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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

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Abstract

This study examines the ratio of ice crystal number concentration (ICNC) to cloud droplet number concentration (CDNC), which is ICNC/CDNC, as a microphysical factor that induces differences in cloud development, its interactions with aerosols and impacts of ice processes on them among cases of mixed-phase clouds. This examination is performed using a large-eddy simulation (LES) framework and one of efforts toward a more general understanding of mechanisms controlling those development and impacts in mixed-phase clouds. For the examination, this study compares a case of polar mixed-phase clouds to that of midlatitude mixed-phase clouds with weak precipitation. It is found that ICNC/CDNC plays a critical role in making differences in cloud development with respect to the relative proportion of liquid and ice mass between the cases by affecting in-cloud latent-heat processes. Note that this proportion has an important implication for cloud radiative properties and thus climate. It is also found that ICNC/CDNC plays a critical role in making differences in clouds and their interactions with aerosols and impacts of ice processes on them between the cases by affecting in-cloud latent-heat processes. Findings of this study suggest that ICNC/CDNC can be a simplified general factor that contributes to a more general understanding of mixed-phase clouds and roles of ice processes and aerosols in them and thus, to the development of more general parameterizations of those clouds and roles.

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1. Introduction

It is well-known that stratiform clouds (e.g., stratus and stratocumulus clouds) have significant impacts on climate (Warren et al. 1986; Stephens and Greenwald 1991; Hartmann et al. 1992; Hahn and Warren 2007; Wood, 2012; Dione et al., 2019; Zheng et al., 2021). Since industrialization, there have been increases in aerosol concentrations and this has had impacts on stratiform clouds and climate (Twomey, 1974; Albrecht, 1989). However, our level of understanding of these clouds and impacts has been low and this has caused the highest uncertainty in the prediction of future climate (Ramaswamy et al., 2001; Forster et al., 2007; Knippertz et al., 2011; Hannak et al., 2017). Stratiform clouds can be classified into warm and mixed-phase clouds. Mixed-phase clouds involve ice processes and frequently form in midlatitude and polar regions. Most previous studies have focused on warm clouds and their interactions with aerosols, whereas the mixed-phase clouds and their interactions with aerosols are poorly understood mainly due to the more complex ice processes. Hence, mixed-phase clouds and their interactions with aerosols account for the uncertainty more than warm clouds and their interactions with aerosols (Ramaswamy et al., 2001; Forster et al., 2007; Wood, 2012; IPCC, 2021; Li et al., 2022).

It is known that the relative proportion of liquid mass, which can be represented by liquid-water content (LWC) or liquid-water path (LWP), and ice mass, which can be represented by ice-water content (IWC) or ice-water path (IWP), in mixed-phase stratiform clouds plays a critical role in cloud radiative properties and thus their climate feedbacks (Choi et al., 2010 and 2014). This is because radiative properties of liquid particles are substantially different from those of ice particles. The relative proportion is defined to be IWC (IWP) over LWC (LWP) or IWC/LWC (IWP/LWP) in this study. Motivated by this and the above-mentioned uncertainty, this study aims to improve our understanding of mixed-phase stratiform clouds and their interactions with aerosols with the emphasis on ice processes and IWC/LWC (or IWP/LWP).

Lee et al. (2022) have investigated mixed-phase stratocumulus clouds in a midlatitude region and found that microphysical latent-heat processes are more important in the development of mixed-phase clouds and their interactions with aerosols than entrainment and sedimentation processes. Lee et al. (2022) have found that a microphysical factor, the

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ratio of ice crystal number concentration (ICNC) to cloud droplet number concentration (CDNC) or ICNC/CDNC, play an important role in latent processes, the development of mixed-phase clouds and their interactions with aerosols. In particular, Lee et al. (2022) have found that IWC/LWC or IWP/LWP is strongly affected by ICNC/CDNC. This is because deposition (condensation) of water vapor occurs on the surface of ice crystals (droplets). Thus, they act as sources of deposition (condensation) and then IWC or IWP (LWC or LWP). More ice crystals (droplets) provide the greater integrated surface area of ice crystals (droplets) and induce more deposition (condensation) for a given environmental condition (Lee et al., 2009; Khain et al., 2012; Fan et al., 2018; Chua and Ming, 2020; Lee et al., 2022). Note that deposition and condensation are processes through which water vapor is removed, hence ice crystals and droplets are sinks of water vapor when deposition and condensation occur. However, when it comes to deposition and condensation themselves as microphysical processes, ice crystals (droplets) can be considered the sources of deposition and condensation. The higher ICNC/CDNC means more ice crystals or sources of deposition per a droplet as a source of condensation in a given group of ice crystals and droplets. Thus, the higher ICNC/CDNC enables more deposition per unit condensation to occur, which can raise IWC/LWC or IWP/LWP.

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). Lots of factors such as environmental conditions, which can be represented by variables such as stability, humidity and wind shear, can explain those differences. It is important to establish a general principle that explains the differences, since the general principle is useful in the development of a more general or comprehensive parameterization of stratocumulus clouds and their interactions with aerosols for climate models. This contributes to the better prediction of future climate, considering that the absence of the comprehensive parameterization has been considered one of the biggest obstacles to the better prediction (Ramaswamy et al., 2001; Foster et al., 2007; Stevens and Feingold, 2009). As a way of contributing to the establishment of the general principle, this study attempts to take ICNC/CDNC as a general factor, which can constitute the general principle, to explain the differences in IWC/LWC (or IWP/LWP) and aerosol-cloud interactions among clouds. This study also attempts to elucidate how ice processes differentiate mixed-phase clouds

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from warm clouds in terms of cloud development and its interactions with aerosols, and how this differentiation varies among cases of mixed-phase clouds with different ICNC/CDNC values. This attempt is valuable, considering that it is generally accepted that the establishment of the general principle for stratocumulus clouds has been progressed much less than that for other types of clouds such as convective clouds. The attempt is valuable, also considering that our level of understanding of how ice processes differentiate mixed-phase clouds and their interactions with aerosols from much-studied warm clouds and their interactions with aerosols has been low.

For the attempt, this study investigates a case of mixed-phased 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). Through this comparison, this study tests ICNC/CDNC as a general factor, which contributes to the establishment of the general principle, to explain the differences in IWC/LWC (or IWP/LWP) and aerosol-cloud interactions among cases of mixed-phased stratiform clouds. Through this comparison, this study also identifies how ICNC/CDNC contributes to different roles of ice processes in the differentiation between mixed-phase and warm clouds among cases of mixed-phase stratiform clouds.

2. Case, model and simulations

2.1 LES model

LES simulations are performed by using the Advanced Research Weather Research and Forecasting (ARW) model. A bin scheme, which is detailed in Khain et al. (2000) and Khain et al. (2011), is adopted by the ARW for the simulation of microphysics. Size distribution functions for each class of hydrometeors, which are classified into water drops, ice crystals (plate, columnar and branch types), snow aggregates, graupel and hail, and aerosols acting as cloud condensation nuclei (CCN) and ice-nucleating particles (INP) are

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represented with 33 mass doubling bins, i.e., the mass of a particle m_k in the kth bin is determined as $m_k = 2m_{k-1}$. Each of hydrometeors has its own terminal velocity that varies with the hydrometeor mass and the sedimentation of hydrometeors is simulated using their terminal velocity. The evolution of aerosol size distribution at each grid point is controlled by aerosol sinks and sources such as aerosol advection, turbulent mixing and activation. It is assumed that aerosols do not fall down by themselves and move around by airflow that is composed of horizontal flow, updrafts, downdrafts and turbulent motions. When aerosols move with airflow, it is assumed that they move with the same velocity as airflow. Taking activation as an example of the evolution of aerosol size distribution, the bins of the aerosol spectra that correspond to activated particles are emptied. Activated aerosol particles are included in hydrometeors and move to different classes and sizes of hydrometeors through collision-coalescence. In case hydrometeors with aerosol particles precipitate to the surface, those particles are removed from the atmosphere.

The large energetic turbulent eddies are directly resolved by the LES framework, and the effects of the smaller subgrid-scale turbulent motions on the resolved flow are parameterized based on the most widely used method that was proposed by Smagorinsky (1963) and Lilly (1967). In this method, the mixing time scale is defined to be the norm of the strain rate tensor (Bartosiewicz and Duponcheel, 2018). A cloud-droplet nucleation parameterization based on Köhler theory represents cloud-droplet nucleation. Arbitrary aerosol mixing states and aerosol size distributions can be fed to this parameterization. To represent heterogeneous ice-crystal nucleation, the parameterizations by Lohmann and Diehl (2006) and Möhler et al. (2006) are used. In these parameterizations, contact, immersion, condensation-freezing, and deposition nucleation paths are all considered by taking into account the size distribution of INP, temperature and supersaturation. Homogeneous aerosol (or haze particle) and droplet freezing is also considered following the theory developed by Koop et al. (2000).

The bin microphysics scheme is couped to the Rapid Radiation Transfer Model (RRTM; Mlawer et al., 1997). The effective sizes of hydrometeors, which are calculated in the bin scheme, are fed into the RRTM as a way of considering effects of the effective sizes on radiation. The surface process and resultant surface heat fluxes are simulated by the interactive Noah land surface model (Chen and Dudhia, 2001).

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2.2 Case and simulations

2.2.1 Case and standard simulations

In the Svalbard area, Norway, 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. The simulation of the observed system or case, i.e., the control run, is performed for the period on a three-dimensional domain of which horizontal extent is marked by a red rectangle in Figure 1. A100-m resolution is adopted by the horizontal domain in the control run. The length of the domain in the horizontal directions is 50 km. The length of the domain in the vertical direction is ~5 km and the resolution for the vertical domain gets coarsened with height from ~20 m just above the surface to ~ 100 m at the model top. Potential temperature, specific humidity, and wind as initial and boundary conditions, which represent synoptic-scale environment, for the control run are provided by reanalysis data that are produced by Met Office Unified Model (Brown et al., 2012) every 6 hours on a 0.11° × 0.11° grid. The control run employs an open lateral boundary condition. Figure 2 shows the vertical distribution of the domain-averaged potential temperature and humidity at the first time step. There is a neutral, mixed layer between the surface and 1 km in altitude as an initial condition (Figure 2).

There is a ground station in the domain (Tunved et al., 2013; Jung et al., 2018). This station measures the properties of cloud condensation nuclei (CCN) such as the number concentration, size distribution and composition. The measurement by the station 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.

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Aerosol effects on radiation before aerosol is activated are not taken into account for this study, since there is no significant amount of radiation absorbers in the mixture. Based on observation, the size distribution of aerosols acting as CCN is assumed to be a tri-modal log-normal distribution (Figure 3). The shape of distribution, which is a tri-modal log-normal distribution, as shown in Figure 3 is applied to the size distribution of aerosols acting as CCN in all parts of the domain during the whole simulation period. The assumed shape in Figure 3 is obtained by performing the average on the size distribution parameters (i.e., modal radius and standard deviation of each of nuclei, accumulation and coarse modes, and the partition of aerosol number among those modes) over the simulation period. It is assumed that the interpolated CCN concentrations do not vary with height in a layer between the surface and the planetary boundary layer (PBL) top around 1 km in altitude. However, above the PBL top, it is assumed that they decrease exponentially with height, although the shape of size distribution and composition do not change with height. It is assumed that there are no differences in the properties of INP and CCN except for concentrations. It is also assumed that the concentration of aerosols acting as CCN is 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). Hence, the concentration of aerosols acting as INP at the first time step is 2 cm^{-3} in the control run. This assumed concentration of aerosols acting as INP is higher than usual (Seinfeld and Pandis, 1998). However, Hartmann et al. (2021) observed the INP concentration that was higher than assumed here in the Svalbard area when there were strong dust events, meaning that the assumed INP concentration is not that unrealistic.

To examine effects of aerosols on mixed-phase clouds, the control run is repeated by increasing the concentration of aerosols by a factor of 10. In the repeated (control) run, the initial concentrations of aerosols acting as CCN and INP at grid points immediately above the surface are 2000 (200) and 20 (2) cm^{-3}, respectively. Reflecting these concentrations in the simulation name, the control run is referred to as "the 200_2 run" and the repeated run is referred to as "the 2000_20 run". To isolate effects of aerosols acting as CCN (INP) on mixed-phase clouds, the control run is repeated again by increasing the concentration of aerosols acting as CCN (INP) only but not INP (CCN) by a factor of 10. In this repeated run with the increase in the concentration of aerosols acting as CCN (INP), the initial

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concentrations of aerosols acting as CCN and IFN at grid points immediately above the surface are 2000 (200) and 2 (20) cm^{-3}, respectively. Reflecting this, the repeated run is referred to as "the 2000_2 (200_20) run".

2.2.2 Additional simulations

To isolate impacts of ice processes on the adopted case and its interactions with aerosols, the 200_2 and 2000_2 runs are repeated by removing ice processes. These repeated runs are referred to as the 200_2_noice and 2000_2_noice runs. In the 200_2_noice and 2000_2_noice runs, all hydrometeors (i.e., ice crystals, snow, graupel, and hail), phase transitions (e.g., deposition and sublimation) and aerosols (i.e., INP) which are associated with ice processes are removed. Hence, in these runs, only droplets (i.e., cloud liquid), raindrops, associated phase transitions (e.g., condensation and evaporation) and aerosols acting as CCN are present, regardless of temperature. Stated differently, these noice runs simulate the warm-cloud counterpart of the selected mixed-phase cloud system. Via comparisons between a pair of the 200_2 and 2000_2 runs and a pair of the 200_2_noice and 2000_2_noice runs, the role of ice processes in the differentiation between mixed-phase and warm clouds is to be identified. Along with this identification, the role of the interplay between ice crystals and droplets in the development of the selected mixed-phase cloud system and its interactions with aerosols is to be isolated.

As detailed in Sections 3.1.2 and 3.2.2 below, the test of ICNC/CDNC as a general factor requires more simulations to see impacts of ICNCavg/CDCNavg on clouds and their interactions with aerosols. Here, ICNCavg (CDNCavg) represents the average ICNC (CDNC) over grid points and time steps with non-zero ICNC (CDNC). ICNCavg/CDNCavg represents overall ICNC/CDNC over the domain and simulation period. To respond to this requirement, 200_2_fac10, 200_2_fac10_CCN10, 200_2_fac10_INP10 runs are performed and their details are given in Sections 3.1.2 and 3.2.2. The summary of simulations in this study is given in Table 1.

3. Results

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3.1 The 200_2 run vs. the 200_2_noice run

The time- and domain-averaged IWP (IWC) is ~one order of magnitude greater than LWP (LWC) in the 200_2 run (Figure 4 and Table 2). For the sake of simplicity, the averaged IWC (IWP) over the averaged LWC (LWP) is denoted by IWC (IWP)/LWC (LWP), henceforth. IWC/LWC and IWP/LWP are 26.28 and 25.96, respectively, in the 200_2 run. Since IWP and LWP are vertically integrated IWC and LWC over the vertical domain, respectively, the qualitative nature of differences between IWC and LWC is not much different from that between IWP and LWP.

To understand process-level mechanisms that control the results, microphysical processes are analyzed. As indicated by Ovchinnikov et al. (2011), in clouds with weak precipitation, there is a high-degree correlation between IWC (IWP) and deposition or between LWC (LWP) and condensation, considering that deposition and condensation are sources of IWC (IWP) and LWC (LWP), respectively. In the 200_2 run, the surface precipitation rate is ~0.0020 mm hr^{-1}, which can be considered weak. Hence, in this case, condensation and deposition are considered proxies for IWC (IWP) and LWC (LWP), respectively. Based on this, to gain a process-level understanding of microphysical processes that control the simulated IWC (IWP) or LWC (LWP), condensation and deposition are analyzed.

As seen in Figure 5 and Table 2, the average deposition rate is ~one order of magnitude greater than condensation rate in the 200_2 run, leading to much greater IWC (IWP) than LWC (LWP) in the 200_2 run. This is in contrast to the situation in the case of mixed-phase stratocumulus clouds, which were located in a midlatitude region, in Lee et al. (2022). In this case, the average IWC (IWP) and LWC (LWP) are at the same order of magnitude. For the sake of brevity, this case in Lee et al. (2022) is referred to as "the midlatitude case", while the case of mixed-phase clouds, which is adopted by this study, in the Svalbard area is referred to "the polar case", henceforth. In the midlatitude case, IWC/LWC and IWP/LWP are 1.55 and 1.57, respectively, which are ~ one order of magnitude smaller than those in the polar case.

Warm clouds in the 200_2_noice run shows that the time- and domain-averaged condensation rate that is lower than the time- and the domain-averaged sum of

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condensation and deposition rates in the 200_2 run (Figure 5 and Table 2). This leads to a situation where warm clouds in the 200_2_noice run shows the time- and domain-averaged LWC that is lower than the time- and domain-averaged water content (WC), which is the sum of IWC and LWC, in mixed-phase clouds in the 200_2 run (Figure 4 and Table 2). Associated with this, the time- and domain-averaged LWP in the 200_2_noice run is lower than the time- and domain-averaged water path (WP), which is the sum of IWP and LWP, in the 200_2 run (Table 2). This is despite the fact that LWC and LWP in the 200_2_noice run are higher than LWC and LWP, respectively, in the 200_2 run (Figure 4 and Table 2). Here, WC (WP) represents the total cloud mass in mixed-phase clouds, while LWC (LWP) alone represents the total cloud mass in warm clouds. These results are also in contrast to the situation in the midlatitude case. The total cloud mass in warm clouds, which are generated by removing ice processes in the midlatitude case, is greater than that in the midlatitude case.

It should be noted that the average rate of sedimentation of droplets over the cloud base and simulation period reduces from the 200_2_noice run to the 200_2 run (Table 2). This is mainly due to the decrease in LWC or LWP from the 200_2_noice run to the 200_2 run. The average rate of sedimentation of ice crystals over the cloud base and simulation period increases from the 200_2_noice run to the 200_2 run, since there is no sedimentation of ice crystals in the 200_2_noice run (Table 2). The average entrainment rate over the cloud top and simulation period increases from the 200_2_noice run to the 200_2 run (Table 2). Hence, the droplet sedimentation tends to increase the total cloud mass in the 200_2 run, and the ice-crystal sedimentation and entrainment tend to reduce the total cloud mass in the 200_2 run, as compared to that in the 200_2_noice run. This means that the droplet sedimentation contributes to increase in the total cloud mass from the 200_2_noice run to the 200_2 run, while entrainment and the ice-crystal sedimentation counter the increase. Thus, entrainment and the ice-crystal sedimentation should be opted out when it comes to mechanisms leading to the increase in the total cloud mass. Here, the vertical integration of each of condensation and deposition rates is obtained over each cloudy column in the domain for each of the runs. For the sake of the brevity, this vertical integration of condensation (deposition) rate is referred to as the integrated condensation (deposition) rate. Then, each of the integrated condensation and deposition rates is

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averaged over cloudy columns and the simulation period. It is found that the change in the average rate of the droplet sedimentation over the cloud base and simulation period from the 200_2_noice run to the 200_2 run is ~five to six orders of magnitude smaller than that in the sum of the average integrated condensation rate and the average integrated deposition rate (Table 2). Thus, condensation and deposition, but not the droplet sedimentation, are main factors controlling differences in cloud mass in cloudy columns, which is represented by LWP, IWP, and associated LWC and IWC, and in the total cloud mass between the 200_2 and 200_2_noice runs as are between the midlatitude case and its warm-cloud counterpart.

3.1.1 Hypothesis

We hypothesized that ICNC/CDNC can be an important factor that determines above-described differences between the polar and midlatitude cases. Remember that there are more ice crystals as sources of deposition per a droplet when ICNC/CDNC is higher. Thus, when ICNC/CDNC is higher and qv > qsw, there is a higher possibility that more portion of water vapor is deposited onto ice crystals by stealing water vapor, which is supposed to be condensed onto droplets, from droplets in an air parcel. Here, qv and qsw represent water-vapor pressure and water-vapor saturation pressure for liquid water or droplets, respectively. When ICNC/CDNC is higher and qsi< qv <qsw, there are more ice crystals that can absorb water vapor, including that which is produced by droplet evaporation, per a droplet; here, qsi represents water-vapor saturation pressure for ice water or ice crystals. Thus, with higher ICNC/CDNC, there is a higher possibility that more portion of water vapor is deposited onto ice crystals in an air parcel as shown in Lee et al. (2022).

ICNCavg/CDNCavg is 0.22 in the control run (i.e., the 200_2 run) for the polar case and 0.019 in the control run for the midlatitude case which is described in Lee et al. (2022). Henceforth, the control run for the midlatitude case is referred to as the control-midlatitude run. ICNCavg/CDNCavg is ~one order of magnitude higher for the polar case than for the midlatitude case. This is despite the fact that the ratio of the initial number concentration of aerosols acting as INP to that of acting as CCN is identical between the 200_2 and control-midlatitude runs. This is mainly due to the fact that ice nucleation strongly depends

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on air temperature (Prappucher and Klett, 1978). When supercooling is stronger, in general, there is more nucleation of ice crystals for a given group of aerosols acting as INP. The average air temperature immediately below the cloud base over the simulation period is -16 ºC in the 200_2 run and -5 ºC in the control-midlatitude run. The average air temperature immediately above the cloud top is -33 ºC in the 200_2 run and -15 ºC in the control-midlatitude run. Hence, there is more supercooling which contributes to the higher ICNCavg/CDNCavg in the polar case than in the midlatitude case. The higher ICNCavg/CDNCavg is likely to induce more portion of water vapor to be deposited onto ice crystals in the polar case than in the midlatitude case. It is hypothesized that this in turn enables IWC/LWC or IWP/LWP in the 200_2 run to be one order of magnitude greater than that in the control-midlatitude run. Higher IWC/LWC (IWP/LWP) results in WC (WP) in the 200_2 run which is greater than LWC (LWP) in the warm clouds in the 200_2_noice run, while lower IWC/LWC (IWP/LWP) results in WC (WP) in the midlatitude mixed-phase clouds which is lower than LWC (LWP) in their warm-cloud counterpart. This means that with higher ICNC/CDNC, IWC/LWC and IWP/LWP, 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, with lower ICNC/CDNC, IWC/LWC and IWP/LWP, ice processes reduce the total cloud mass as compared to that for the midlatitude warm-cloud counterpart.

3.1.2 Role of ICNC/CDNC

To test the hypothesis above about the role of ICNC/CDNC in above-described differences between the polar and midlatitude cases, the 200_2 run is repeated by reducing ICNCavg/CDNCavg by a factor of 10. This is done by reducing the concentration of aerosols acting as INP but not CCN in a way that ICNCavg/CDNCavg is lower by a factor of 10 in the repeated run than in the 200_2 run. In this way, this repeated run has ICNCavg/CDNCavg at the same order of magnitude as that in the control-midlatitude run. This repeated run is referred to as the 200_2_fac10 run. As shown in Figure 6 and Table 2, the 200_2_fac10 run shows much lower deposition rate, IWC and IWP than the 200_2 run does. However, as we move from the 200_2 run to the 200_2_fac10 run, the time- and

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domain-averaged condensation rate, LWC and LWP increases (Figure 6 and Table 2). This is because reduction in deposition increases the amount of water vapor, which is not consumed by deposition but available for condensation. Associated with this, in the 200_2_fac10 run, the time- and domain-averaged deposition rate, IWC and IWP become similar to the average condensation rate, LWC and LWP, respectively (Figure 6 and Table 2). Hence, IWC/LWC and IWP/LWP reduce from 26.28 and 25.96 in the 200_2 run to 1.05 and 1.02, respectively, in the 200_2_fac10 run. Here, IWC/LWC and IWP/LWP in the 200_2_fac10 run are similar to those in the midlatitude-control run, which demonstrate that the difference in ICNC/CDNC is able to explain the difference in IWC/LWC and IWP/LWP between the polar and midlatitude cases. It is notable that the reduction in deposition is dominant over the increase in condensation with the decrease in ICNCavg/CDNCavg. Hence, the sum of condensation and deposition rates, WC and WP reduce from the 200_2 run to the 200_2_fac10 run. It is also notable that the sum of condensation and deposition rates, WC and WP reduce in a way that the sum, WC and WP in the mixed-phase clouds in the 200_2_fact10 run are lower than condensation rate, LWC and LWP in the warm clouds in the 200_2_noice run, respectively (Figure 6 and Table 2). This is similar to the situation in the midlatitude case and thus demonstrates that the different relation between the mixed-phase and warm clouds can be explained by the difference in ICNC/CDNC between the polar and midlatitude cases.

The rate of the sedimentation of ice crystals at the cloud base reduces as ICNCavg/CDNCavg reduces between the 200_2 and 200_2_fac10 runs, mainly due to reduction in the ice-crystal mass (Table 2). The rate of droplet sedimentation at the cloud base increases as ICNCavg/CDNCavg reduces mainly due to increases in droplet mass and size in association with the increases in LWC and LWP (Table 2). The entrainment rate at the cloud top reduces as ICNCavg/CDNCavg reduces (Table 2). Hence, the changing sedimentation tends to reduce LWC or LWP and increase IWC or IWP, while the changing entrainment tends to increase the total cloud mass, WC or WP with the reducing ICNCavg/CDNCavg. Hence, changes in the sedimentation counter the increase in LWC or LWP, and the decrease in IWC or IWP with the reducing ICNCavg/CDNCavg. Changes in the entrainment counters the decrease in WC or WP with the reducing ICNCavg/CDNCavg between the 200_2 and 200_2_fac10 runs. Here, we see that changes

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in the sedimentation and entrainment are not factors that lead to the increase in LWC or LWP, and the decrease in IWC or IWP, and eventually the decrease in WP with the reducing ICNCavg/CDNCavg. The analysis of the sedimentation and entrainment exclude them from factors inducing above-described differences between the 200_2 and 200_2_fac10 runs. Instead, this analysis grants more confidence in the fact that deposition and condensation, which are strongly dependent on ICNC/CDNC, are main factors inducing those differences.

3.2 Aerosol-cloud interactions

Comparisons between the 200_2 and 2000_20 runs show that with the increasing concentration of both of aerosols acting as CCN and those as INP, there are increases in IWC and IWP but decreases in LWC and LWP in the polar case (Figures 7 and Table 2). These decreases in LWC and LWP are negligible as compared to these increases in IWC and IWP. Hence, the increases in IWC and IWP outweigh the decreases in LWC and LWP, leading to aerosol-induced increases in WC and WP, respectively (Figures 7 and Table 2). To identify roles of specific types of aerosols in these aerosol-induced changes, comparisons not only between the 200_2 and 200_20 runs but also between the 200_2 and 2000_2 runs are performed. Comparisons between the 200_2 and 200_20 runs show that the increasing concentration of aerosols acting as INP induces increases in IWC and IWP but decreases in LWC and LWP (Figure 7 and Table 2). The magnitudes of these increases and decreases are similar to those between the 200_2 and 2000_20 runs (Figure 7 and Table 2). However, comparisons between the 200_2 and 2000_2 runs show that the increasing concentration of aerosols acting as CCN induces negligible changes in either a pair of IWC and IWP or a pair of LWC and LWP. Thus, there are negligible CCN-induced changes in the total cloud mass, although the increasing concentration of aerosols acting as CCN induces a slight decrease in IWC and IWP, and a slight increase in LWC and LWP (Figure 7 and Table 2). This demonstrates that INP plays a much more important role than CCN when it comes to the response of the liquid, ice and total cloud mass to increasing aerosol concentrations. However, in the midlatitude case, the increasing concentration of aerosols

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acting as CCN generates changes in the mass as significantly as the increasing concentration of aerosols acting as INP does.

To identify roles played by ice processes in aerosol-cloud interactions, a pair of the 200_2_noice and 2000_2_noice runs are analyzed and compared to the previous four standard simulations (i.e., the 200_2, 200_20, 2000_2 and 2000_20 runs). The CCN-induced increases in LWC and LWP in those noice runs are much greater than the CCN-induced changes in WC and WP, respectively, in the 200_2 and 2000_2 runs (Figure 7 and Table 2). However, these CCN-induced increases in LWC and LWP in the noice runs are smaller than the INP-induced increases in WC and WP, respectively, in the 200_2 and 200_20 runs. This is different from the midlatitude case where changes in the total cloud mass, whether they are induced by the increasing concentration of aerosols acting as CCN or INP, in the mixed-phase clouds are much lower than those CCN-induced changes in the warm clouds.

3.2.1 Deposition, condensation, sedimentation and entrainment

There are the CCN-induced negligible increases (decreases) in condensation (deposition) rate, leading to the CCN-induced negligible increases (decreases) in LWC and LWP (IWC and IWP) between the 200_2 and 2000_2 runs (Figure 7 and Table 2). However, between the 200_2 and 200_20 runs, there are rather the significant INP-induced increases in deposition rate, leading to the significant INP-induced increases in IWC and IWP (Figure 7 and Table 2). Between the 200_2 and 200_20 runs, there are negligible INP-induced decreases in condensation rate, leading to the negligible INP-induced decreases in LWC and LWP, as compared to the INP-induced increases in deposition rate, IWC and IWP (Figure 7 and Table 2). With the increasing concentration of aerosols acting as INP from the 200_2 run to the 200_20 run, there are decreases in the sedimentation of ice crystals at the cloud base (Table 2). This is mainly due to decreases in the size of ice crystals in association with increases INP and resultant increases in ICNC. From the 200_2 run to the 200_20 run, there are decreases in the sedimentation of droplets at the cloud base as shown in Table 2, mainly due to decreases in LWC or LWP. From the 200_2 run to the 200_20 run, there are increases in the entrainment at the cloud top (Table 2). Hence, the INP-

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induced changes in the sedimentation contribute to the INP-induced increases in IWC or IWP but counter the INP-induced reduction in LWC or LWP. The entrainment counters the INP-induced increases in WC or WP. Hence, we see that changes in entrainment and the droplet sedimentation are not factors that lead to the INP-induced increases in WC (WP) and decreases in LWC (LWP), respectively. The INP-induced increases in deposition and decreases in the sedimentation of ice crystals both contribute to the INP-induced increases in IWC and IWP. However, the INP-induced changes in the average integrated deposition rate over cloudy columns and the simulation period is ~ four orders of magnitude greater than those in the average rate of ice-crystal sedimentation at the cloud base and simulation period (Table 2). Hence, the role of the ice-crystal sedimentation in the INP-induced changes in IWC and IWP is negligible as compared to that of deposition.

In the warm clouds in the 200_2_noice and 2000_2_noice runs, there are the CCN-induced increases in condensation rate, leading to those in LWC and LWP (Figure 7 and Table 2). However, the CCN-induced increases in condensation rate in the warm clouds associated with the polar case are lower than the INP-induced increases in deposition rate in the polar case (Table 2). This contributes to aerosol-induced smaller changes in the total cloud mass in the polar warm clouds than in the polar mixed-phase clouds. The sedimentation of droplets at the cloud base reduces and the entrainment at the cloud top increases from the 200_2_noice run to 2000_2_noice run (Table 2). The increasing concentration of aerosols acting as CCN induces increases in CDNC and decreases in the droplet size, leading to the reduction in the droplet sedimentation from the 200_2_noice run to 2000_2_noice run. The CCN-induced changes in the sedimentation contribute to the CCN-induced increases in LWC and LWP. The entrainment counters the CCN-induced increases in LWC or LWP. Hence, the entrainment is not a factor which induces the CCN-induced increases in LWC or LWP between the 200_2_noice and 2000_2_noice runs. As seen in Table 2, the CCN-induced changes in the sedimentation rate are ~ three orders of magnitude smaller than those in the integrated condensation rate. Hence, the role of sedimentation in changes in LWP or WP between the 200_2_noice and 2000_2_noice runs is negligible as compared to that of condensation.

3.2.2 Understanding differences between the polar and midlatitude cases

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Roughly speaking, the CCN-(INP-)induced changes in LWC (IWC) or LWP (IWP) via CCN-(INP-)induced changes in autoconversion of droplets (ice crystals) are proportional to LWC (IWC) or LWP (IWP) that changing CCN (INPs) affect (e.g., Liu and Daum (2004); Kogan (2013); Lee and Baik (2017); Dudhia, 1989; Lim and Hong, 2010; Mansell et al. 2010). This is for given environmental conditions (e.g., temperature and humidity) and given CCN-(INP-)induced changes in microphysical factors such as sizes and number concentrations of droplets (ice crystals). Hence, in the polar case, with a given much lower LWC (LWP) than IWC (IWP), the changing concentration of aerosols acting as CCN is likely to induce smaller changes in the given LWC (LWP) via CCN impacts on the droplet autoconversion. This is as compared to changes in the given IWC or IWP which are induced by the changing concentration of aerosols acting as INP and thus changing ice-crystal autoconversion.

The smaller (larger) changes in the given LWC or LWP (IWC or IWP) are related to changes in CDNC (ICNC), which are initiated by those in droplet (ice crystal) autoconversion, and associated integrated droplet (ice-crystal) surface area. Remember that condensation (deposition) occurs on droplet (ice-crystal) surface and thus droplets (ice crystals) act as a source of condensation (deposition). Hence, those changes in CDNC (ICNC) and integrated droplet (ice-crystal) surface area can lead to changes in condensation (deposition) and thus feedbacks between condensation (deposition) and updrafts. The smaller CCN-induced changes in LWC or LWP involve changes in CDNC and associated smaller changes in condensation and associated feedbacks between condensation and updrafts in the polar case. This is as compared to changes in deposition and feedbacks between deposition and updrafts which are associated with the INP-induced changes in ICNC and the related larger INP-induced changes in IWC and IWP in the polar case. The smaller CCN-induced changes in LWC (or LWP) involve smaller changes in water vapor that is consumed by droplets in the polar case. The larger INP-induced changes in IWC (or IWP) involve larger changes in water vapor that is consumed by ice crystals in the polar case. This leaves the CCN-induced smaller changes in the amount of water vapor available for deposition, which induce the smaller CCN-induced changes in IWC and IWP in the polar case. This is as compared to the INP-induced changes in the amount of water

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vapor which is available for condensation and associated changes in LWC or LWP in the polar case. The lower LWC (LWP) in the polar warm clouds than IWC (IWP) in the polar case contributes to the INP-induced greater changes in IWC (IWP) than the CCN-induced changes in LWC (LWP) in the polar warm clouds. The lower LWC (LWP) in the polar case than that in the polar warm clouds contributes to the CCN-induced greater changes in LWC (LWP) in the polar warm clouds than those in LWC (LWP) and subsequent changes in IWC (IWP) in the polar case.

In contrast to the situation in the polar case, in the midlatitude case, remember that a given LWC (LWP) is at the same order of magnitude of IWC (IWP). Hence, the CCN-induced changes in LWC (LWP) and subsequent changes in IWC (IWP) are similar to the INP-induced changes in IWC (IWP) and subsequent changes in LWC (LWP). The greater LWC (LWP) in the midlatitude warm cloud than both of LWC (LWP) and IWC (IWP) in the midlatitude case contributes to the greater CCN-induced changes in LWC (LWP) in the midlatitude warm cloud. This is as compared to either the CCN-induced changes in LWC (LWP) and subsequent changes in IWC (IWP) or the INP-induced changes in IWC (IWP) and subsequent changes in LWC (LWP) in the midlatitude case.

To confirm above-described mechanisms in this section, which explain different aerosol-cloud interactions between the polar and midlatitude cases, the 200_2_fac10 run is repeated by increasing INP by a factor of 10 in the PBL at the first time step. This repeated run is referred to as “the 200_2_fac10_INP10 run. Then, the 200_2_fac10 run is repeated again by increasing CCN by a factor of 10 in the PBL at the first time step. This repeated run is referred to as the 200_2_fac10_CCN10 run. These repeated runs are to see the response of IWC, IWP, LWC and LWP to the increasing concentration of aerosols acting as INP and CCN. This is when IWC (IWP) and LWC (LWP) are at the same order of magnitude and lower in mixed-phase clouds than LWC (LWP) in the warm-cloud counterpart as in the 200_2_fac10 run and midlatitude case. Comparisons between the 200_2_fac10, 200_2_fac10_INP10 and 200_2_fac10_CCN10 runs show that the INP-induced changes in IWC (IWP) and LWC (LWP) are at the same order of magnitude of the CCN-induced changes in IWC (IWP) and LWC (LWP), respectively, as in the midlatitude case. These comparisons also show that the CCN-induced changes in LWC (LWP) in the polar warm cloud are greater. This is as compared to either the CCN-induced changes in

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LWC (LWP) and subsequent changes in IWC (IWP) between the 200_2_fac10 and 200_2_fac10_CCN10 runs or the INP-induced changes in IWC (IWP) and subsequent changes in LWC (LWP) between the 200_2_fac10 and 200_2_fac10_INP10 runs. These comparisons demonstrate that differences in ICNC/CDNC play a critical role in differences in aerosol-cloud interactions between the polar and midlatitude cases, considering that differences in ICNC/CDNC between the 200_2 and 200_2_fac10 runs are at the same order of magnitude of that between the cases.

5. Summary and conclusions

In this study, a case of mixed-phase clouds in a polar area, which is referred to as "the polar case" is compared to that in a midlatitude area, which is referred to as "the midlatitude case". This is to gain an understanding of how different ICNC/CDNC plays a role in making differences in cloud properties, their interactions with aerosols and impacts of ice processes on them between two representative areas (i.e., polar and midlatitude areas) where mixed-phase stratiform clouds form and develop. Among those cloud properties, this study focuses on is IWC/LWC or IWP/LWP that plays an important role in cloud radiative properties.

Due to lower air temperature, more ice crystals are nucleated, leading to higher ICNC/CDNC in the polar case than in the midlatitude case. This higher ICNC/CDNC enables the more efficient deposition of water vapor onto ice crystals in the polar case. This leads to much higher IWC/LWC or IWP/LWP in the polar case. The more efficient deposition of water vapor onto ice crystals enables the polar mixed-phase clouds to have the greater total cloud mass than the polar warm clouds. However, the less efficient deposition of water vapor onto ice crystals causes the midlatitude mixed-phase clouds to have less total cloud mass than the midlatitude warm clouds. With the increasing ICNC/CDNC from the midlatitude case to the polar case, impacts of CCN (IFN) on the total cloud mass become less (more) important.

This study picked ICNC/CDNC, which is affected by air temperature and its impacts on ice-crystal nucleation, as an important factor which differentiates interactions among cloud properties, aerosols and ice processes in the polar area from those in the midlatitude

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area. Differences in ICNC/CDNC initiate differences in the microphysical properties (e.g., the integrated surface area), and then, subsequently induce those in thermodynamic latent-heat processes (e.g., condensation and deposition), dynamics of clouds and interactions among clouds, aerosols and ice processes. However, this does not mean that there are no other potential factors which can explain the variation of cloud properties and interactions among those properties, aerosols and ice processes between those areas. For example, differences in environmental factors (e.g., stability and wind shear) between the areas can have impact on the variation. Particularly, differences in stability and wind shear can initiate those in the dynamic development of turbulence. Then, this subsequently induces differences in the microphysical and thermodynamic development of clouds and interactions among clouds, aerosols and ice processes. Hence, factors such as stability and wind shear can have different orders of procedures, which involve dynamics, thermodynamics and microphysics, than ICNC/CDNC in terms of differentiation between the polar and midlatitude mixed-phase clouds. Thus, different mechanisms controlling the differentiation can be expected regarding factors such as stability and wind shear as compared to ICNC/CDNC. The examination of these different mechanisms among stability, wind shear and ICNC/CDNC deserves future study for more comprehensive understanding of the differentiation.

Another point to make is that the cases in this study have weak precipitation and the associated weak sedimentation of ice crystals and droplets. In mixed-phase clouds with strong precipitation and the sedimentation, they can play roles as important as in-cloud latent-heat processes in cloud development, interactions among clouds, aerosols and ice processes, and their variation among different cases of mixed-phase clouds. Hence, in those clouds with strong precipitation, the sedimentation can take part in the interplay between ICNC/CNDC and latent-heat processes, and play a role in the differentiation of cloud properties and interactions among those properties, aerosols and ice processes when it comes to different cases of mixed-phase clouds. For more generalization of results here, this potential role of sedimentation needs to be investigated by performing more case studies involving cases with strong precipitation in the future.

It should be emphasized that although this study mentions air temperature as a factor that affects ICNC/CDNC, ICNC/CDNC can be affected by other factors such as sources of

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aerosols acting as INP and those acting as CCN, and/or the advection of those aerosols. Hence, even for cloud systems that develop with a similar air-temperature condition, for example, when those systems are affected by different sources of aerosols and/or their advection, they are likely to have different ICNC/CDNC, IWP/LWP and relative importance of impacts of INP and CCN on IWP and LWP.

This study suggests that differences in IWP/LWP and the relative importance of the impacts of INP and CCN on IWP and LWP among different systems of stratocumulus clouds can be explained by a microphysical factor, which is ICNC/CDNC. This factor can be a simplified and useful tool to understand differences among those different systems in terms of IWP/LWP and the relative importance of INP and CCN in aerosol-cloud interactions. This factor can also be a useful tool for a simplified understanding of different roles of ice processes when mixed-phase clouds are compared to their warm-cloud counterparts in terms of the cloud development and its interactions with aerosols among those different systems. It should be noted that warm clouds have been studied much more than mixed-phase clouds, although mixed-phase clouds play as important roles as warm clouds in the evolution of climate and its change. This study provides preliminary mechanisms which differentiate mixed-phase clouds and their interactions with aerosols from their warm-cloud counterparts as a way of improving our understanding of mixed-phase clouds. It should be mentioned that the efficient way of developing general parameterizations, which are for climate models and consider all of warm, mixed-phase clouds and their interactions with aerosols, can be achieved by just adding those mechanisms to pre-existing parameterizations of warm clouds instead of developing brand new parameterizations from the scratch. Hence, although those mechanisms identified in this study may not be complete, they can act as a valuable building block that can streamline the development of general parameterizations.

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Code/Data source and availability

Our private computer system stores the code/data which are private and used in this study. Upon approval from funding sources, the data will be opened to the public. Projects related to this paper have not been finished, thus, the sources prevent the data from being open to the public currently. However, if information on the data is needed, contact the corresponding author Seoung Soo Lee (slee1247@umd.edu).

Author contributions

Essential initiative ideas are provided by SSL, CHJ and YJY to start this work. Simulation and observation data are analyzed by SSL, CHJ and JU. YZ, JP, MGM and SKS review the results and contribute to their improvement.

Competing interests

The authors declare that they have no conflict of interest.

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FIGURE CAPTIONS

Figure 1. A red rectangle marks the simulation domain in the Svalbard area, Norway. The light blue represents the ocean and the green the land area.

Figure 2. The vertical distributions of the domain-averaged potential temperature and humidity at the first time step.

Figure 3. Aerosol size distribution at the surface. N represents aerosol number concentration per unit volume of air and D represents aerosol diameter.

Figure 4. The vertical distributions of the time- and domain-averaged IWC and LWC in the 200_2 and 200_2_noice runs.

Figure 5. The vertical distributions of the time- and domain-averaged deposition and condensation rates in the 200_2 and 200_2_noice runs.

Figure 6. The vertical distributions of the time- and domain-averaged IWC and LWC in the 200_2, 200_2_noice and 200_2_fac10 runs.

Figure 7. The vertical distributions of the time- and domain-averaged (a) IWC and (b) LWC in the 200_2, 2000_20, 200_2_fac10, 200_20, 2000_2, 200_2_fac10_CCN10, and 200_2_fac10_INP10 runs.

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Simulations	The number concentration of aerosols acting as CCN at the first time step in the PBL (cm^{-3})	The number concentration of aerosols acting as INP at the first time step in the PBL (cm^{-3})	ICNCavg/CDNCavg	Ice processes
200_2	200	2	0.220	Present
2000_20	2000	20	0.201	Present
2000_2	2000	2	0.108	Present
200_20	200	20	0.512	Present
200_2_noice	200	2	0.000	Absent
2000_2_noice	2000	2	0.000	Absent
200_2_fac10	200	0.07	0.022	Present
200_2_fac10_CCN10	2000	0.07	0.012	Present
200_2_fac10_INP10	200	0.7	0.041	Present

Table 1. Summary of simulations

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Simulations	IWC (10^{-3} g m^{-3})	LWC (10^{-3} g m^{-3})	IWP (g m^{-2})	LWP (g m^{-2})	IWC/LWC	IWP/LWP	Condensation rate		Deposition rate		Cloud-base sedimentation (10^{-3} g m^{-2} s^{-1})		Entrainment (cm s^{-1})
							Over grid points (10^{-2} g m^{-3} s^{-1})	Over cloudy columns (g m^{-2} s^{-1})	Over grid points (10^{-2} g m^{-3} s^{-1})	Over cloudy columns (g m^{-2} s^{-1})	Ice-crystal	Droplet	
200_2	6.57	0.25	31.94	1.23	26.28	25.96	0.11	1.98	1.30	23.40	1.17	0.17	0.25
2000_20	7.82	0.21	40.91	1.08	37.24	37.91	0.09	1.62	1.57	28.26	0.94	0.06	0.53
2000_2	6.55	0.29	31.85	1.46	22.58	21.81	0.12	2.16	1.28	23.04	1.11	0.08	0.28
200_20	7.80	0.20	40.82	1.01	39.00	40.42	0.09	1.62	1.56	28.08	0.97	0.11	0.51
200_2_noice	0.00	2.06	0.00	10.35	0.00	0.00	0.72	12.48	0.00	0.00	0.00	0.36	0.08
2000_2_noice	0.00	2.25	0.00	11.29	0.00	0.00	0.76	12.80	0.00	0.00	0.00	0.14	0.10
200_2_fac10	0.89	0.85	4.27	4.20	1.05	1.02	0.32	5.76	0.35	6.30	0.19	0.28	0.06
200_2_fac10_CCN10	0.79	0.97	3.82	4.83	0.81	0.79	0.38	6.84	0.31	5.58	0.17	0.19	0.07
200_2_fac10_INP10	0.98	0.78	4.73	3.88	1.25	1.22	0.31	5.58	0.39	7.02	0.14	0.22	0.07

Table 2. The averaged IWC, LWC, IWP, LWP, condensation and deposition rates over all of grid points and the simulation period in each of simulations. IWC/LWC (IWP/LWP) is the averaged IWC (IWP) over the averaged LWC (LWP). Also, as shown are the vertically integrated condensation and deposition rates over each cloudy column which are averaged over those columns and the simulation period. The average cloud-base sedimentation rate, which is for each of ice crystals and droplets, over the cloud base and simulation period, and the average cloud-top entrainment rate over the cloud top and simulation period are shown as well.

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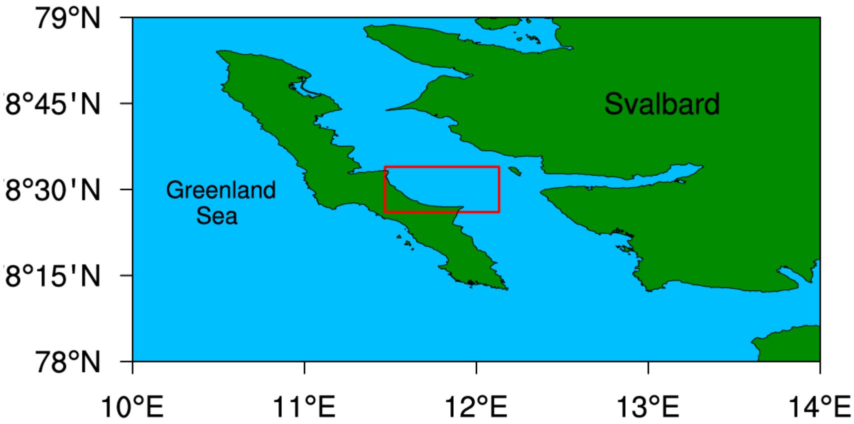

Figure 1

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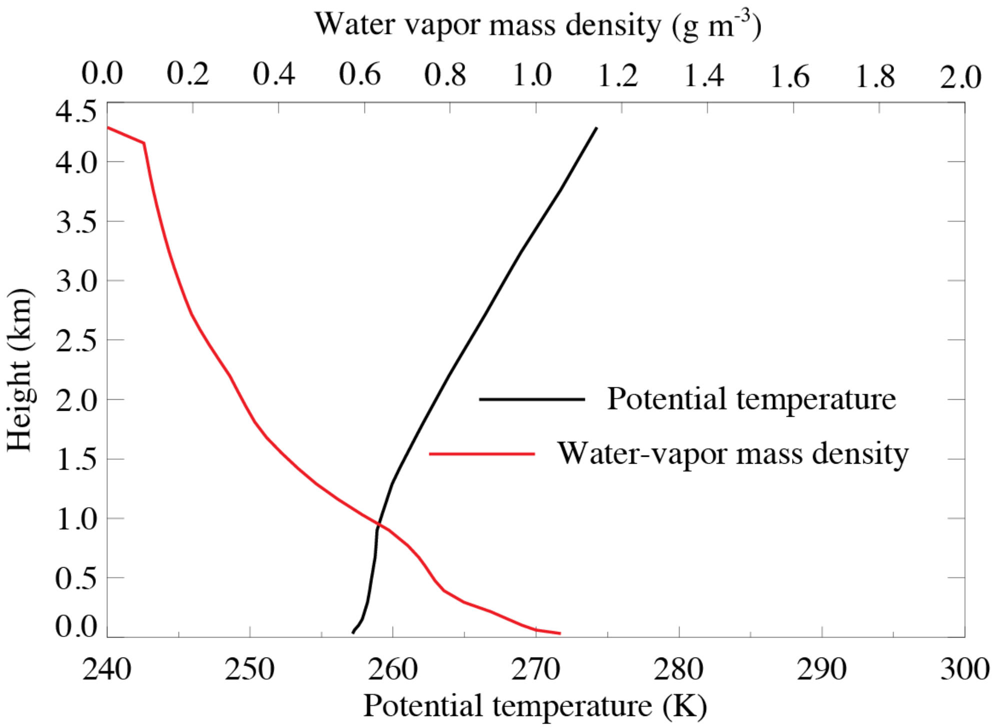

Figure 2

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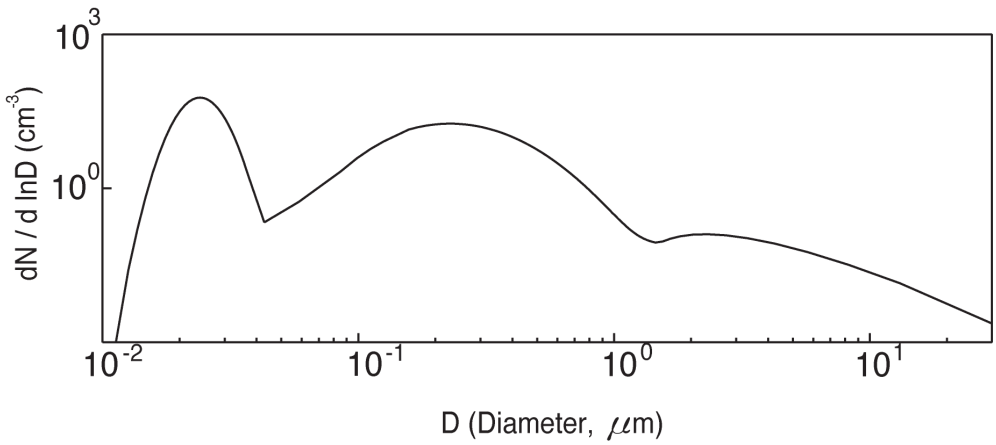

Figure 3

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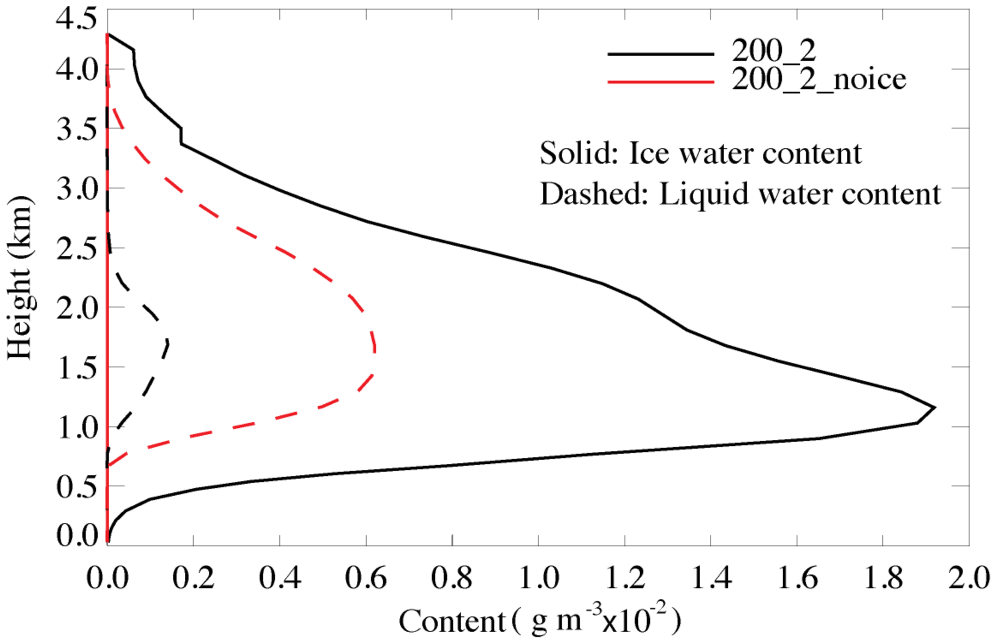

Figure 4

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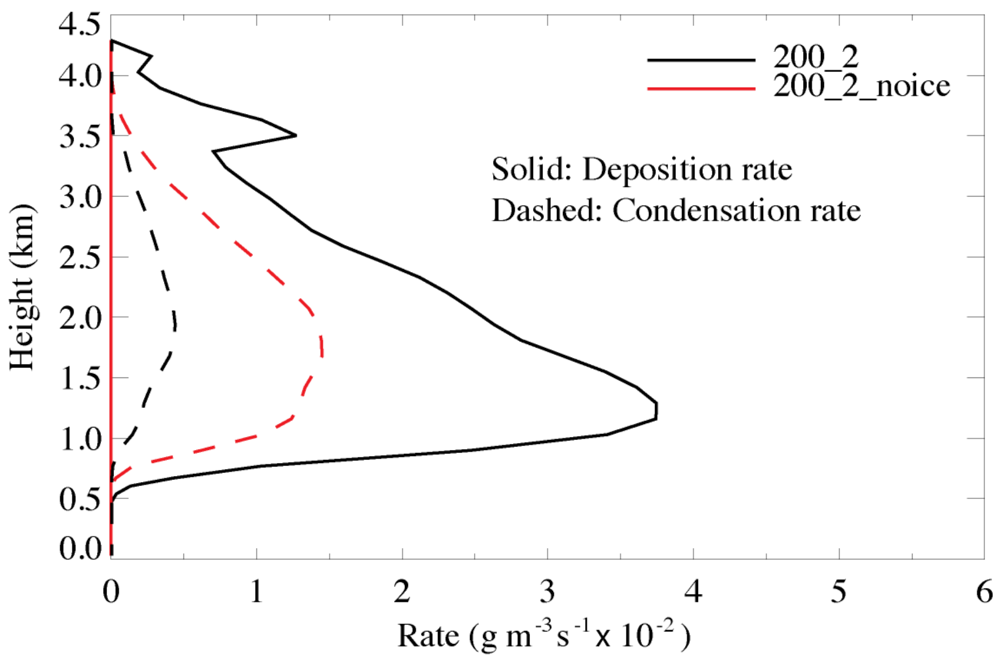

Figure 5

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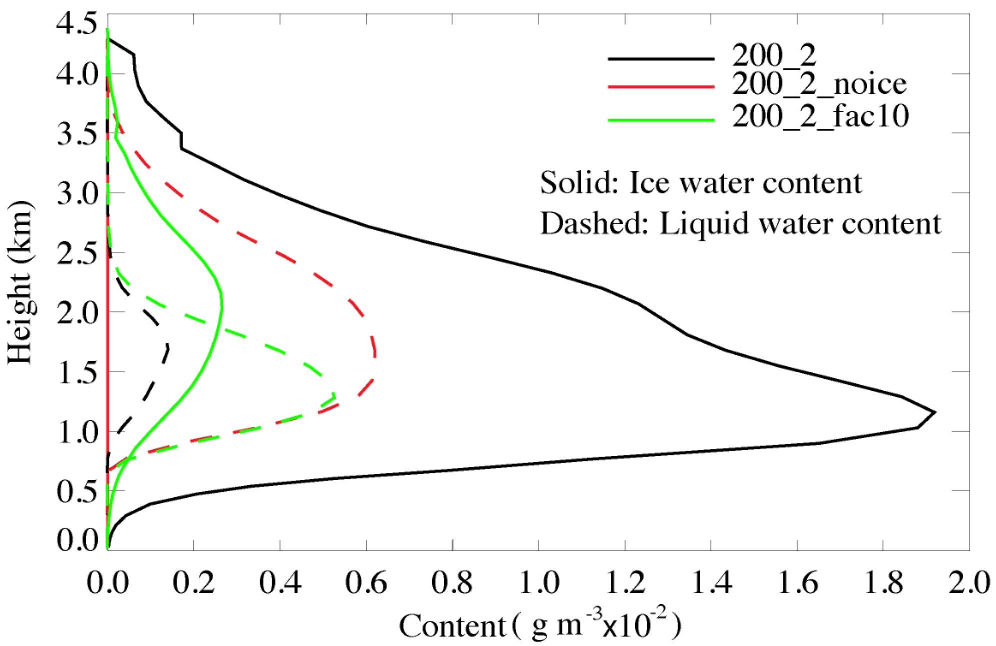

Figure 6

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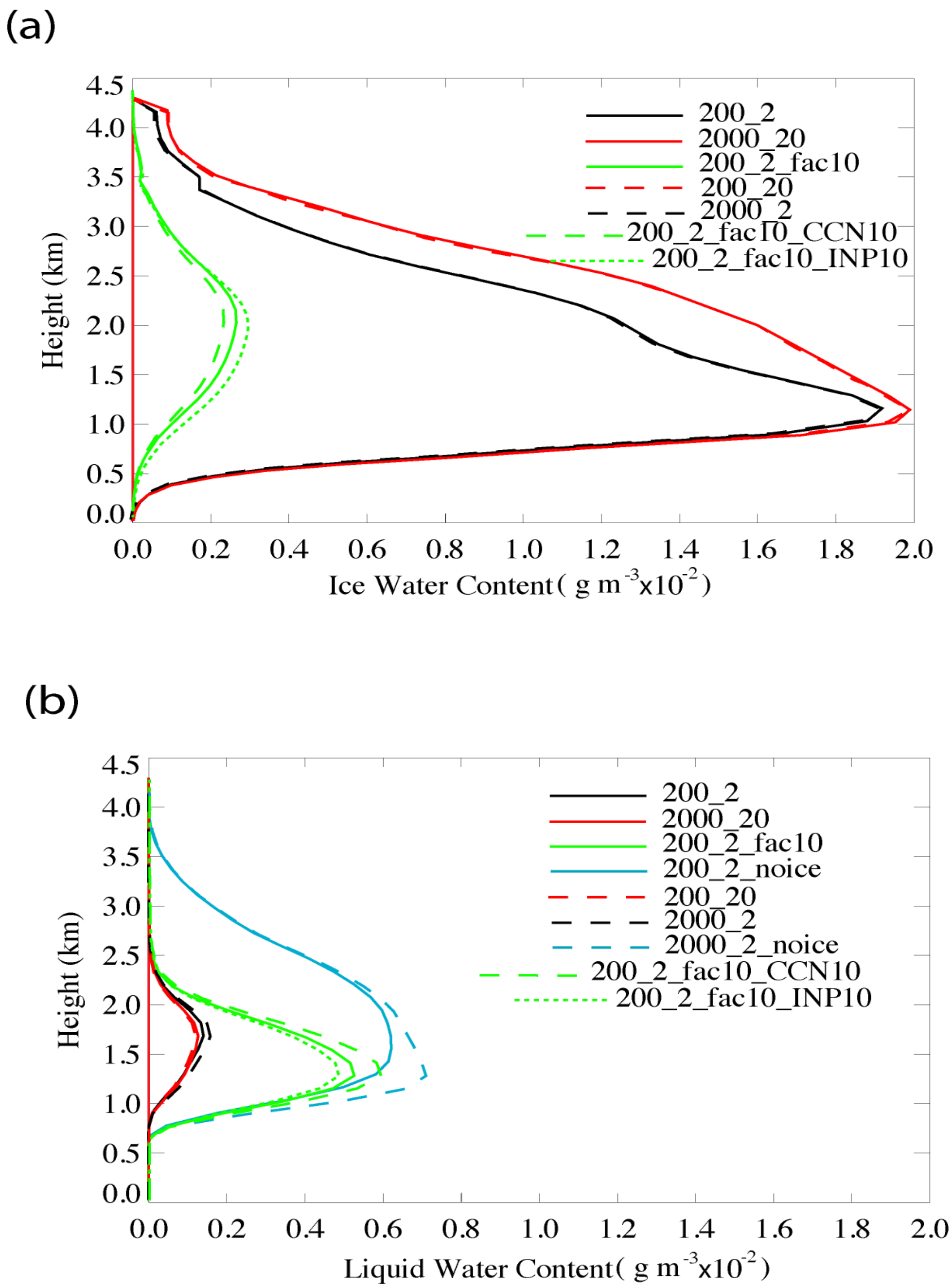

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1045 **Figure 7**