1. Introduction

Mixed-phase clouds, which are composed of both ice crystals and supercooled liquid droplets, are one of the most frequently observed clouds during the spring and fall seasons in the Arctic (de Boer et al., 2009; Shupe et al., 2006, 2011; D. Zhang, Vogelmann, et al., 2019). They have large impacts on the sea ice and ice sheet melt (Bennartz et al., 2013; Hofer et al., 2019; Nicolas et al., 2017) along with regional and global climate changes (Lawson & Gettelman, 2014; Lohmann & Neubauer, 2018; Tan & Storelvmo, 2019). The phase partitioning between liquid and ice water in mixed-phase clouds can substantially impact the radiative fluxes at the surface and can alter the surface energy budget due to the vastly different optical properties between liquid droplets and ice crystals (Bennartz et al., 2013; Hofer et al., 2019; Nicolas et al., 2017).

It is imperative for general circulation models (GCMs) to accurately capture the microphysical properties of mixed-phase clouds in order to achieve a reliable future climate prediction. However, large uncertainties remain in the modeling of mixed-phase clouds in current GCMs (Barrett et al., 2017; Klein et al., 2009; Komurcu et al., 2014; Morrison et al., 2009). For example, the temperature at which the amount of cloud liquid water and ice water is equally abundant in the simulated mixed-phase clouds over the Southern Ocean varies by 40°C among 19 Coupled Model Intercomparison Project Phase 5 (CMIP5) models (McCoy et al., 2015, 2016). One challenge in modeling mixed-phase clouds lies in the representation of heterogeneous ice nucleation that occurs at temperatures warmer than −37°C (Liu et al., 2011; Shi & Liu, 2019; Xie et al., 2008, 2013). The heterogeneous ice nucleation parameterizations commonly used in current GCMs are derived from laboratory measurements (DeMott et al., 2015; Niemand et al., 2012), field observations (DeMott et al., 2010), or are based on the Classical Nucleation Theory (CNT) (Hoese et al., 2010; Wang et al., 2014). However, considerable uncertainties in simulated ice particle number concentration of mixed-phase clouds remain due to the poor representations of atmospheric processes of ice nucleating...
Another challenge exists in the treatment of ice depositional growth through the Wegner-Bergeron-Findeisen (WBF) process in mixed-phase clouds. In the WBF process, ice particles grow at the expense of coexisting liquid droplets because of the lower equilibrium vapor pressure with respect to ice than that with respect to liquid at temperatures colder than 0°C. It has been found that the simulated phase partitioning in mixed-phase clouds is strongly sensitive to the treatment of the WBF process in GCMs. The representation of the WBF process in current GCMs often ignores subgrid cloud structures, which leads to an underestimation of liquid water mass mixing ratio (Storelvmo et al., 2008; Tan & Storelvmo, 2016; M. Zhang, Liu, et al., 2019). In addition, the interaction between cloud microphysics and other physical processes (e.g., shallow convection) has also been found to play an important role in modeled mixed-phase cloud properties. For example, the detrainment of liquid from shallow convection to stratiform clouds increases the amount of cloud liquid water in simulated mixed-phase clouds over the Southern Ocean. This leads to a large reduction of the surface shortwave radiative fluxes over that region as demonstrated in the Community Atmosphere Model version 5 (CAM5) (Kay et al., 2016; Wang et al., 2018).

The mixed-phase cloud properties simulated by the newly developed U.S. Department of Energy (DOE) state-of-the-art GCM, Energy Exascale Earth System Model (E3SM, Golaz et al., 2019) Atmosphere Model version 1 (EAMv1) (Rasch et al., 2019; Xie et al., 2018) have shown a substantial change from the EAMv1 predecessor, CAM5. In particular, EAMv1 is found to have too large liquid phase cloud fraction and a moderate underestimation of ice phase cloud fraction between −20°C and −30°C over the high latitudes in both hemispheres (Y. Zhang, Xie, et al., 2019). This is different from what is found in Kay et al. (2016), which showed that CAM5 had insufficient supercooled liquid clouds. The EAMv1 simulated mixed-phase cloud supercooled liquid fraction (SLF), which is defined as the ratio of liquid water mass to total condensed water mass, is significantly larger than in CAM5 over the Southern Ocean for temperatures colder than −13°C. This leads to smaller biases in shortwave cloud radiative effect when comparing to the observation (Rasch et al., 2019). The increased supercooled liquid in EAMv1 is partially related to the reduced WBF process rate that has been artificially slowed down by 10 times through a tuning parameter compared to CAM5. In a sensitivity test, Y. Zhang, Xie, et al. (2019) showed that the EAMv1 simulated SLF is still much larger than that produced by CAM5 even after the tuning of the WBF process was eliminated. This indicates that other changes in model physics made in the development of EAMv1 from CAM5 also play an important role in the increased SLF in simulated mixed-phase clouds.

As described in Xie et al. (2018), there are three major changes in model physics associated with mixed-phase clouds made during the development of EAMv1 from CAM5. First, EAMv1 adopts the CNT ice nucleation scheme to replace the previous temperature dependent heterogeneous ice nucleation scheme (Meyers et al., 1992) used in CAM5 in mixed-phase cloud regime. As shown in Wang et al. (2018), this change leads to a large increase in SLF at the temperatures colder than −20°C in the polar regions because the Meyers scheme predicts much higher INP number concentrations than CNT (Liu et al., 2011; Xie et al., 2013) in clean environments. This may cause the model to significantly overestimate INP number concentrations compared to observations (Prenni et al., 2007). Second, EAMv1 uses a simplified third-order turbulence closure parameterization (CLUBB) (Golaz et al., 2002; Larson, 2017; Larson & Golaz, 2005) that unifies the treatment of planetary boundary layer (PBL) turbulence, shallow convection, and cloud macrophysics to remove the unrealistic separation of these physical processes, which are the characteristics of most climate models including CAM5. This will impact the detrainment of cloud water from shallow convection to stratiform clouds, which in turn affects the simulated mixed-phase clouds. Meanwhile, the CLUBB has been found to explain the improvements in EAMv1 simulated cloud climatology. These improvements include the increased cloud fraction of low-level stratocumulus (Sc) and trade wind cumulus (Cu) near the subtropical coasts, and the better transition from Sc to Cu, compared to CAM5 (Xie et al., 2018). Third, the last major relevant change is to use the second version of the two-moment cloud microphysics scheme, MG2 (Gettelman & Morrison, 2015). The new scheme predicts the mass and number mixing ratios of snow and rain hydrometeors instead of the diagnostic treatment applied in its first version (MG1, Morrison & Gettelman, 2008). The collection of liquid droplets by rain drops through the accretion process tends to become more dominant than autoconversion, which is more comparable to the cloud-resolving model simulations (Gettelman et al., 2015).
The goal of this study is to provide a process-level understanding on how these changes, which were made to improve cloud physical processes during the EAMv1 development, impact the model simulated high-latitude single-layer mixed-phase clouds in the Arctic. This is done through well-designed sensitivity experiments, which are conducted by utilizing the short-term hindcast framework developed by the DOE Cloud-Associated Parameterizations Testbed (CAPT) project (Ma et al., 2015; Phillips et al., 2004). Under the CAPT framework, a climate model is initialized with realistic conditions from Numerical Weather Prediction (NWP) center analysis, and its representation of atmospheric physical processes is tested in short-range weather forecasts. As there are no real-time operational constraints, retrospective forecasts (hindcasts) are performed. The rationales behind this approach are (1) the large-scale state of the atmosphere in the early periods of a forecast is realistic enough that errors can be ascribed to the parameterizations of atmospheric processes; and (2) atmospheric physical processes (e.g., moist processes) are often fast (~hr) and the large-scale state changes more slowly (~days). As indicated in earlier studies (Ma et al., 2014; Williams & Brooks, 2008; Xie et al., 2012), there is a strong correspondence between short- and long-term systematic errors in climate models, particularly for those fields that are related to fast physics (e.g., clouds). Most systematic errors are apparent in day 2 hindcasts. These errors steadily grow with the hindcast lead time and typically saturate after 5 days with amplitudes comparable to the climate errors. Using initialized climate models for testing physical parameterizations allows for evaluation of the nature of parameterization errors before longer-time scale feedbacks develop and thus provides essential clues to the origin of climate errors (Liu et al., 2011; Xie et al., 2008; Zheng et al., 2016). It facilitates process studies by directly linking model deficiencies to atmospheric processes through case studies using data collected from field campaigns.

In this study the observations collected from the ARM Mixed-Phase Arctic Cloud Experiment (M-PACE) field campaign (Verlinde et al., 2007), which was conducted at the ARM North Slope of Alaska (NSA) site during October 2004, are used to evaluate the EAMv1 simulated mixed-phase clouds.

This paper is organized as follows. Section 2 provides the details about EAMv1, particularly its parameterizations related to mixed-phase clouds, model experiments, and observation data used in this study. Section 3 discusses the simulated mixed-phase clouds and their microphysical properties. Section 4 presents a detailed process analysis. Conclusions and discussions are given in section 5.

2. Model, Model Experiments, and Observation Data

2.1. EAMv1

EAMv1 is developed from CAM5 with a significant increase of model resolution and notable changes to its physical parameterizations (Rasch et al., 2019; Xie et al., 2018). It can be run at either 1° or 0.25° in horizontal and 72 layers in vertical with the model top extended to ~60 km. Within the PBL, 17 vertical layers are included below 1.5 km with the vertical resolution from 20 to 200 m.

The updated physics includes using CLUBB for a unified treatment of PBL turbulence, shallow convection, and cloud macrophysics. These processes were represented by the University of Washington (UW) PBL turbulence scheme (Bretherton & Park, 2009), shallow convection scheme (Park & Bretherton, 2009), and cloud macrophysics scheme (Park et al., 2014) in CAM5. CLUBB achieves the high-order closure through a set of triple joint probability density function (PDF) of vertical velocity (w), liquid water potential temperature (θl), and total specific water content (q). A double Gaussian function is assumed to define the shape of trivariate PDF. CLUBB predicts the variances of and correlations between θl, q, and w, as well as the third moment \( \overline{w^3} \) to determine the parameters of the assumed joint PDF. Momentum terms such as \( \overline{u'^2} \) and \( \overline{v'^2} \) are also prognostically determined in CLUBB, while other momentum terms such as \( \overline{uw} \) and \( \overline{uw'} \) are determined diagnostically and closed using a down-gradient approach as described in Golaz et al. (2002). Once the joint PDF is known, other higher-order moments (turbulent advection terms such as \( \overline{w^2q_l'} \), \( \overline{w q_l'^2} \), and \( \overline{w \theta_l'^2} \)) can be closed by integrating over the assumed PDF to achieve the closure in CLUBB prognostic equations. Cloud quantities such as the cloud fraction and cloud liquid water mixing ratio can be diagnosed directly via the integration of the joint PDF over the saturated portion (Larson et al., 2002). We note that the current CLUBB scheme is designed for liquid phase processes. Only the transport of cloud ice mass mixing ratio is treated via a turbulence eddy diffusion scheme (Bogenschutz et al., 2013). Ice phase processes are not explicitly included in the
CLUDBB’s PDF approach but are treated via cloud microphysics. The ice cloud fraction is determined based on relative humidity when using CLUDBB (Gettelman et al., 2010).

CLUDBB is paired with the same deep convection scheme used in CAM5 (i.e., the ZM scheme developed by Zhang & McFarlane, 1995) and the updated cloud microphysics scheme MG2. MG2 prognoses the mass and number concentrations of cloud liquid and ice and precipitating hydrometeors (snow and rain). The reduction in number concentrations of precipitating hydrometeors due to evaporation is also accounted for in the prognostic treatment. To better couple with the CLUDBB parameterization, sub-time step of 5 min is used in the cloud microphysics. Compared to the MG1 microphysics, MG2 updates the number concentration of prognostic cloud droplets due to activation at the beginning of the cloud microphysics scheme. Furthermore, the CNT ice nucleation scheme is adopted to represent the immersion, contact, and deposition heterogeneous freezing in the mixed-phase cloud regime (Wang et al., 2014). CNT links the ice particle formation to aerosol (i.e., dust and soot) properties such as aerosol number concentration and particle size (Hoos et al., 2010). Other major updates include the 4-mode version of the Modal Aerosol Module (MAM4) (Liu et al., 2016), the unified treatment for convective transport and scavenging of aerosols (Wang et al., 2013), the resuspension of aerosol particles from evaporated raindrops to coarse mode, the representation of marine organic aerosols, and a linearized ozone chemistry (Linoz2) mechanism (Hsu & Prather, 2009; McLinden et al., 2000) for representing stratospheric ozone and its radiative effects in the stratosphere.

As indicated in Xie et al. (2018), EAMv1 is quite sensitive to the changes made in physics and model resolution. To obtain a reasonable TOA energy flux and optimize the model performance, substantial model re-tuning was performed during the EAMv1 development. The model tuning has emphasized on exploring simulation sensitivity to a few loosely constrained parameters used in the model parameterizations (e.g., CLUDBB, ZM, and MG2), guided by using the perturbed-physics ensemble method as described in Qian et al. (2018) and Zhang et al. (2012), with the goal to identify a model configuration that yields the best simulation against observations while keeps the TOA energy budget balanced to avoid a drift of climate. The tuning was made primarily to those parameters that have major impacts on the simulations of clouds and precipitation, in particular over the tropical and subtropical regions. Mixed-phase clouds at high latitudes were not the target for the tuning. More details about the changes made in turbulence, cloud, and convection related parameterizations and model tuning are provided in Xie et al. (2018).

2.2. Model Experiments

Table 1 lists the model experiments conducted in this study. The control experiment (“CTL”) has the same model configuration as the default low resolution EAMv1, except that we remove the artificial parameter that is applied to the WBF process. This is also the case for all other sensitivity experiments. In this way, we can exclude the impact of changes in the WBF process on the model simulated Arctic mixed-phase clouds.

Three sensitivity tests are performed in this study. In “MEYERS,” the CNT scheme in CTL is replaced by the Meyers et al. (1992) scheme. As the number concentration of nucleated ice particles differs largely between these two schemes, this experiment is designed to understand the influence of heterogeneous ice nucleation on the partitioning of cloud condense. In “UW,” CLUDBB in CTL is replaced by the UW schemes for PBL turbulence, shallow convection, and cloud microphysics that were used in CAM5, to test the role of CLUDBB on the simulated cloud properties. Finally, in “UW_MG1” which is based on the “UW,” MG2 is replaced by MG1 to test the impact of the MG2 microphysics. We note that we use EAMv1 as the baseline, because we want to trace back reasons for the model behavior change during the EAMv1 development of physical parameterizations. EAMv1 provides the option for users to switch back to certain old parameterizations without too much effort.

For each experiment, a series of 3-day hindcasts (Ma et al., 2015) are initialized every day from 30 September 2004 to 31 October 2004 to cover the M-PACE period. The initial conditions of the large-scale states (i.e., horizontal wind, temperature, and water vapor) are from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis (Dee et al., 2011). Since the model is initialized from a foreign model data assimilation system, and to avoid potential problems in the model spin-up, we skip day 1 (0–24 hr) hindcasts and use day 2 (24–48 hr) hindcasts in the analysis (Ma et al., 2013, 2014). The large-scale
state in the day 2 hindcasts is still close to the initial state so that we can focus on deficiencies in model parameterizations. To compare with the ARM M-PACE observations, model outputs at the land grid point closest to the ARM NSA Utqiagvik site (71.3°N, 156.6°W) are extracted. We note that using “nudging” instead of “the short-term forecasts” is another way to facilitate the comparison to field data (Zhang et al., 2014). In the nudging approach, model states are continuously nudged toward reanalysis to ensure realism. However, nudging limits the freedom for model errors to grow.

2.3. M-PACE Observations

Table 2 summarizes the observational data used for model evaluation in this study. The cloud microphysical properties were retrieved using different algorithms as summarized in the ARM cloud retrieval ensemble data set (ACRED) (Zhao et al., 2012). ACRED provides a rough estimate of uncertainties in derived cloud microphysical properties that are attributed to the retrieval techniques. For M-PACE, several different retrieval products are available, which are either from the ARM baseline retrievals (MICROBASE) or from individual research groups. At the NSA site, four products are available for liquid water (MICROBASE, SHUPE_TURNER, WANG, and DONG) while ice water retrievals contain three different methods (MICROBASE, SHUPE_TURNER, and WANG) (Zhao et al., 2012). MICROBASE is the ARM baseline cloud retrieval product. Different from other physically based methods, MICROBASE utilizes an empirical parameterization to retrieve liquid water content (LWC) (Frisch et al., 1995; Liao & Sassen, 1994) and ice water content (IWC) (Ivanova et al., 2001; Liu & Illingworth, 2000) in mixed-phase clouds. SHUPE_TURNER adopts both physically based and empirical methods to retrieve mixed-phase cloud properties. Turner (2005) is used for liquid phase in optical thin clouds, and Frisch et al. (1995) is used for pure liquid clouds. Ice phase properties are retrieved utilizing the method of Shupe et al. (2005). Algorithms used in the WANG product are designed specifically for mixed-phase clouds. Both radar and lidar measurements are combined to retrieve cloud properties (Wang et al., 2004; Wang & Sassen, 2002). Last, the DONG product only includes cloud properties in the liquid phase, with LWP retrieved based on the microwave radiometer (MWR) and millimeter-wavelength cloud radar (MMCR) measurements following Dong and Mace (2003). More details can be found in Zhao et al. (2012). The hourly averaged ACRED data in October 2004 are used for validating the short-term hindcast results.

Other observational data used in this study include the frequency of cloud occurrence based on the integrated measurements from ARM cloud radar, lidar, and laser ceilometer with the Active Remotely Sensed Clouds Locations (ARSCL) algorithm (Clothiaux et al., 2000). In situ measurements of the microphysical

| Observation | Quantity | Source and reference |
|-------------|----------|----------------------|
| ACRED       | LWC/LWP and IWC/IWP | ARM cloud retrieval ensemble data set (ACRED; Zhao et al., 2012) |
| ARSCL       | Cloud fraction | Active Remotely Sensed Clouds Locations (ARSCL) algorithm (Clothiaux et al., 2000) |
| UND Citation| LWC and IWC  | University of North Dakota (UND) Citation aircraft (McFarquhar et al., 2007) |
properties of single-layer boundary layer mixed-phase clouds between 9 and 12 October 2004 (McFarquhar et al., 2007) are also used. During this period, four flights were conducted with the University of North Dakota (UND) Citation aircraft. Each flight lasted for 1–2 hr with cloud data collected every 10 s.

3. Results
3.1. Modeled Mixed-Phase Clouds

Large-scale synoptic circulation played an important role in the formation and maintenance of clouds during the M-PACE field campaign (Verlinde et al., 2007; Xie et al., 2006). A high-pressure system was developed to the northeast of the Alaska coast in the early period of the experiment (5−14 October). The east-northeasterly flow prevailed over the NSA site in the lower troposphere. Cold air associated with the cold pack ice to the north of Alaska reached the NSA. Together with a weak trough in the upper level, surface temperature dropped considerably below −10°C by 8 October. From 9 to 14 October, resilient single-layer boundary layer mixed-phase clouds formed over the open ocean and were advected to the NSA site (Figure 1a). Weak updrafts (~0.5 m/s) were associated with these clouds. After 14 October, the surface high-pressure system slowly propagated southeastward, and a strong low-pressure center that formed near Kamchatka began to influence Alaskan coasts, which brought southerly and southwesterly flow to the NSA. Deep clouds were frequently observed during this time period, associated with frontal systems generated by this low-pressure system.

Figure 1 compares the time-pressure cross section of ARM observed cloud frequency of occurrence and modeled grid-mean cloud fraction from the day 2 hindcasts at the NSA Utqiagvik site. Note that the single-layer low-level mixed-phase clouds from 9 to 14 October are typical and ubiquitous over the Arctic region. In the following discussion, we will focus our analysis on this type of clouds, to understand how changes of EAMv1 physical parameterizations affect their simulation. Compared with the ARSCL observation (Figure 1a), CTL well simulates the resilient low-level mixed-phase clouds between 9 and 14 October (Figure 1b). Cloud temporal evolution and the cloud top height are captured by the model. Simulated cloud base, however, is slightly lower than the observation. We note that the cloud base (top) is defined as the lowest (highest) level with nonzero cloud fraction simulated in the model.

In general, simulated maximum cloud fraction shows little sensitivity to the parameterization change during the examined time period (Figures 1c, 1d, and 1e). In contrast, simulated cloud boundary is quite sensitive to the examined parameterizations. For example, the change of ice nucleation scheme from the Meyers to CNT leads to an increased cloud base height and cloud top height, closer to the observations (Figure 1c). Using CLUBB to replace the UW schemes, however, results in a lower cloud base height and cloud top height (Figure 1d). Because cloud fraction is determined via the relative humidity in the UW cloud macrophysics scheme (Park et al., 2014), the clearer separation between cloud base and surface below 950 hPa in UW is mostly attributed to the drier atmosphere near the surface, while more moisture near the cloud top is responsible for the higher cloud top in UW (not shown). Compared to MG1, the MG2 microphysics parameterization improves cloud base height as indicated in Figure 1e. Cloud top also becomes higher with the use of MG2 microphysics. Note that the pattern with noisier cloud base in UW and UW_MG1 may be the result of total consumption of liquid water in the lower portion of clouds, which will be discussed later.

Although the overall cloud structure is reasonably produced for the single-layer mixed-phase clouds, large impacts from different model schemes are found on the simulated liquid water and ice water mass mixing ratios. Figure 2 shows the modeled LWC, IWC, and SLF in the CTL and three sensitivity experiments. Note that rain and snow water mass mixing ratios are added to LWC and IWC, respectively, to better compare with ground-based observations which cannot distinguish them. One unexpected result shown in Figure 2 is that CTL simulates almost no ice water mass mixing ratio during 9–14 October. Supercooled liquid water constitutes nearly all the cloud condensate mass mixing ratio, at temperatures about −14°C, in the single-layer low-level mixed-phase clouds (Figures 2a and 2e). SLF is therefore close to 1 for these clouds (Figure 2i). This model behavior is in contrast to previous M-PACE studies with CAM5, where cloud ice water was commonly overestimated, and cloud liquid water was substantially underestimated (Liu et al., 2011; Xie et al., 2008, 2013). Since the artificial tuning parameter for the WBF process is removed in CTL, the significant underestimation of IWC is most likely a result of too little ice being produced in the single-layer mixed-phase clouds. More discussion will be provided later.
Compared to CTL, more IWC is produced in MEYERS, which indicates that the use of CNT leads to lower simulated IWC in single-layer mixed-phase clouds. This can be explained by the fact that CNT produces four orders of magnitude lower number concentration of INPs than MEYERS at temperatures ~−15°C (figure not shown). Consistent with earlier studies, Shi and Liu (2019) found that CNT tends to generate lower INP number concentration than observations at warm temperatures, while the Meyers scheme overestimates observed INP number concentrations (DeMott et al., 2010). The use of CLUBB also plays an important role in the decrease of cloud ice, as seen by comparing CTL and UW (Figures 2e and 2g). MG2 microphysics slightly reduces IWC and increases LWC when comparing UW to UW_MG1 (Figures 2c and 2g with Figures 2d and 2h). Even though the sequence of updating the number concentration of cloud droplets due to activation is changed in MG2, the difference between UW and UW_MG1 is mainly due to the higher accretion rate of cloud liquid by rain. The conversion from cloud liquid to ice becomes weaker as more liquid is collected by rain drops. Moreover, compared to CTL, UW_MG1 substantially decreases LWC and increases IWC in the modeled single-layer mixed-phase clouds. Despite the use of CNT in the UW_MG1 experiment, the partitioning pattern between LWC and IWC in UW_MG1 is similar to what was shown in CAM5 (Liu et al., 2011; Xie et al., 2013). When the Meyers ice nucleation scheme is used in UW_MG1, more IWC and less LWC are produced (not shown), making UW_MG1 more comparable to CAM5. Nevertheless, the similarity between UW_MG1 (using either Meyers scheme or CNT scheme) and CAM5 demonstrates that changes of model dynamic core, vertical and horizontal resolutions, and model tuning are not the important reasons for the largely underestimated IWC in this single-layer mixed-phase cloud case.
Figure 2 also shows the time-pressure cross sections of SLF for modeled mixed-phase clouds. It is shown that the distribution of high SLF (close to 1) corresponds well with that of LWC. Less spatial occurrence of high SLF is simulated when Meyers ice nucleation, UW schemes, and MG1 cloud microphysics are utilized. Consistent with the lack of total cloud ice mass mixing ratio, a very low number concentration (<0.01 L⁻¹) of cloud ice particles is produced in CTL between 9 and 14 October, particularly at temperatures between −10°C and −15°C, within the single-layer boundary layer mixed-phase clouds (Figure 3). It is clear that the three updated physical parameterizations during the EAMv1 development tend to decrease the ice particle number concentration as shown in Figures 3b–3d. Substantially more ice crystals are produced after replacing the new schemes (i.e., CNT, CLUBB, and MG2) with the old ones (i.e., Meyers, UW, and MG1). Comparing these three parameterizations, uses of CLUBB and MG2 have stronger impacts than CNT.

Figure 4 compares modeled LWP and IWP to various retrievals contained in the ARM ACRED data product. In general, differences are smaller among liquid phase retrievals compared to those of ice phase retrievals. One to two orders of magnitude difference can be found in IWP products, which could be the result of assumptions made in different algorithms (Zhao et al., 2012). For example, assumptions about size distribution, shape, and density of ice crystals can vary substantially, contributing to large uncertainties in IWP retrievals. Compared to the ground-based observations, CTL overpredicts LWP during more than half of
the time from 10 to 13 October. Meanwhile, CTL underestimates the observed IWP by three to five orders of magnitude during 9–14 October. When comparing sensitivity experiments to CTL, we note that less LWP and more IWP are simulated given a particular suite of parameterizations.

Figure 5 shows the comparison of SLF as a function of normalized cloud height between in situ measurements from the UND Citation aircraft and the EAM hindcast experiments. Aircraft data were processed by McFarquhar et al. (2007). Note that cloud altitude is normalized from 0 at cloud base to 1 at cloud top for both the observations and model results. Modeled clouds are defined when total cloud water mass mixing ratios are larger than 0.001 g kg\(^{-1}\). The in situ measurements were obtained on 9, 10, and 12 October during the M-PACE field campaign, to capture the vertical structures of single-layer mixed-phase clouds and their microphysical properties (e.g., LWC and IWC). There were two flights on 9 October, and one flight on 10 and 12 October, respectively. In Figure 5, data from the two flights on 9 October are combined with the same color.

The aircraft measurements (Figure 5a) show that the observed SLF increases with normalized cloud height and is larger than 80% near the cloud top. Larger fraction of cloud ice is observed in the lower portion of clouds, indicated by the lower SLF near the cloud base. The vertical distribution of SLF is similar among the four research flights. Consistent with earlier discussion, Figure 5b shows that CTL substantially overestimates SLF within the single-layer mixed-phase clouds. Simulated SLF remains close to 100% for all cloud layers during the examined period. Compared to CTL, MEYERS better reproduces the vertical distribution of SLF in observations, but its SLF near the cloud base is underestimated. In addition to the fact that cloud ice water mass mixing ratio is included in our definition of cloud base, the underestimated SLF can also be explained by the overestimated INP number concentration by the Meyers scheme near the cloud base. Higher number concentration of ice particles and larger ice water content are generated near the surface...
in MEYERS than CTL, as shown in earlier figures. It is clearly shown in Figures 2b and 2f that cloud liquid water tends to distribute separately from cloud ice water in modeled clouds. Figure 5d shows that the feature of SLF increasing with normalized cloud height is captured by the UW schemes on 10 and 12 October, while such trend is poorly simulated on 9 October. Too much cloud ice water is simulated near the cloud base in UW on 9 October. We note that 9 October is a transition period in terms of the large-scale synoptic conditions during the M-PACE campaign. A high-pressure system was built over the pack ice to the northeast direction of Alaskan coast and brought cooled air to the Utqiagvik site, decreasing surface temperature by ~5°C during 9 October (Verlinde et al., 2007). The different SLF patterns between 9 October and 10 and 12 October shown in Figure 5d may be explained by the inadequate representation of this transition in the UW schemes. In contrast to UW, UW_MG1, in which MG2 is replaced by MG1, does not show the inclining SLF along the normalized cloud height on 10 and 12 October, indicating that the use of MG2 microphysics is able to improve the SLF vertical distribution of modeled single-layer mixed-phase clouds.

4. Mass Budget Analysis

In this section we further analyze detailed cloud microphysical budgets for the four hydrometeors—cloud liquid, cloud ice, rain, and snow—for the single-layer mixed-phase clouds during the period between 9 and 11 October. The purpose is to understand which cloud microphysical process is most important to model behavior changes. The budget terms of microphysical process tendencies are vertically integrated over the whole cloud layers and are averaged over the selected time period.
A more detailed discussion of how different physical parameterizations in EAMv1 interact with each other is provided in Figure 1 of Zhang et al. (2018). In this section, we will only focus on the impacts of shallow convection, cloud macrophysics, ice nucleation, and cloud microphysics as well as their interactions on simulated mixed-phase cloud properties. In EAMv1, CLUBB (or shallow convection scheme and cloud macrophysics in the UW schemes), ice nucleation, and cloud microphysics are updated subsequently. Calculated physical process rates are used to update the quantities of cloud properties before passing them to the next parameterization. Therefore, the calculation sequence of physical processes is important when interpreting the following discussion.

### 4.1. Impact of Heterogeneous Ice Nucleation

Figure 6a shows that liquid water condensation constitutes the major source for cloud liquid condensate in both CTL and MEYERS. Note that the amount of condensed liquid water is directly diagnosed from the assumed joint PDF in the CLUBB parameterization (Bogenschutz et al., 2012; Golaz et al., 2002). Although four orders of magnitude difference are found in the number concentration of nucleated ice particles between CTL and MEYERS (figure not shown), comparable liquid condensation tendencies are found in both experiments. This is expected, as different heterogeneous ice nucleation schemes should have minimal impacts on the liquid water formation.

With a small amount of total ice mass mixing ratio produced in the single-layer mixed-phase clouds between 9 and 11 October in CTL, ice phase associated microphysical processes are active at limited rates. For instance, the WBF process with respect to ice and snow, and the snow accretion of liquid droplets are weakly activated to transfer formed liquid water to ice and snow. However, almost all the generated cloud ice water is converted to snow via autoconversion (Figure 6c). Snow water then tends to sediment out of clouds, leaving negligible amount of total ice water mass mixing ratio in CTL simulated mixed-phase clouds. Comparing

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**Figure 5.** Distribution of supercooled liquid fraction as a function of normalized height in clouds. (a) The in situ measurements obtained from the University of North Dakota Citation aircraft (McFarquhar et al., 2007) on 9 October (black dots), 10 October (red dots), and 12 October (blue dots) during the M-PACE field campaign. (b-e) Results of model simulations from CTL, MEYERS, UW, and UW_MG1, respectively. Model results are sampled on 9, 10, and 12 October which correspond to the same time period as the measurements.
MEYERS to CTL, with a higher ice particle number concentration from the heterogeneous ice production, larger tendencies of ice associated processes are shown in MEYERS. In particular, the WBF process rate with respect to ice is much increased, which leads to a larger cloud ice mass mixing ratio. As the growth of snow water mass mixing ratio is strongly influenced by the autoconversion of cloud ice, larger snow growth rates such as the WBF process with respect to snow, and snow accretion of liquid droplets are shown in Figure 6d in MEYERS. Meanwhile, the different ice number concentration also changes the
pathway of whether liquid droplets are collected by rain drops or snow particles. For example, when higher ice number concentration is formed by MEYERS, more liquid droplets are collected by snow, inhibiting the accretion of liquid droplets by rain drops (Figure 6b). This further increases the ratio of total ice water mass mixing ratio to total liquid water mass mixing ratio. Therefore, the number of concentration of ice particles generated from heterogeneous ice nucleation is important for the Arctic single layer mixed-phase clouds. Ice production from the CNT scheme in CTL is too weak at temperatures warmer than –15°C. We note that the impact of heterogeneous ice nucleation on simulated mixed-phase clouds is important more through its influence on cloud ice number concentration, not on ice mass mixing ratio. As shown in Figure 6a, the mass tendency for heterogeneous ice nucleation is substantially small. This is because the mass of newly formed ice crystals is so small that ice nucleation cannot have a comparable mass tendency to other processes such as the WBF process. However, this does not impair the importance of heterogeneous ice nucleation, as cloud ice mass growth rate depends sensitively on the number concentration of ice particles.

4.2. Impact of CLUBB

Comparing UW to CTL, the change of physical processes due to the use of CLUBB can be analyzed. In the UW experiment, liquid condensation is determined by cloud macrophysics (Park et al., 2014), and the shallow convection is calculated by Park and Bretherton (2009). When shallow convection is separately treated in the UW parameterization, liquid mass mixing ratio detrained from shallow convection is of comparable magnitude to the condensation (Figure 6a). However, the detrainment and condensation processes cannot be diagnosed separately in CTL, since CLUBB implicitly calculates the total production of cloud liquid water via the integral over saturated portion of the joint PDF (Golaz et al., 2002; Larson et al., 2002).

Similar to the cloud liquid water mass budget, detrainment from shallow convection also constitutes the source for cloud ice mass mixing ratio when CLUBB is not used (Figure 6c). Such detrained cloud ice particles, together with the nucleated ice particles from heterogeneous ice nucleation, participate in the cloud ice mass growth. We emphasize here the importance of initial cloud ice amount (either from the shallow convection detrainment or from the heterogeneous ice nucleation), because one prerequisite for cloud ice mass growth is that sufficient ice particles exist at the beginning of cloud microphysics calculation. As noted in section 2.1, ice phase related processes are currently not explicitly treated in the CLUBB’s PDF method. Instead, only the transport of cloud ice mass mixing ratio is treated in CLUBB through an eddy diffusion scheme. However, the eddy diffusion transport is found to be inactive in the examined low-level boundary layer mixed-phase clouds (shown as CLUBB process in Figure 6c). Compared to UW, without initial ice from the shallow convection when CLUBB is used, the increase of cloud ice mass mixing ratio by subsequent cloud microphysical processes becomes substantially weaker in CTL. Example includes the lower WBF process tendency with respect to ice.

Meanwhile, it is shown in Figure 6c that the growth of ice crystals through water vapor deposition also contributes to the cloud ice mass mixing ratio in UW, but this source is not evident in CTL. In the MG cloud microphysics scheme, ice depositional growth is parameterized as two separate processes: the WBF process and ice deposition at the expense of water vapor. The WBF process represents the conversion of cloud liquid to ice (and snow), assuming homogeneous mixing between liquid and ice (and snow) in each grid cell at subfreezing temperatures. Since the MG scheme does not treat the evaporation of cloud liquid water, the evaporation of liquid droplets in the WBF process is not numerically represented. When abundant cloud ice coexists with cloud liquid in mixed-phase clouds, the WBF process will first consume the available liquid water. Under the circumstance that cloud liquid water is totally consumed within one model time step (5 min, as sub-step is used in cloud microphysics), ice crystals will then continue their growth at the expense of water vapor until the end of that sub-step. The latter process is referred to as ice depositional growth in the MG scheme. Therefore, the indication of ice deposition in UW implies that all available liquid water in simulated clouds is completely consumed at certain levels or at certain time steps, but such complete consumption never occurs in CTL. Furthermore, because of the larger source for cloud ice mass mixing ratio in UW, snow water also becomes more abundant via autoconversion of cloud ice. Accretion of liquid and rain by snow particles is enhanced, which further increases the amount of ice phase cloud condensates. Therefore, in CTL modeled single-layer low-level mixed-phase clouds, CLUBB parameterization substantially underestimates one source of cloud ice water that is represented in Park and Bretherton (2009). As a
result, the lack of initial cloud ice amount substantially reduces the ice mass growth through subsequent microphysical processes, leading to the underestimation of total ice mass mixing ratio.

4.3. Impact of MG2

The impact of cloud microphysics parameterization change from MG1 to MG2 can be examined by comparing UW and UW_MG1 experiments. The use of MG2 reduces the process tendencies for ice and snow growth at the expense of cloud liquid water. For example, the WBF process with respect to both ice and snow and the snow accretion of liquid droplets become weaker in UW than UW_MG1. It is noted that the change in the sequence of updating activated droplet number concentration in MG2 has insignificant impact on our examined Arctic single-layer mixed-phase clouds (not shown). Thus, these changes of process tendencies are attributed to the prognostic treatment of precipitation hydrometeors (rain and snow) in the MG2 microphysics. Another important aspect in MG2 simulated mixed-phase clouds lies in the higher accretion rate of liquid droplets by rain drops as shown in Figures 6a and 6b. Although the total cloud ice mass mixing ratio is reduced in MG2 simulated mixed-phase clouds, there is no significant change in the formation of initial cloud ice. For example, the heterogeneous ice nucleation is the same between UW and UW_MG1. The detrained cloud ice from shallow convection also behaves similarly. Therefore, the change of cloud microphysics should not be as important as the other two parameterizations. Nevertheless, as noted in Gettelman et al. (2015), MG2 simulated mixed-phase clouds are strongly sensitive to the ice particle number concentration. The change of initial ice source can then have a stronger impact on the cloud microphysical processes in MG2 than MG1.

5. Summary and Discussions

In this study, we utilize the short-term hindcast approach to understand which physical process is most responsible for the significant behavior change in Arctic single-layer mixed-phase clouds simulated by the U.S. DOE E3SM atmospheric model (EAMv1), compared to its predecessor, CAM5. Hindcast results show that the amount of total ice water mass mixing ratio is substantially underestimated in the default EAMv1, particularly for the single-layer boundary layer mixed-phase clouds during the M-PACE. On the other hand, total liquid water mass mixing ratio is overestimated when compared with the ARM ground-based remote sensing data. By tracing back the changes made in EAMv1, we find that uses of the CNT scheme, CLUBB parameterization, and MG2 microphysics all tend to decrease ice mass mixing ratio. When all three schemes are combined, the decrease of ice mass mixing ratio resulting from individual scheme change tends to add up, leading to a large underestimation of ice water amount in modeled clouds. A detailed budget analysis of cloud microphysical process tendencies indicates that the initial ice particles, generated from heterogeneous ice nucleation and detrainment of cloud ice from shallow convection, are critical for the ice mass increase through subsequent cloud microphysical processes. When CNT and CLUBB are used to respectively replace the Meyers ice nucleation scheme and the UW schemes, a minimal number of initial ice particles are generated and passed to cloud microphysics. As the mass growth rate of ice crystals depends sensitively on the number concentration of ice particles, simulated cloud ice mass mixing ratio is then reduced. For example, the WBF process with respect to ice is much weaker in CTL compared to the three sensitivity experiments. In addition, the formation of snow water is also reduced in CTL, which leads to a weaker collection of liquid droplets, rain drops, and ice particles by snow. Since MG2 microphysics scheme does not impact the initial ice crystals, change in microphysics should not be a primary reason for the underestimation of cloud ice. However, the introduction of MG2 reduces the WBF process with respect to both ice and snow, as well as the snow accretion of liquid droplets, which also results in lower total ice mass mixing ratio.

Along with the change from UW to CLUBB, the treatment of PBL turbulence is also changed. We notice changes in the simulated PBL. For example, the vertical updraft and potential temperature profiles produced from CLUBB and UW scheme are different. However, the difference is not substantial. Therefore, the PBL change may not be an important factor to influence the phase partitioning of mixed-phase clouds in this study.

We note that the issue analyzed in this study is mostly related to the Arctic single-layer boundary layer mixed-phase clouds. In particular, the insufficient ice formation from the CNT heterogeneous ice production is more problematic for mixed-phase clouds at temperatures warmer than −15°C. With the CNT ice
nucleation linked to aerosol properties, the model deficiency in aerosol fields can influence modeled mixed-phase clouds. EAMv1, like many other GCMs, underestimates the dust transport from mid-latitude sources, misses the Arctic local dust sources, and neglects biological aerosols. This leads to the substantial underestimation of INP number concentrations over the Arctic region (Shi & Liu, 2019). Such biases in modeled aerosols and INPs contribute to the biased phase partitioning of high latitude mixed-phase clouds in EAMv1. Future model development should focus on the treatment of aerosol emission and scavenging processes to obtain accurate aerosol concentrations and distributions in the atmosphere. In addition to the CNT scheme, other advanced ice nucleation parameterizations also determine INP number concentrations based on aerosol properties. For example, DeMott et al. (2015) parameterization determines INP number concentration based on temperature and number concentration of dust particles with sizes larger than 0.5 μm in diameter. Niemand et al. (2012) links the INP concentration to the surface area of dust particles and temperature. Therefore, biases in the aerosol simulation will affect the modeled ice nucleation due to aerosol-cloud interactions. To address the issue in CLUBB parameterization, a similar approach from Park and Bretherton (2009) to partition condensed cloud water may help. Ice phase should also be considered in CLUBB’s PDF parameterization in order to develop a unified framework for shallow convection, PBL turbulence, and cloud macrophysics for mixed-phase clouds. Moreover, other cloud microphysical processes, which are important for increasing cloud ice mass or number concentration, may not be reasonably parameterized in current microphysics scheme. For example, the secondary ice production is not well represented in current GCMs (Field et al., 2017).

Although this study is based on an analysis of the M-PACE field campaign at one single location, the overly dominated cloud liquid water is a common phenomenon beyond this ARM site in EAMv1 modeled mixed-phase clouds (figures not shown). Results based on the global evaluation of EAMv1 simulated mixed-phase clouds will be reported in a separate paper. As indicated in earlier studies, cloud feedback and climate sensitivity can be strongly influenced by the phase partitioning in mixed-phase clouds (Tan et al., 2016; Tan & Storelvmo, 2019). The biased phase partitioning of condensate in low-level mixed-phase clouds identified in this study may introduce biases to the cloud feedback and climate sensitivity estimated by E3SM (Golaz et al., 2019), which is also of interest in the future study.

Data Availability Statement

The model data used in this study can be downloaded online (http://portal.nersc.gov/project/m2136/E3SMv1/Zhang-SLF). The ARM M-PACE observational data set is available from DOE ARM website (https://www.archive.arm.gov/discovery/).

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