First of all, we appreciate the reviewers' comment and suggestion. In response to them, we have made relevant revisions to the manuscript. Listed below are our answers and the changes made to the manuscript according to the question and suggestion given by the reviewer. The comment of the reviewer (in black) is listed and followed by our responses (in blue).

This study examines the impact of ICNC and CDNC on the properties of mixed-phase clouds using large-eddy simulations. However, I do not see new and exciting findings in this study, and some results are not convincing. Therefore, I recommend rejecting this paper in the current format.

Major comments:

1. The authors seem to be not familiar with the literature in the field. The impact of ICNC and CDNC on the properties of mixed-phase clouds, which arises from the efficiency of INP and CCN, has been explored extensively in the past. Key conclusions of this study are very similar to some previous studies, e.g, by Solomon et al. 2018 (doi: 10.5194/acp-18-17047-2018). I do not see any new or exciting results out of this study.

This study talks about impacts of INP and CCN on latent-heat processes such as condensation and deposition thorough INP- and CCN-induced changes in ICNC and CDNC as sources of deposition and condensation, respectively. These impacts of INP and CCN on condensation and deposition eventually have a significant impact on the response of LWP and IWP to changing INP and CCN concentrations. In contrast to this, Soloman et al. (2018) have focused on CCN and INP impacts on cloud-top radiative cooling via aerosol-induced changes in droplet sizes. They have focused on the fact that these impacts on radiative cooling eventually alter dynamics and then LWP and IWP. This study focuses only on aerosol-induced changes in deposition and condensation excluding those changes on radiative cooling. In other words, the main driver of results in this study is aerosol-induced changes in deposition and condensation themselves but not aerosol-induced changes in radiative cooling. Hence, we believe that this study can be distinguished from Soloman et al. (2018). Regarding this, we repeated all of the previous simulations in the old manuscript by turning off radiative processes and comparisons between these repeated simulations and the previous simulations have shown that the qualitative nature of results in this study is robust to whether radiative processes, which include cloud-top radiative cooling, are considered for the simulations or not. This confirms that aerosol impacts on radiative cooling are not a main thrust for results in this study and the main thrust is aerosol-induced changes in ICNC, CDNC and associated deposition and condensation.

Also, want to mention that most of the previous studies of mixed-phase stratocumulus clouds have raised entrainment, detrainment, and hydrometeor sedimentation as important factors that control cloud mass and aerosol impacts on it (e.g., Albrecht, 1989; Ackerman, 2004: Ovchinnikov et al., 2011; Possner et al., 2017); cloud mass is represented by IWP and LWP. However, this study finds that entrainment, detrainment, and sedimentation are not important factors that control cloud mass, aerosol-induced changes in cloud mass, and their variation between different cloud systems at different locations. This study finds that CDNC, ICNC and then condensation and deposition are important factors for cloud mass, aerosol impacts on it and their variation between different cloud systems. Hence, this study can be distinguished even from other previous studies focusing on entrainment, detrainment, and hydrometeor sedimentation.

Regarding the argument here, the following is added:

(LL828-837 on p28)

Previous studies on mixed-phase stratocumulus clouds (e.g., Ovchinnikov et al., 2011; Possner et al., 2017; Solomon et al., 2018) have primarily focused on investigating the impacts of cloud-top radiative cooling, entrainment, and sedimentation of ice particles on these clouds, as well as their interactions with aerosols. However, there are a scarcity of studies that specifically examine the role of microphysical interactions, involving processes such as condensation and deposition, as well as factors like cloud-particle concentrations, between ice and liquid particles in mixed-phase stratocumulus clouds, and their interactions with aerosols as performed in this study. Therefore, our study contributes to a more comprehensive understanding of mixed-phase clouds and their intricate interplay with aerosols.

Regarding the simulations with radiation turned off, Section 3.3 is added.

To better put this study in the context of the previous studies of mixed-phase stratocumulus clouds, the following is added in introduction:

(LL136-141 on p5)

Choi et al. (2010 and 2014) and Zhang et al. (2019) have shown that as temperature lowers, IWC/LWC or IWP/LWP tends to increase and indicated that temperature is a primary environmental condition to explain the differences in IWC/LWC among different regions or clouds. However, Choi et al. (2010 and 2014) and Zhang et al. (2019) have not discussed process-level mechanisms that govern the role of temperature in those differences.

(LL175-187 on p6-7)

This comparison is based on Choi et al. (2010 and 2014) and Zhang et al. (2019) which have shown that temperature is an important factor which explains the differences in IWC/LWC among regions or clouds. Due to significant differences in latitudes, noticeable differences in the temperature of air are between the polar and midlatitude cases. Hence, through this comparison, this study looks at the role of temperature in those differences in IWC/LWC and associated aerosol-cloud interactions. More importantly than that, as a way of identifying process-level mechanisms that control the role of temperature, this study tests how ICNC/CDNC as the general factor is linked to the role of temperature, using the LES framework. Through this test, this study also identifies process-level mechanisms that control how ICNC/CDNC affects roles of ice processes in the differentiation between mixed-phase and warm clouds in terms of cloud development and its interactions with aerosols, and causes the variation of the differentiation between the cases of mixed-phase stratiform clouds.

2. The authors stated “ICNC/CDNC can be a simplified general factor that contributes to a more general understanding of mixed-phase clouds”. If the authors can establish "a general principle" for the mixed-phase cloud, I think it would be very useful and this study would be worth for a publication. However, this argument is not convincing for the following reasons:

2.1. The author conducted nine idealized simulations of the mixed-phase clouds. It is not convincing to me how results from nine idealized simulations can be helpful to establish a general principle or a general parameterization for the mixed-phase cloud.

Just want to emphasize that as described in text, this study is only about an “attempt” to test a factor that can help us with the development of the general principle but not about the establishment of a perfect, complete general principle. To clarify this, the following is added:

(LL161-168 on p6)

Here, we want to emphasize that this study does not aim to gain a fully established general principle, but aims to test the factor that can be useful to move ahead on our path to a more complete general principle. Hence, this study should be regarded a steppingstone to the established principle, and should not be considered a perfect study that get us the fully established principle. Taking into account the fact that even attempts to provide general factors for the general principle have been rare, the fulfilment of the aim is likely to provide us with valuable preliminary information that streamlines the development of a more established general principle.

Just want to add that this study focuses on a factor, explaining differences in IWC/LWC among different clouds, as a steppingstone to the general principle, motivated by the fact that IWC/LWC plays an important role in cloud radiative properties and thus their climate feedbacks as discussed in Choi et al. (2010 and 2014). Choi et al. (2010 and 2014) and Zhang et al. (2019) have shown that temperature is an important factor which explains the differences in IWC/LWC among different clouds. However, Choi et al. (2010 and 2014) and Zhang et al. (2019) have not discussed process-level mechanisms that govern the role of temperature in those differences. Motivated by this, this study aims to find process-level mechanisms controlling the role of temperature in those differences by using the LES framework and to fulfill the aim, this study tests ICNC/CDNC which potentially can act as the factor or a general factor, explain the differences in IWC/LWC among different clouds and thus contribute to the development of the general principle in connection to the role of temperature. Regarding this, the following is added:

(LL132-141 on p5)

Mixed-phase stratocumulus clouds in different regions are known to have different IWC/LWC or IWP/LWP and aerosol-cloud interactions (e.g., Choi et al., 2010 and 2014; Zhang et al., 2019). Lots of factors such as environmental conditions, which can be represented by variables such as temperature, humidity and wind shear, can explain those differences. Choi et al. (2010 and 2014) and Zhang et al. (2019) have shown that as temperature lowers, IWC/LWC or IWP/LWP tends to increase and indicated that temperature is a primary environmental condition to explain the differences in IWC/LWC among different regions or clouds. However, Choi et al. (2010 and 2014) and Zhang et al. (2019) have not discussed process-level mechanisms that govern the role of temperature in those differences.

(LL169-187 on p6-7)

For the attempt, this study investigates a case of mixed-phase stratiform clouds in the polar region. Via the investigation, this study aims to identify process-level mechanisms that control the development of those clouds and their interactions with aerosols, and the impact of ice processes on the development and interactions using a large-eddy simulation (LES) framework. Then, this study compares the mechanisms in the case of polar clouds to those in a case of midlatitude clouds which have been examined by Lee et al. (2022). This comparison is based on Choi et al. (2010 and 2014) and Zhang et al. (2019) which have shown that temperature is an important factor which explains the differences in IWC/LWC among regions or clouds. Due to significant differences in latitudes, noticeable differences in the temperature of air are between the polar and midlatitude cases. Hence, through this comparison, this study looks at the role of temperature in those differences in IWC/LWC and associated aerosol-cloud interactions. More importantly than that, as a way of identifying process-level mechanisms that control the role of temperature, this study tests how ICNC/CDNC as the general factor is linked to the role of temperature, using the LES framework. Through this test, this study also identifies process-level mechanisms that control how ICNC/CDNC affects roles of ice processes in the differentiation between mixed-phase and warm clouds in terms of cloud development and its interactions with aerosols, and causes the variation of the differentiation between the cases of mixed-phase stratiform clouds.

In addition, based on comments from both the reviewers, to improve the generality of findings of this study and thus to better streamline the establishment of the general principle, more simulations are performed as described in Sections 3.3, 4.1 and 4.2.

2.2. Observations are missing to justify the model setup and evaluate simulation results. For example, it said that “a system of mixed-phase stratocumulus clouds was observed to exist over a period between 02:00 local solar time (LST) and 20:00 LST on March 29th, 2017. On average, the bottom and top of these clouds are at ~400 m and ~3 km in altitude, respectively.” Is there any ground-based observations to support this statement? See Fig. 1 in Solomon’s paper as a good example.

The following is added:

(LL235-243 on p8-9)

In the Svalbard area, Norway, a system of mixed-phase stratocumulus clouds existed over the horizontal domain marked by a red rectangle in Figure 1 and a period between ~02:00 local solar time (LST) and 10:00 LST on March 29th, 2017. These clouds are observed by ground radar and lidar and these radar and lidar are a part of the Cloudnet ground observation that is deployed at a location in the red rectangle. The Cloudnet ground observation is composed of a suite of instruments such as lidar, radar and radiometer and described in Hogan et al. (2006). On average, the bottom and top of these clouds are at ~400 m and ~3 km in altitude, respectively, according to observation by those radar and lidar.

(LL343-358 on p12)

This study adopts the Cloudnet ground observation to evaluate the 200_2 run. Observed LWP is provided by radiometer. The retrieval of IWP is performed by using radar reflectivity and lidar backscatter as described in Donovan et al. (2001), Donovan (2003) and Tinel et al. (2005). As mentioned above, observed cloud-bottom and -top heights are obtained from radar and lidar measurements. Simulated LWP and IWP, as shown in Figure 4 and Table 2, are compared to the observed LWP and retrieved IWP, respectively. The average LWP over all time steps and grid columns is 1.23 in the 200_2 run and 1.12 in observation. The average IWP over all time steps and grid columns is 31.94 in the 200_2 run and 29.10 in retrieval. Cloud-bottom height, which is averaged over grid columns and time steps with non-zero cloud-bottom height, is 420 and 440 m in the 200_2 run and observation, respectively. Cloud-top height, which is averaged over grid columns and time steps with non-zero cloud-top height, is 3.5 and 3.3 km in the 200_2 run and observation, respectively. Each of LWP, cloud-bottom and -top heights shows an ~10% difference between the 200_2 run and observation. IWP also shows an ~10% difference between the 200_2 run and retrieval. Thus, the 200_2 run is considered performed reasonably well for these variables.

Following the comment by the other reviewer, among the observed variables, the time series of the observed cloud-top height is compared to that of the simulated height as follows:

(LL359-366 on p12-13)

To provide additional or supplementary information of cloud development, the time evolution of the simulated and observed cloud-top height is shown together with the simulated evolution of the surface sensible and latent-heat fluxes in Supplementary Figure 1. This is based on the fact that the cloud-top height is considered a good indicative of cloud development and the surface fluxes are considered important parameters controlling the overall development of clouds. Simulated evolutions in Supplementary Figure 1 are from the 200_2 run. The cloud-top height increases between 02:00 and ~05:00 LST and after ~05:00 LST, it reduces gradually.

2.3. Model setup for the initial CCN and INP measurements is also not convincing. One weird result is the extremely high IWC for the control run. As far as I know, IWC in the mixed-phase stratocumulus cloud is usually much smaller than LWC. However, in the control run, IWC/LWC is 26.28, which is extremely high. Do you have any observations to support this result? Can you find any literature to support such high ratio exist in the mixed-phase cloud? If you cannot find observations to support such high IWC/LWC value, it means that the control run might not be setup correctly, and the goal to establish “a general principle” from those simulation results is not convincing.

First of all, as described above in our response to the reviewer’s comment 2.2, the Cloudnet observation is used to evaluate the 200_2 run. As described in the response, the Cloudnet observation shows that the average observed/retrieved IWP is 29.10 and the average observed LWP is 1.12. Hence, the Cloudnet-based IWP/LWP is 25.98.

IWP/LWP in the 200_2 run is 25.96. This demonstrates that the simulated high IWP/LWP is well supported by the Cloudnet observation.

Moreover, Choi et al. (2014) have done work on the supercoold cloud fraction (SCF), which is equivalent to LWP/(LWP+IWP), using satellite-observed data collected over the period of ~5 years. As seen in Figure 1 in Choi et al. (2014), their work has shown that SCF can be lower than 0.05 and as low as 0.01 for the temperature range between -16 and -33 ºC. Regarding the temperature, as stated in the manuscript, the average air temperature immediately below the cloud base over the simulation period is -16 ºC and the average air temperature immediately above the cloud top is -33 ºC in the 200_2 run. Note that SCF in the 200_2 run in this study is 0.04. Zhang et al. (2019) have also shown that for the temperature range between -16 and -33 ºC, SCF can be as low as ~0.03, though clouds with SCF below 0.05 are rare, based on ground observations in the Arctic area over a one-year period; for details, see Figure 7 in Zhang et al. (2019).

In association with Choi et al. (2014) and Zhang et al. (2019), the following is added:

(LL381-391 on p13)

Choi et al. (2014) and Zhang et al. (2019) have obtained the supercooled cloud fraction (SCF), which is basically the ratio of LWC to the sum of LWC and IWC and denoted by LWC/(LWC+IWC), using satellite- and ground-observed data collected over the period of ~5 years and ~1 year, respectively. Choi et al. (2014) have shown that SCF is as low as ~0.01 for the temperature range between -16 and -33 ºC. Zhang et al. (2019) have also shown that SCF is as low as ~0.03 for the same temperature range, although the occurrence of SCF of ~0.03 or lower is rare. Note that the average air temperature immediately below the cloud base and above the cloud top over the simulation period is -16 and -33 ºC, respectively, in the 200_2 run, and SCF in the 200_2 run is 0.04. Hence, based on Choi et al. (2014) and Zhang et al. (2019), we believe that SCF in the 200_2 run is observable and thus not that unrealistic, although it may not occur frequently.

In summary and conclusion, to explain reasoning behind the choice of the possibly rare polar case with SCF of 0.04, the following is added:

(LL774-777 on p26)

To gain the understanding efficiently, the polar case is chosen in a way to make stark contrast with the midlatitude case in terms of ICNC/CDNC and IWC/LWC. Although such polar cases may be uncommon, the stark contrast provides an opportunity to elucidate mechanisms that control the above-mentioned role of different ICNC/CDNC.

Here is one suggestion to improve the paper quality: whenever you refer to the observation (cloud, CCN, INP, LWP, IWP...), you should either cite a reference if the results are published or add it in the paper to support your statement. If you don't have those observations, you should provide reasonable assumptions. If results are quite different from previous studies (e.g., extremely high IWC/LWC), you should provide strong justifications.

As stated in our response above, observed LWP and observed/retrieved IWP are obtained from the Cloundnet observation and these LWP and IWP are compared to simulated counterparts as a way of evaluating the simulation. As stated in our response above, these observed LWP and observed/retrieved IWP also justify the simulated extremely high IWC/LWC. Associated text is added in the new manuscript as described above. Moreover, as stated in our response above, important cloud variables such as cloud-top and cloud-bottom heights are compared between observations and the 200_2 run. As stated above, this comparison demonstrates that the simulation of these cloud variables is performed reasonably well, and text about this is added in the new manuscript.

With respect to the observation of CCN and the associated assumption on INP, the following is added with associated text:

(LL263-271 on p9-10)

The properties of cloud condensation nuclei (CCN) such as the number concentration, size distribution and composition are measured in the domain (Tunved et al., 2013; Jung et al., 2018). The measurement indicates that on average, aerosol particles are an internal mixture of 70 % ammonium sulfate and 30 % organic compound. This mixture is assumed to represent aerosol chemical composition over the whole domain and simulation period for this study. The observed and averaged concentration of aerosols acting as CCN is ~200 cm^{-3} over the simulation period. Based on this, 200 cm^{-3} as an averaged concentration of aerosols acting as CCN is interpolated into all of grid points immediately above the surface at the first time step.

(LL285-288 on p10)

It is assumed that the properties of INP and CCN are not different except for concentrations. The concentration of aerosols acting as CCN is assumed to be 100 times higher than that acting as INP over grid points at the first time step based on a general difference in concentrations between CCN and INP (Pruppacher and Klett, 1978).

Review of the manuscript “EGUsphere-2023-862” entitled “Examination of varying mixed-phase stratocumulus clouds in terms of their properties, ice processes and aerosol-cloud interactions between polar and midlatitude cases: An attempt to propose a microphysical factor to explain the variation” written by Lee, Jung, Yoon, Um, Zheng, Guo, Manoj, and Song.

This study shows simulation results of idealized clouds that can occur in a polar region using the Weather Research and Forecasting model with a bin cloud microphysics scheme at a spatially fine resolution. The authors endeavor to examine how variations in cloud development are influenced by changes in cloud condensation nuclei (CCN) and ice-nucleating particle (INP) concentrations.

The authors propose that the ratio between the concentrations of ice crystals and cloud droplets may constitute a pivotal factor influencing cloud development. However, substantiating such a claim is challenging due to the scarcity of supporting evidence, and numerical experiments do not appear to be appropriately designed to substantiate this assertion. Furthermore, despite simulations of stratocumuli in a polar region are conducted, there is a notable absence of evidence regarding the adequacy of the model's cloud representation. Additionally, the experimental design lacks sufficient information for simulating stratocumuli adequately. The authors also introduce logical leaps in their arguments at several junctures. Consequently, for these reasons, the reviewer recommends against the publication of this paper. Detailed discussions on specific issues are provided below.

Major:

1. To convincingly demonstrate that the ratio between ICNC and CDNC (ICNC/CDNC) is indeed a critical factor in cloud development, as emphasized by the authors, it is imperative to systematically vary this ratio and conduct numerical experiments. This research, however, has scarcely undertaken such an approach. The ratios presented in Table 1 vary across all experiments, rendering it challenging to discern whether the differences revealed in each experiment stem simply from disparities in CCN and INP or from the ICNC/CDNC. To substantiate the authors' claims, it is essential that similar outcomes emerge in experiments with matched ICNC/CDNC but differing CCN and INP concentrations, thereby providing evidence for the significance of this ratio. Furthermore, as depicted in Figure 7, all four experiments—200_2, 2000_20, 200_20, and 2000_2—exhibit similar profiles for IWC and LWC. However, the ICNC/CDNC ratios vary significantly among these experiments, ranging from 0.108 to 0.512. Therefore, based on these findings, it is challenging to assert that ICNC/CDNC is a critical factor.

We believe that the suggestion by the reviewer here that “ICNC/CDNC should be systematically varied and simulations should be performed accordingly” can be followed up by looking at simulations in Table 1. For the follow-up, simulations for mixed-phase clouds in Table 1 in the old manuscript are re-arranged as in Table 4. We see that ICNC/CDNC gradually increases from 0.012 in the 200_2_fac10_CCN10 run to 0.512 in the 200_20 run through values in between among the other runs in Table 4. We believe that this achieves the suggested systematic variation of ICNC/CDNC to the reasonable extent. For this variation of ICNC/CDNC, the variation of IWC/LWC among the simulations in Table 4 is examined as detailed in Section 4.1. We think that findings from this examination in Section 4.1 resolves the issue fairly well related to the reviewer’s comment “Furthermore, as depicted in Figure 7, all four experiments—200_2, 2000_20, 200_20, and 2000_2—exhibit similar profiles for IWC and LWC. However, the ICNC/CDNC ratios vary significantly among these experiments, ranging from 0.108 to 0.512. Therefore, based on these findings, it is challenging to assert that ICNC/CDNC is a critical factor”

Regarding the reviewer’s comment that “the ratios presented in Table 1 vary across all experiments, rendering it challenging to discern whether the differences revealed in each experiment stem simply from disparities in CCN and INP or from the ICNC/CDNC. To substantiate the authors' claims, it is essential that similar outcomes emerge in experiments with matched ICNC/CDNC but differing CCN and INP concentrations, thereby providing evidence for the significance of this ratio”, we performed additional simulations. For these additional simulations, as described in Section 4.2, the 200_2 run for the polar case and the 200_2_fac10 run representing the midlatitude case are selected among the runs in Section 4.1. For the additional simulations, each of these selected runs is repeated by varying the number concentration of aerosols acting as CCN and INP in a way that ICNCavg/CDNCavg does not vary as described in Section 4.2. As detailed in Section 4.2 and Table 5, these additional simulations demonstrate that the basic findings of the role of ICNC/CDNC in IWC/LWC from the comparison between the 200_2 and 200_2_fac10 runs in Section 3.1.2 are robust to whether the concentrations of aerosols acting as CCN and INP vary for a given ICNC/CDNC.

2. The authors present cloud development based solely on profiles of horizontally (and temporally) averaged IWC and LWC. However, it should be noted that cloud development is influenced by a multitude of physical quantities beyond these metrics. Offering results exclusively in the form of averaged IWC and LWC profiles is not considered appropriate.

   As stated in introduction in the old and new manuscripts, this study focuses on the relative proportion of liquid mass and ice mass, since this proportion plays an important role in cloud radiative properties and thus their climate feedbacks, according to Choi et al. (2010 and 2014) and Zhang et al. (2019). Choi et al. (2010 and 2014) and Zhang et al. (2019) quantified the relative proportion with liquid mass (ice mass) represented by LWC or LWP (IWC or IWP). With this quantification, these previous studies have found that the relative proportion, which can be noted to be “IWC/LWC” or “IWP/LWP”, varies with regions and clouds. These previous studies have indicated that this variation is closely linked to temperature. However, they have not discussed process-level mechanisms that are associated with cloud-scale microphysics and dynamics and govern the role of temperature in the variation. We believe that understanding these mechanisms is important, since with this understanding, we can come up with process-oriented ideas about how to parameterize or represent the variation of IWC/LWC with varying clouds in varying regions or in varying temperature regimes. These ideas can eventually act as a valuable steppingstone to the development of a more general parameterization of clouds. As stated in introduction, the absence of the general parameterization has been considered one of the biggest obstacles to the better prediction of climate changes. Hence, pursuing those ideas as done by this study is worthy of research efforts.

In summary, this study is motivated by the findings of the variation of IWC/LWC with varying clouds in varying regions in the previous studies (e.g., Choi et al., 2010 and 2014; Zhang et al., 2019). Note that these previous studies basically deal with IWC, which is averaged over the time period and the specific area or region of interest, and LWC, which is also averaged over the time period and the specific area or region of interest, to examine the variation of the relative proportion of liquid mass, which is represented by the average LWC, and ice mass, which is represented by the average IWC. Following these previous studies, this study also adopts the time- and domain-averaged IWC and LWC to examine the variation of the relative proportion of liquid mass and ice mass; as stated in the manuscript, for the sake of simplicity, the averaged IWC over the averaged LWC is denoted by IWC/LWC for this study and IWC/LWC represents the relative proportion in this study, following the previous studies. Then, this study aims to identify process-level mechanisms which control the variation of none other than “IWC/LWC”, as a representation of the relative proportion of liquid mass and ice mass, with varying clouds in varying regions or varying temperature regimes and have not been studied in the previous studies. Just want to emphasize that since the previous studies have focused on the variation of the supercooled cloud fraction (SCF), which is basically a quantity regarding the ratio between the average LWC and the average IWC, this study focuses on IWC/LWC and associated process-level mechanisms. This study wants to make a continuity between itself and the previous studies and via the continuity, this study wants to further develop the findings of the previous studies in terms of IWC/LWC. For this, this study does not adopt other quantities and delve only into IWC/LWC and associated cloud-scale microphysics and dynamics. In this way, our findings can be in line with the previous studies and this can enrich both this study and the previous studies.

Although this study delves into IWC/LWC, to identify above-mentioned process-level mechanisms that are associated with cloud-scale microphysics and dynamics, this study examines other physical and dynamic quantities such as ICNC, CDNC, condensation, deposition, sedimentation and entrainment. Hence, authors do not believe that results here are offered exclusively in the form of the average IWC and LWC.

For your information, to identify the process-level mechanisms efficiently, this study chooses two cases, which are in stark contrast to each other in terms of temperature regimes where they reside and IWC/LWC, and compares them.

Regarding the argument above, the following is added:

(LL132-141 on p5)

Mixed-phase stratocumulus clouds in different regions are known to have different IWC/LWC or IWP/LWP and aerosol-cloud interactions (e.g., Choi et al., 2010 and 2014; Zhang et al., 2019). Lots of factors such as environmental conditions, which can be represented by variables such as temperature, humidity and wind shear, can explain those differences. Choi et al. (2010 and 2014) and Zhang et al. (2019) have shown that as temperature lowers, IWC/LWC or IWP/LWP tends to increase and indicated that temperature is a primary environmental condition to explain the differences in IWC/LWC among different regions or clouds. However, Choi et al. (2010 and 2014) and Zhang et al. (2019) have not discussed process-level mechanisms that govern the role of temperature in those differences.

(LL169-187 on p6-7)

For the attempt, this study investigates a case of mixed-phase stratiform clouds in the polar region. Via the investigation, this study aims to identify process-level mechanisms that control the development of those clouds and their interactions with aerosols, and the impact of ice processes on the development and interactions using a large-eddy simulation (LES) framework. Then, this study compares the mechanisms in the case of polar clouds to those in a case of midlatitude clouds which have been examined by Lee et al. (2022). This comparison is based on Choi et al. (2010 and 2014) and Zhang et al. (2019) which have shown that temperature is an important factor which explains the differences in IWC/LWC among regions or clouds. Due to significant differences in latitudes, noticeable differences in the temperature of air are between the polar and midlatitude cases. Hence, through this comparison, this study looks at the role of temperature in those differences in IWC/LWC and associated aerosol-cloud interactions. More importantly than that, as a way of identifying process-level mechanisms that control the role of temperature, this study tests how ICNC/CDNC as the general factor is linked to the role of temperature, using the LES framework. Through this test, this study also identifies process-level mechanisms that control how ICNC/CDNC affects roles of ice processes in the differentiation between mixed-phase and warm clouds in terms of cloud development and its interactions with aerosols, and causes the variation of the differentiation between the cases of mixed-phase stratiform clouds.

(LL774-777 on p26)

To gain the understanding efficiently, the polar case is chosen in a way to make stark contrast with the midlatitude case in terms of ICNC/CDNC and IWC/LWC. Although such polar cases may be uncommon, the stark contrast provides an opportunity to elucidate mechanisms that control the above-mentioned role of different ICNC/CDNC.

3. The authors numerically simulate clouds in a polar region using the UM data as initial conditions. However, the adequacy of the model's cloud representation cannot be assessed as there is no comparison between the simulated clouds and those that can form under the actual conditions. For instance, in the control run, the averaged total water path of the simulated clouds is approximately 33 g m^{-2}. Without a comparison to the total water path of clouds formed under the corresponding conditions in the corresponding region, it is impossible to gauge the fidelity of the model's cloud simulation.

   Comparisons between observation and the 200_2 run have been made in terms of cloud variables including IWP and LWP, the sum of which is the total cloud mass (or total water path), as follows:

   (LL343-358 on p12)

   This study adopts the Cloudnet ground observation to evaluate the 200_2 run. Observed LWP is provided by radiometer. The retrieval of IWP is performed by using radar reflectivity and lidar backscatter as described in Donovan et al. (2001), Donovan (2003) and Tinel et al. (2005). As mentioned above, observed cloud-bottom and -top heights are obtained from radar and lidar measurements.

Simulated LWP and IWP, as shown in Figure 4 and Table 2, are compared to the observed LWP and retrieved IWP, respectively. The average LWP over all time steps and grid columns is 1.23 in the 200_2 run and 1.12 in observation. The average IWP over all time steps and grid columns is 31.94 in the 200_2 run and 29.10 in retrieval. Cloud-bottom height, which is averaged over grid columns and time steps with non-zero cloud-bottom height, is 420 and 440 m in the 200_2 run and observation, respectively. Cloud-top height, which is averaged over grid columns and time steps with non-zero cloud-top height, is 3.5 and 3.3 km in the 200_2 run and observation, respectively. Each of LWP, cloud-bottom and -top heights shows an ~10% difference between the 200_2 run and observation. IWP also shows an ~10% difference between the 200_2 run and retrieval. Thus, the 200_2 run is considered performed reasonably well for these variables.

4. According to Figure 2, the potential temperature in the near-surface atmosphere is approximately 257 K, which, assuming a pressure of 1000 hPa, corresponds to an extremely low temperature of approximately –16°C. However, the way SST (and/or surface heat fluxes) is prescribed under these atmospheric conditions remains undisclosed. For example, if the SST is assumed to be near 0°C, this would anticipate significant sensible heat flux. In this situation, it becomes vital to provide details on many cloud-related quantities and synoptic conditions, such as SST evolution, surface heat fluxes, large-scale subsidence, and cloud top height development.

The following is added:

(LL254-262 on p9)

Figure 2b shows the time evolution of the domain-averaged large-scale subsidence or downdraft in the reanalysis data and at the model top. The large-scale subsidence gradually reduces with time (Figure 2b). Figure 2c shows the time evolution of the domain-averaged surface temperature in the reanalysis data. This evolution of the surface temperature is mostly controlled by the sea surface temperature (SST) considering that most portion of the red-rectangle domain is accounted for by the ocean (Figure 1). Between ~06:00 LST around when the sun rises and ~08:00 LST, the surface temperature increases from -2.2 to -1.6 ºC, and after that, it does not show significant increase or decrease (Figure 2c).

(LL359-369 on p12-13)

To provide additional or supplementary information of cloud development, the time evolution of the simulated and observed cloud-top height is shown together with the simulated evolution of the surface sensible and latent-heat fluxes in

Supplementary Figure 1. This is based on the fact that the cloud-top height is considered a good indicative of cloud development and the surface fluxes are considered important parameters controlling the overall development of clouds. Simulated evolutions in Supplementary Figure 1 are from the 200_2 run. The cloud-top height increases between 02:00 and ~05:00 LST and after ~05:00 LST, it reduces gradually. The surface fluxes reduce with time, although the reduction rate of the fluxes starts to decrease around 08:00 LST in association with the increase in the surface temperature between ~06:00 and ~08:00 LST as shown in Figure 2c.

Supplementary Figure 1 or Figure S1 is as follows:

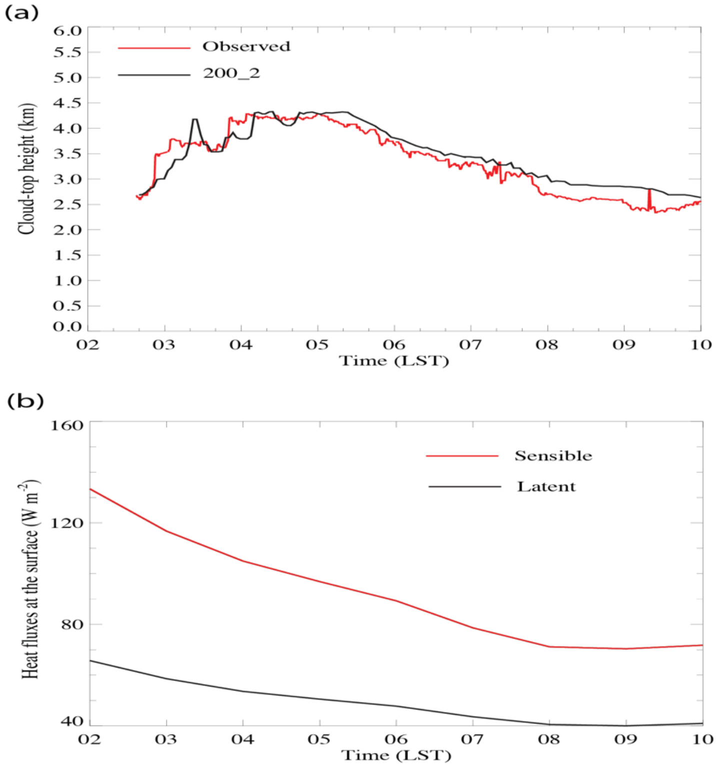

Figure S1. (a) The time series of observed and simulated cloud-top height. The simulated height is averaged over grid points with cloud tops at each time step in the 200_2 run. (b) The time series of the surface sensible and latent heat surfaces that are averaged over the domain in the 200_2 run.

5. In some points of the paper, the authors present arguments with substantial logical leaps. For instance, at L351, the authors assert that drop sedimentation “increases” total cloud mass. However, this assertion is neither logical nor supported by simulation results. The experimental findings merely demonstrate that in the comparison between the 200_2 run and the 200_2_noice run, the

former exhibits greater total cloud mass and greater drop sedimentation. This can be attributed to the inherent fact that denser clouds yield more precipitation.

Our argument at L351is based on the previous studies (e.g., Albrecht, 1989; Ackerman et al., 2004; Ovchinnikov et al., 2011; Possner et al., 2017) focusing on sedimentation and entrainment to explain the development of cloud mass in stratocumulus clouds. These previous studies have demonstrated that more (less) sedimentation of hydrometeors contributes to greater (smaller) loss of cloud mass by moving more (less) hydrometeors out of clouds when it comes to sedimentation itself or when we restrain our argument only to sedimentation; the argument at L351 is based on this. These studies have indicated that changes in sedimentation are a main driver that controls changes in cloud mass. The purpose of making the argument at L351and after L351 in the corresponding paragraph is to check on how important the much-studied sedimentation is in terms of changes in cloud mass as compared to condensation and deposition. Through this check, we want to show that contrary to the previous studies, sedimentation is not an important factor driving changes in cloud mass but condensation and deposition are the critical factor.

In addition, at L403, the authors describe that a higher IWC/LWC ratio in the 200_2 run than in the 200_2_noice run results in more water content (WC), but no logical rationale for this claim is provided, and it is evident only that the inclusion of INP leads to an increase in total water mass.

Just want to start with the finding that WC in the polar mixed-phase clouds is higher than LWC in the polar warm clouds, while WC in the midlatitude mixed-phase clouds is lower than LWC in the midlatitude warm clouds. The main reason for this is that IWC in the polar mixed-phase clouds is much higher than LWC in the polar warm clouds, while IWC in the midlatitude mixed-phase clouds is smaller than LWC in the midlatitude warm clouds. Note that LWC in the polar (midlatitude) mixed-phase clouds is lower than that in the polar (midlatitude) warm clouds. Hence, we see that the higher IWC in the polar mixed-phase clouds than LWC in the polar warm clouds overcomes lower LWC in the polar mixed-phase clouds than that in the polar warm clouds to lead to higher WC in the polar mixed-phase clouds than that in the polar warm clouds, while lower IWC in the midlatitude mixed-phase clouds than LWC in the midlatitude warm clouds is not able to overcome lower LWC in the midlatitude mixed-phase clouds than that in the midlatitude warm clouds to lead to lower WC in the midlatitude mixed-phase clouds than that in the midlatitude warm clouds. The higher IWC in the polar mixed-phase clouds than LWC in the polar warm clouds overcoming lower LWC in the polar mixed-phase clouds than that in the polar warm clouds is associated with a situation where IWC is much higher than LWC “in the polar mixed-phase clouds”, thus there is a high IWC/LWC in the polar mixed-phase clouds, while the lower IWC in the midlatitude mixed-phase clouds than LWC in the midlatitude warm clouds not overcoming lower LWC in the midlatitude mixed-phase clouds than that in the midlatitude warm clouds is associated with a situation where the magnitude of IWC is similar to that of LWC “in the midlatitude mixed-phase clouds”, thus, there is a low IWC/LWC, which is lower than IWC/LWC “in the polar mixed-phase clouds”, in the midlatitude mixed-phase clouds.

In summary, reflecting the comment by the reviewer here, it is not logical to say that higher IWC/LWC itself in the 200_2 run (or in the polar mixed-phase clouds) than that in the midlatitude case (or in the midlatitude mixed-phase clouds) is a reason for WC in the 200_2 run which is greater than LWC in the warm clouds in the 200_2_noice run (or in the polar warm clouds), while it is not logical to say that lower IWC/LWC itself in the midlatitude case than that in the 200_2 run is a reason for WC in the midlatitude mixed-phase clouds which is lower than LWC in their warm-cloud counterpart (or in the midlatitude warm clouds); just want to note that the argument here is not about higher IWC/LWC in the 200_2 run than that in the 200_2_noice run, which is mentioned in the reviewer’s comment here about “L403”, but about the higher IWC/LWC in the 200_2 run than that in the midlatitude case. However, as described in the first paragraph of authors’ response to the reviewer’s comment here about “L403”, the situation where higher IWC in the polar mixed-phase clouds than LWC in the polar warm clouds overcomes lower LWC in the polar mixed-phase clouds than that in the polar warm clouds is “associated” with higher IWC/LWC “in the 200_2 run than that in the midlatitude case”, while the situation where the lower IWC in the midlatitude mixed-phase clouds than LWC in the midlatitude warm clouds is not able to overcome lower LWC in the midlatitude mixed-phase clouds than that in the midlatitude warm clouds is “associated” with lower IWC/LWC “in the midlatitude case than that in the 200_2 run”. Based on the argument here and focusing on word “associated” in the argument, corresponding paragraphs are revised as follows:

(LL478-491 on p16-17)

Much higher IWC than LWC, which results in a much higher IWC/LWC in the polar case than in the midlatitude case, in the 200_2 run overcomes lower LWC in the 200_2 run than that in the 200_2_noice run, which leads to the greater total cloud mass in the 200_2 run than in the 200_2_noice run (Figure 4 and

Table 2). However, IWC whose magnitude is similar to the magnitude of LWC, which results in a much lower IWC/LWC in the midlatitude case than in the polar case, in the midlatitude case is not able to overcome lower LWC in the midlatitude case than that in the midlatitude warm clouds, which leads to the greater total cloud mass in the midlatitude warm clouds than in the midlatitude case; here, the midlatitude warm clouds are generated by removing ice processes in the midlatitude case. This means that associated with higher ICNC/CDNC and IWC/LWC, ice processes enhance the total cloud mass for the polar case as compared to that for the polar warm-cloud counterpart. However, in the midlatitude case, associated with lower ICNC/CDNC and IWC/LWC, ice processes reduce the total cloud mass as compared to that for the midlatitude warm-cloud counterpart.

Minor:

1. I strongly recommend refine the writing. The authors excessively use sentences beginning with "There" and passive voice constructions.

   We revised sentences pointed out here by removing unnecessary “there” and passive voice constructions.

2. Although the authors have discussed the strong correlation between IWC and IWP in the early sections of the paper (e.g., Table 2), they consistently describe them as "IWC (IWP)" throughout the manuscript, which diminishes the readability of the paper. If the correlation is indeed evident, it is advisable to mention either IWC or IWP alone for clarity.

   Following the comment here, both a pair of IWC and LWC and that of IWP and LWP are mentioned only in the early part of the manuscript and only a pair of LWC and IWC are mentioned in text after the early part. To indicate this, the following is added:

   (LL376-380 on p13)

   Hence, mentioning both a pair of IWC and LWC and that of IWP and LWP is considered redundant, and mentioning either a pair of IWC and LWC or that of IWP and LWP enhances the readability. Henceforth, IWC and LWC are chosen to be mentioned in text, although all of IWC, LWC, IWP and LWP are displayed in Tables 2 and 3.