration were considered to be continuous}. If a cloud-free period between subsequent cloud fields exceeded 60 minutes, the next cloud field, crossing {\it Polarstern } at that height level, was counted as a new cloud. We assume in this specific cloud length statistics that all cloud segments, separated even by 30-60~minutes, still developed at the same meteorological and aerosol conditions and, thus, should not be counted as individual, independent cloud layers.

Lines 229–230: ‘The retrieval of these particle number concentrations are explained in detail in Ansmann et al. (2023)’ – it would still be good to have a sentence or two briefly outlining the methods here.

In the new Sect. 2.3 (POLIPHON…) we explain the method in more detail now.

Line 240: ‘At these high temperatures, mineral dust particles are ice-inactive’ – a citation would be good here.

We rewrote the entire Sect. 3 (MOSAiC free tropospheric aerosol conditions). The sentence above is removed.

Lines 296–297: ‘Increasing cooling of the MPC top layer also leads to an increase of available INPs.’ By what mechanism?

Yes, this statement is misleading.

In Sect. 4.1.1, now we write: Increasing cooling of the MPC top layer also leads to an increase of the ice nucleation efficiency of activatable INPs \citep{Demott2015, Kanji2017, Wex2019}.

That must be sufficient here. It has been shown in the lab, that the efficiency roughly increases by a factor of 10 when the temperatures decrease by 5 Kfor temperatures from -20 to -30°C.

Lines 281–282: ‘The longevity of the MPC deck is, to our opinion, the result of the continuous production of liquid water, especially of the formation of new droplets’ – the water itself is not being produced. Rephrase to something like ‘The longevity of the MPC deck is, in our opinion, the result of the continuous nucleation of liquid water to form new droplets’.

Improved!

Line 307: ‘seeder-feeder effects’ is used on this line for the first time but not defined in physical terms until lines 349–351; move that definition to accompany this first occurrence.

We changed that accordingly.

Line 364: ‘ice-phase fraction’ is used on this line for the first time but not defined in physical terms until line 401; move that definition to accompany this first occurrence.

Improved!

Line 379: ‘permanently’ is an odd word here; rephrase. ‘Persistently’ would be one alternative.

Improved!

Line 387: Explain in greater detail the significance of the time-dependent ice nucleation mechanism in the model and how this relates to your results. This is interesting but seems as though it is mentioned almost in passing.

This is done already in Sect. 1. A new paragraph is given on this in the Introduction.

Line 391: ‘the number of ice-nucleating particles (INPs) available for ice formation, termed INP reservoir’ – move this definition earlier, to lines 150–152 when you first introduce the term.

Also the ‘reservoir’ is now introduced in Sect. 1.

Line 419–420: ‘As on 30-31 December 2019, the air mass came from Iceland, Greenland, northern Canada, and even from Alaska.’ I suggest rephrasing to something like ‘the air mass contained aerosols from …’, and clarifying that this was known through the Radenz air mass attribution scheme (assuming that was how) and explaining briefly.

We rephrased it. As in Sect. 4.1.1 (29-31 Dec case) we avoid to mention sources of aerosols. We only know the transport ways. But this now better described in Sect 4.1.1 and 4.2.

Line 455: as on line 379, ‘permanently’ is not the right word here.

We rephrased this part.

Lines 456–459: The phenomenon you describe (vertical motions at 12:00 and 12:40) is frankly still not visible to me in Figure 5c despite the adjustments.

Yes. So, we improved the text We mention that the perturbation is not visible in the radar data. Only the triggered ice formation and intensification of the virga structures is visible.

Line 479–480: ‘The alternative hypothesis that changes in the cloud properties are simply the result of changing aerosol conditions is not convincing’ – explain why not.

We skipped this sentence. We wanted to simply emphasize that the observations are consistent with CCN activation. Whether this CCN activation is a result of changing aerosol conditions or of other reasons is not needed to be known in this context.

Lines 528–529: ‘Mineral dust particles were probably responsible for strong ice nucleation in the air mass above 6 km height’ – what is your reason for assuming this?

We removed the entire Sect. 4.3 (June-July 2020 MPC observations). So, no explanation is needed anymore.

Lines 539–540: ‘Mineral dust is the most favorable INP type at these low temperatures’ – c.f. line 240, a citation would be good here.

We did that somewhere else in the article. As mentioned, Sect. 4.3 is removed.

Lines 558–559: ‘A careful data quality check with special focus on properly aligned dual FOV receiver characteristics was applied to all of the selected cloud events’ – again, outline what this check consisted of. An appendix detailing what all of these checks were (c.f. line 210) would be very useful as supplementary material.

Note that we analyzed 147 cloud cases and not 94. The 147 cloud cases covered the 360 cloud hours.

Regarding the criteria we write in the revised version in Sect. 5 (statistics section): The observations during these 360 hours fulfilled all signal quality criteria, stated in Sect. 2.6 and the measurement conditions were perfect for dual FOV lidar applications, i.e., fog and low clouds were absent and the analyzed cloud layers showed well defined, sharp cloud base structures.

And in Sect. 2.6 we write: The quality assurance procedure includes checks of the inter-channel constants between all four channels used to determine the two volume depolarisation ratios. Here, long data sets with clouds and cloud-free conditions are used to check the long-term stability of the counting efficiencies of the polarization sensitive channels. It was also checked that none of the lidar signal counts (in each channel) reached the saturation level of the detectors during cloud events.

We do not like to introduce a supplementary part.

Line 579: ‘The histograms of the PL cloud properties in Fig. 11a, b,d, and e are slightly and partly even considerably broader’ – this phrasing is not at all clear. Rephrase to something like ‘The histograms of the PL cloud properties in Fig. 11a, b, d, and e are all at least slightly broader, and some considerably broader, than the respective frequency-of-occurrence distributions for MPCs’.

We improved that accordingly.

Line 679: ‘We presented two case studies’ – rephrase to four case studies, unless you have decided to omit the June and July cases.

We removed the Section 4.3 with the two additional case studies.

Lines 685-686: ‘The measurements further provided the impression that the CCN and INP reservoirs were always well filled, i.e., never depleted upon ice crystal formation.’ This statement only makes sense if you are treating CCN as synonymous with INP – rephrase.

We rephrased it. Note, that we now give numbers for the reservoirs in the sections for the different cases (29-31 Dec, 21 Sep).

Lines 690–691: ‘A first MPC lidar study was performed by Hofer et al. (2024)’ – add a sentence or two with more detail on this.

Done!

Technical corrections

The use of ‘rather’ throughout (e.g. line 92, ‘A rather detailed monitoring of the atmosphere…’) sounds informal and could in all occurrences be omitted without changing the meaning of the sentence.

Improved!

‘Year-around’ and ‘year around’ are nonstandard and should be replaced with ‘year-round’ in all cases.

Improved!

Figure 2: ‘indicate times with now useful lidar observations’ should read ‘indicate times with non-useful lidar observations’.

Improved!

Figure 10: ‘as a function of the time period, needed by the cloud field to cross the Polarstern’ should read ‘as a function of the time period needed by the cloud field to cross the Polarstern’.

Improved!

Figure 11: ‘The black histogram lines s are based on 3070 cloud data sets’ should read ‘The black histogram lines are based on 3070 cloud data sets’. Because all the histograms are outlined in black, consider rephrasing as ‘The thick black histogram lines are based on 3070 cloud data sets’ to differentiate that set of lines.

Improved

Line 50: ‘recognozed as the mian’ should read ‘recognized as the main’.

Improved!

Line 80: ‘an introduction in the MOSAiC Polarstern route’ should read ‘an introduction to the MOSAiC Polarstern route’.

Improved!

Line 113: ‘cloud micropyhsical properties’ should read ‘cloud microphysical properties’.

Improved!

Line 157 and onwards: ‘recently introduced’ and ‘new’ are already established as a property of the dual FOV polarization lidar method. This does not need to be repeated on subsequent occurrences.

Improved!

Lines 162–163: ‘The multiple scattering effect is a strong function of the number concentration of cloud droplets, their size, as well as of the receiver FOV of the lidar’ should read ‘The multiple scattering effect is a strong function of the number concentration of cloud droplets and of their size, as well as of the receiver FOV of the lidar’.

Improved!

Lines 275–276: ‘The strongest temperatures decrease’ should read ‘the strongest temperature decrease’.

Improved!

Line 307: ‘These crystals may have influence the MPC evolution’ should read ‘These crystals may have influenced the MPC evolution’.

Improved!

Line 302: ‘Microphyscial properties’ should read ‘Microphysical properties’.

We changed all ‘microphyscial’ to ‘microphysical’.

Line 315: ‘clout top layer’ should read ‘cloud top layer’.

Improved!

Line 337: ‘the retrieval products for both, the liquid and the ice phase’ should read ‘the retrieval products for both the liquid and the ice phase’.

Improved!

Line 350: ‘on the expense of liquid water droplets’ should read ‘at the expense of liquid water droplets’.

Improved!

Line 479: ‘taking strong CCN activation into considerations’ should read ‘taking strong CCN activation into consideration’.

Improved!

Line 494–495: ‘covered the sky above Polarstern in 50-55% of the time’ should read ‘covered the sky above Polarstern 50-55% of the time’.

We removed Section 4.3.

Line 603: ‘ice cyrstal growth’ should read ‘ice crystal growth’.

We improved all ‘cyrstal’ to ‘crystal’.

Line 611: ‘Most PL clouds layers’ should read ‘Most PL cloud layers’.

We improved all ‘clouds layers’ to ‘ cloud layers’.

Line 634: ‘before ice nucleation sets’ should read ‘before ice nucleation sets in’ or ‘before ice nucleation starts’.

Improved!

Lines 665–666: ‘Low clouds layers occurr approximately 50% of the time’ should read ‘Low cloud layers occur approximately 50% of the time’.

Improved!

Line 666: ‘the aerosol emitted in the Arctic..’ should read ‘the aerosol emitted in the Arctic.’

We changed the text.

Lines 681–682: ‘These observations demonstrate, that CCN activation is an important process to assure a longevity of an MPC deck’ should read ‘These observations demonstrate that CCN activation is an important process to assure the longevity of an MPC deck’.

Improved accordingly.

Line 705: ‘the elaboration of the final design of the manuscript’ should read ‘the elaboration of the final design of the manuscript.’

Improved!

Line 707: ‘a member of the editorial board of Atmospheric Chemistry and Physics’ should read ‘a member of the editorial board of Atmospheric Chemistry and Physics.’

Improved!

Lines 774–779: The citation for Baars et al. 2016, ‘An overview of the first decade of PollyNET: an emerging network of automated Raman-polarization lidars for continuous aerosol profiling’ is incomplete.

Improved!