Toward Understanding the Simulated Phase Partitioning of Arctic Single-Layer Mixed-Phase Clouds in E3SM

Meng Zhang\textsuperscript{1}, Shaocheng Xie\textsuperscript{2}, Xiaohong Liu\textsuperscript{1}, Wuyin Lin\textsuperscript{3}, Kai Zhang\textsuperscript{4}, Hsi-Yen Ma\textsuperscript{5}, Xue Zheng\textsuperscript{5}, and Yuying Zhang\textsuperscript{6}

\begin{itemize}
  \item \textsuperscript{1}Texas A\&M University
  \item \textsuperscript{2}LLNL
  \item \textsuperscript{3}Brookhaven National Laboratory (DOE)
  \item \textsuperscript{4}Pacific Northwest National Laboratory
  \item \textsuperscript{5}Lawrence Livermore National Laboratory (DOE)
  \item \textsuperscript{6}Lawrence Livermore National Lab
\end{itemize}

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Abstract

Significant changes are found in the modeled phase partitioning of Arctic mixed-phase clouds in the U.S. Department of Energy (DOE) Energy Exascale Earth System Model (E3SM) Atmosphere Model version 1 (EAMv1) compared to its predecessor, the Community Atmosphere Model version 5 (CAM5). In this study, we aim to understand how the changes in modeled mixed-phase cloud properties are attributed to the updates made in the EAMv1 physical parameterizations. Impacts of the Classical Nucleation Theory (CNT) ice nucleation scheme, the Cloud Layer Unified By Binormals (CLUBB) parameterization, and updated Morrison and Gettelman microphysical scheme (MG2) are examined. Sensitivity experiments using the short-term hindcast approach are performed to isolate the impact of these new features on simulated mixed-phase clouds. Results are compared to the DOE’s Atmospheric Radiation Measurement (ARM) Mixed-Phase Arctic Cloud Experiment (M-PACE) observations. We find that mixed-phase clouds simulated in EAMv1 are overly dominated by supercooled liquid and cloud ice water is substantially underestimated. The individual change of physical parameterizations is found to decrease cloud ice water mass mixing ratio in EAMv1 simulated single-layer mixed-phase clouds. A budget analysis of detailed cloud microphysical processes suggests that the lack of ice particles that participate in the mass growth processes strongly inhibits the mass mixing ratio of cloud ice. The insufficient heterogeneous ice nucleation at temperatures warmer than -15C in CNT and the negligible ice processes in CLUBB are primarily responsible for the significant underestimation of cloud ice water content in the Arctic single-layer mixed-phase clouds.
Toward Understanding the Simulated Phase Partitioning of Arctic Single-Layer Mixed-Phase Clouds in E3SM

Meng Zhang¹, Shaocheng Xie², Xiaohong Liu¹*, Wuyin Lin³, Kai Zhang⁴, Hsi-Yen Ma², Xue Zheng², Yuying Zhang²

¹ Department of Atmospheric Sciences, Texas A&M University, College Station, Texas, USA
² Lawrence Livermore National Laboratory, Livermore, CA, USA,
³ Brookhaven National Laboratory, Upton, NY, USA,
⁴ Pacific Northwest National Laboratory, Richland, WA, USA

* Correspondence to X. Liu, xiaohong.liu@tamu.edu

Key Points:

- EAMv1 simulated Arctic single-layer mixed-phase clouds are overly dominated by supercooled liquid with little ice produced;
- Insufficient heterogeneous ice nucleation by CNT at warm temperatures is responsible for the underestimation of cloud ice formation;
- Lacking the ice phase processes in CLUBB and its interaction with stratiform cloud microphysics limits the growth of cloud ice.
Abstract

Significant changes are found in the modeled phase partitioning of Arctic mixed-phase clouds in the U.S. Department of Energy (DOE) Energy Exascale Earth System Model (E3SM) Atmosphere Model version 1 (EAMv1) compared to its predecessor, the Community Atmosphere Model version 5 (CAM5). In this study, we aim to understand how the changes in modeled mixed-phase cloud properties are attributed to the updates made in the EAMv1 physical parameterizations. Impacts of the Classical Nucleation Theory (CNT) ice nucleation scheme, the Cloud Layer Unified By Binormals (CLUBB) parameterization, and updated Morrison and Gettelman microphysical scheme (MG2) are examined. Sensitivity experiments using the short-term hindcast approach are performed to isolate the impact of these new features on simulated mixed-phase clouds. Results are compared to the DOE’s Atmospheric Radiation Measurement (ARM) Mixed-Phase Arctic Cloud Experiment (M-PACE) observations. We find that mixed-phase clouds simulated in EAMv1 are overly dominated by supercooled liquid and cloud ice water is substantially underestimated. The individual change of physical parameterizations is found to decrease cloud ice water mass mixing ratio in EAMv1 simulated single-layer mixed-phase clouds. A budget analysis of detailed cloud microphysical processes suggests that the lack of ice particles that participate in the mass growth processes strongly inhibits the mass mixing ratio of cloud ice. The insufficient heterogeneous ice nucleation at temperatures warmer than -15°C in CNT and the negligible ice processes in CLUBB are primarily responsible for the significant underestimation of cloud ice water content in the Arctic single-layer mixed-phase clouds.
1. Introduction

Mixed-phase clouds, which are composed of both ice crystals and supercooled liquid droplets, are found to have significant impacts on the sea ice and ice sheet melt (Bannartz et al., 2013; Hofer et al., 2019; Nicolas et al., 2017) and regional and global climate change (Lawson & Gettelman, 2014; Lohmann & Neubauer, 2018; Tan & Storelvmo, 2019). Observations show that mixed-phase clouds occur with high spatial and temporal frequencies in the high latitudes (de Boer et al., 2009; Zhang D. et al., 2018, 2019) and are observed most frequently during the spring and fall seasons in the Arctic (Shupe et al., 2006, 2011). Because of the vastly different optical properties between liquid droplets and ice crystals, cloud water phase partitioning between liquid and ice in mixed-phase clouds can substantially impact the radiative fluxes at the surface and alter the surface energy budget (Bannartz et al., 2013; Hofer et al., 2019; Nicolas et al., 2017).

It is imperative for global climate models (GCMs) to capture the spatial distribution and microphysical properties of mixed-phase clouds in order to achieve an accurate future climate prediction. However, large uncertainties remain in the modeling of mixed-phase clouds in most current GCMs (Barrett et al., 2017; Klein et al., 2009; Komurcu et al., 2014; Morrison et al., 2009). For example, the temperature at which amounts of cloud liquid water and ice water are equally abundant in 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 of the challenges 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). Different parameterizations for heterogeneous ice
nucleation derived from laboratory measurements (DeMott et al., 2015; Niemand et al., 2012),
field observations (DeMott et al., 2010) or based on the Classical Nucleation Theory (CNT)
(Hoose et al., 2010; Wang et al., 2014) are used in GCMs, which results in considerable
uncertainties in the simulated ice particle number concentration of mixed-phase clouds. Another
challenge exists in the treatment of ice depositional growth through the Wegner-Bergeron-
Findeisen (WBF) process in mixed-phase clouds. The WBF process controls the growth of ice
particles 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℃. It is
found that simulated mixed-phase cloud phase partitioning is strongly sensitive to the treatment
of WBF process in GCMs. The representation of WBF process which ignores the subgrid cloud
structures generally leads to underestimation of liquid water mass mixing ratio (Storelsvmo et al.,
2008; Tan & Storelsvmo, 2016; Zhang M. et al., 2019). In addition, the interaction between cloud
microphysics and other physical processes, such as shallow convection, is also found to play an
important role in modeled mixed-phase cloud microphysical properties. For example, the
excessive surface shortwave radiative fluxes over the Southern Ocean are much reduced with an
enhanced amount of cloud liquid water in simulated mixed-phase clouds when more liquid is
allowed to be detrained from shallow convection into stratiform clouds in the Community
Atmosphere Model version 5 (CAM5) (Kay et al., 2016; Wang et al., 2018).

The treatment of stratiform and convective cloud processes in the U.S. Department of
Energy (DOE) state-of-the-art GCM, Energy Exascale Earth System Model (E3SM) atmosphere
model version 1 (EAMv1) (Golaz et al., 2019; Rasch et al., 2019; Xie et al., 2018), has been
developed in many ways from CAM5, which EAMv1 is built on. In terms of the cloud physical
parameterizations associated with mixed-phase clouds, first of all, EAMv1 adopts the CNT ice nucleation scheme to represent immersion, contact, and deposition nucleation in mixed-phase clouds (Wang et al., 2014). Compared to the previous temperature dependent heterogeneous ice nucleation scheme (Meyers et al., 1992) in CAM5, 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 increased at temperatures colder than -20°C over the polar areas with CNT. Reduced ice nucleating particle (INP) number concentration with CNT is found to mostly explain the increased SLF in modeled clouds (Wang et al., 2018). Second, the Cloud Layers Unified By Binormals (CLUBB) parameterization is implemented in EAMv1 to treat planetary boundary layer (PBL) turbulence, shallow convection, and cloud macrophysics in a unified framework (Golaz et al., 2002; Larson, 2017; Larson & Golaz, 2005). Simulated marine boundary layer clouds show significant improvements in terms of the vertical distribution of cloud layers and the daily variability of cloud cover (Zheng et al., 2016). The transition from stratocumulus to cumulus clouds is also better simulated by CLUBB (Bogenschutz et al., 2012, 2013). Moreover, EAMv1 uses the second version of two-moment cloud microphysical scheme (Gettelman & Morrison, 2014) (MG2). The new scheme predicts the mass and number mixing ratios of snow and rain hydrometeors instead of the diagnostic treatment in its earlier 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 idealized simulations (Gettelman et al., 2015). Finally, the WBF process with respect to both ice and snow has been slowed down by 10 times in EAMv1 through a tuning parameter. The growth rate of ice crystals at the expense of liquid droplets is then reduced by a
factor of 10 globally, regardless of the spatial distribution of mixed-phase clouds. This parameter has been found to be over-tuned, particularly with the use of the new CNT ice nucleation scheme in EAMv1 as we discuss later. This issue is being addressed by the E3SM development team.

With these new features and other improvements, EAMv1 shows promising improvements in the simulated cloud climatology, cloud radiative effect, and global precipitation (Xie et al., 2018). In contrast to CAM5, however, 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 temperature range over the high-latitudes in both hemispheres (Zhang Y. et al., 2019). The simulated SLF of mixed-phase clouds is significantly larger than CAM5 for temperatures colder than -13°C, and larger than observations for temperatures colder than -25°C. The increased supercooled liquid in EAMv1 is partially related to the artificially reduced WBF process rate and the use of CNT ice nucleation scheme as illustrated in Zhang Y. et al. (2019). They found that SLF is significantly reduced by setting the tuning parameter back to 1. However, it is still much larger than that produced by CAM5. This indicates that other changes in the model physics made in EAMv1 also play an important role in increasing SLF in mixed-phase clouds from CAM5 to EAMv1.

The goal of this study is to provide a process-level understanding on how the changes in EAMv1 physical parameterizations impact the simulated single-layer mixed-phase clouds, with an emphasis on the Arctic, beyond the impact from the artificial tuning parameter applied to the WBF process. This is done through well-designed sensitivity experiments, which are conducted by utilizing a 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, climate models can be initialized with reanalysis dataset and run in the short-term hindcast mode. This allows a direct comparison between model simulations and observation data collected in field campaigns, such as those conducted from the DOE Atmospheric Radiation Measurement (ARM) program. Earlier studies indicate that most climate model errors in clouds and precipitation, which are associated with fast physical processes, could appear in the day-2 hindcasts and the errors then gradually saturate (Ma et al., 2014; Xie et al., 2012). This approach has been widely used to understand and improve cloud related parameterizations in climate models (Liu et al., 2011; Xie et al., 2008; Zheng et al., 2016).

In this study, a series of short-term hindcasts with EAMv1 are conducted for the DOE 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. Hindcasts are initialized with the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis data (Dee et al., 2011) as described in Ma et al. (2015). Comprehensive observational data associated with mixed-phase cloud macrophysical and microphysical properties are obtained from M-PACE and are used in the model evaluation. Sensitivity experiments are performed to understand the individual impact of CNT, CLUBB, and MG2 on EAMv1 simulated Arctic single-layer mixed-phase clouds. The remaining text is organized as follows. Section 2 provides details about EAMv1, particularly its parameterizations related to mixed-phase clouds, model experiments, and observation data. 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 was developed from CAM5 with notable changes to its physical parameterizations. Its vertical resolution was also increased from 30 layers (used in CAM5) to 72 layers with 17 vertical layers are below 1.5 km. The updated physics package includes 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 turbulence, shallow convection, and cloud macrophysics to remove the unrealistic separation of these physical processes, which is characteristic of most climate models. CLUBB achieves the high-order closure through a set of triple joint probability density function (PDF) of vertical velocity ($w$), liquid water potential temperature ($\theta_l$), and total specific water content ($q_t$). A double Gaussian function is assumed to define the shape of trivariate PDF. CLUBB predicts the variances and correlations between $\theta_l$, $q_t$, and $w$, as well as the third moment $\bar{w^3}$ to determine the parameters of the assumed joint PDF. Once the joint PDF is known, other higher-order moments can be closed by integrating over the assumed PDF to achieve the closure in CLUBB prognostic equations. Cloud quantities such as cloud fraction and cloud liquid water mixing ratio can be diagnosed directly via the integration of joint PDF over the saturated portion (Larson et al., 2002). We note that the current CLUBB scheme is only designed for warm cloud processes. Ice phase processes are not explicitly included in the CLUBB’s PDF approach. Ice cloud fraction is determined in EAMv1 based on the relative humidity (Gettelman et al., 2010). Cloud ice mass mixing ratio, on the other hand, is transported via a turbulence eddy diffusion scheme (Bogenschutz et al., 2013).
The MG2 two-moment cloud microphysical scheme (Gettelman & Morrison, 2014) is also incorporated into EAMv1. The new scheme prognoses the mass and number mixing ratios of snow and rain hydrometeors to replace the diagnostic treatment in MG1 (Morrison & Gettelman, 2008). To better couple with the CLUBB parameterization, sub-time steps of 5 min are used in the cloud microphysics. Furthermore, EAMv1 adopts the CNT to represent 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 the aerosol number concentration and particle size (Hoose et al., 2010). Other physical parameterizations used in EAMv1 include the four-mode version of modal aerosol module (MAM4) (Liu et al., 2016) and Zhang and McFarlane (1995) deep convection scheme.

2.2. Model experiments

Table 1 lists the model experiments conducted in this study to understand the impact of each individual change on EAMv1 simulated Arctic mixed-phase clouds. The control experiment (“CTL”) has the same model configuration as default EAMv1, except that we remove the artificial parameter that is applied to the WBF process. This is also the case for all the sensitivity experiments. In this way, we can emphasize our study on the impact of changes in model physical parameterizations on simulated Arctic mixed-phase clouds. In “MEYERS”, the Meyers et al. (1992) heterogeneous ice nucleation parameterization replaces the CNT scheme in CTL. As nucleated ice particle number concentrations largely differ between the two schemes, this experiment is designed to understand how different heterogeneous nucleation schemes would influence the partitioning of condensed cloud water in EAMv1. The experiment “UW” replaces
the CLUBB with the CAM5 University of Washington (UW) PBL turbulence scheme
(Bretherton & Park, 2009), shallow convection scheme (Park & Bretherton, 2009), and cloud
macrophysics scheme (Park et al., 2014), which is used to study the impact of CLUBB on the
simulated SLF. Finally, in the experiment “UW_MG1”, the MG2 two-moment cloud
microphysics is further changed to MG1 based on the experiment “UW”. By comparing the
“UW” with “UW_MG1”, the impact of prognostic treatment of precipitating hydrometeors on
simulated mixed-phase clouds can be analyzed. We note that we use EAMv1 as the baseline,
because we want to trace back which parameterization changes that have been made during the
EAMv1 development are responsible for the model behavior change. EAMv1 provides the
option for the user to switch back to certain old parameterizations without too much effort
involved.

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 large-scale states (i.e., horizontal wind, temperature, and water vapor) are from the
ERA-Interim reanalysis. To avoid potential problems associated with model initial spin-up and
surface types, Day 2 (24 - 48 hr) hindcasts at the land grid point that is closest to the ARM NSA
Barrow observation site (71.3°N, 156.6°W) are extracted and used for our analysis.

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 dataset (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, five different retrieval products are available, which are either from the ARM baseline retrievals (MICROBASE) or from individual research groups (See Zhao et al., 2012 for more details). The hourly-averaged ACRED data in October 2004 is used for validating the short-term hindcast results.

Other observational data comprises the frequency of cloud occurrence based on the integrated measurements from ARM cloud radars, lidars, and laser ceilometers with the Active Remotely Sensed Clouds Locations (ARSCL) algorithm (Clothiaux et al., 2000), and in-situ measurements of the microphysical properties of single-layer boundary layer mixed-phase clouds from the University of North Dakota (UND) Citation aircraft between 9 - 12 October 2004 (McFarquhar et al., 2007). During the M-PACE field campaign, four flights were conducted to measure the cloud microphysical properties of single-layer boundary layer mixed-phase clouds. Each flight lasted for 1 - 2 hours with cloud data collected every 10s.

3. Results

3.1. Modeled mixed-phase clouds

Figure 1 compares the time-pressure cross sections of the ARM observed cloud frequency of occurrence at the NSA Barrow site and modeled grid-mean cloud fraction from the day-2 hindcasts. Multi-layer mixed-phase clouds were observed between 5 - 8 October 2004, whereas single-layer boundary layer mixed-phase clouds existed for the following 6-day period (9 - 14 October). Maximum cloud fraction was observed at ~900 hPa. High clouds associated
with frontal systems dominated the last period of the M-PACE field campaign. The single-layer low-level mixed-phase clouds from 9 to 14 October is a classic example of the Arctic mixed-phase clouds that are ubiquitous over the Arctic region. In the following discussion, we will emphasize our analysis on the single-layer mixed-phase clouds to understand how the changes in physical parameterizations in EAMv1 affect their simulations.

Figure 1b shows that CTL simulates the resilient low-level single-layer mixed-phase clouds between 9 - 14 October reasonably well. The cloud lifetime and temporal evolution, as well as the cloud top height are also captured by the model. The simulated cloud base, however, is slightly lower than the observations. We note that the cloud base (top) are defined as the lowest (highest) level with non-zero cloud fraction simulated in the model. In general, the simulated maximum cloud fraction shows little sensitivity to the parameterization changes during the examined time period (Figures 1c, 1d, and 1e). In contrast, the simulated cloud boundary is quite sensitive to the examined parameterizations. For example, the ice nucleation scheme changed from the Meyers scheme to CNT leads to an increased cloud base height, closer to the observations (Figure 1c), while using CLUBB to replace the UW schemes results in a lower cloud base (Figure 1d). As cloud fraction is determined via the relative humidity in 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 (not shown). For cloud microphysical parameterizations, the MG2 microphysics largely improves cloud base height as indicated in Figure 1e compared to MG1.

Although the overall cloud structure is reasonably produced for the single-layer mixed-phase clouds, large impacts from different model physical 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 the three sensitivity experiments. Note that the rain and snow water mass mixing ratios are added to LWC and IWC, respectively, to better compare with the observations which cannot distinguish them. One unexpected result shown in Figure 2 is that CTL simulates almost no ice water mass mixing ratio in the mixed-phase clouds during 9 - 14 October. Supercooled liquid water constitutes nearly all the condensed water mass mixing ratio for the persistent single-layer low-level mixed-phase clouds at temperatures about -14°C (Figures 2a and 2e). SLF is therefore close to 1 for these clouds (Figure 2i). This model behavior is in contrast to the previous M-PACE studies with CAM5 where cloud ice water was commonly overestimated while cloud liquid water was significantly 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 for the single-layer mixed-phase clouds is most likely a result of too little ice being produced in the low-level mixed-phase clouds as we will discuss later.

Compared to CTL, more IWC is produced in MEYERS, indicating that the use of CNT in EAMv1 leads to fewer IWC simulated for the single-layer mixed-phase clouds. Shi and Liu (2019) found that this was due to the lower number concentration of ice particles formed from the CNT heterogeneous ice nucleation while Meyers et al. overestimates INP number concentrations compared to observations (DeMott et al., 2010). The use of CLUBB also plays an important role on the decrease of cloud ice by comparing CTL and UW (Figures 2e and 2g). MG2 microphysics slightly reduces IWC and increases LWC by comparing UW and UW_MG1 (Figures 2c and 2g with Figures 2d and 2h). This is because MG2 microphysics tends to have a higher accretion rate of cloud liquid by rain than MG1. The conversion from cloud liquid to ice
then 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. 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), although CNT is used in the UW_MG1 experiment. When Meyers et al. 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 et al. or CNT scheme) and CAM5 demonstrates that the change of model dynamic core, vertical and horizontal resolutions, and model tuning should not be the important reasons for the significant 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 LWC. Less spatial occurrence of high SLF is simulated in the single-layer mixed-phase clouds when Meyers et al. ice nucleation, UW parameterizations, and MG1 cloud microphysics are used, respectively.

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 - 14 October for single-layer boundary layer mixed-phase clouds, particularly at temperatures between -10°C and -15°C (Figure 3). It is clear that all the three changes of physical parameterizations 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 old ones (i.e., Meyers, UW, and MG1), and 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 in liquid phase retrievals among different retrieval algorithms compared to those in ice phase retrievals. One to two orders of magnitude differences can be found in the retrieved IWP, which could be the result of different assumptions made in the IWP retrieval algorithms (Zhao et al., 2012). Compared to the ground-based retrievals, CTL overpredicts LWP by a factor of 2 - 3 during more than half of the M-PACE time, especially during 10 - 13 October when the low-level boundary layer mixed-phase clouds were observed. Regarding IWP, it is shown that CTL underestimates the observed IWP by 3 - 5 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. Note that cloud altitude is normalized from 0 at cloud base to 1 at cloud top for both the observations and model results, where 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 (i.e., LWC and IWC). There were two flights on 9 October, and one flight on 10 and 12 October, respectively. In Figure 5, as we plot the in-situ observations based on the date, so we combine the two flights on 9 October using the same color. The aircraft data were processed by McFarquhar et al. (2007).
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 as lower SLF is found 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 significantly overestimates SLF in the single-layer mixed-phase clouds. The simulated SLF remains close to 100% for all cloud layers during the examined time period. Compared to CTL, MEYERS better reproduces the vertical distribution of SLF in the observations, but its SLF near the cloud base tends to be underestimated compared to observations. This underestimation is probably because we include total water mass mixing ratio to define the cloud base in our sampling strategy. As high ice particle number concentration is generated from the Meyers et al. ice nucleation parameterization near the cloud base, cloud ice water dominates the sampled cloud base in MEYERS. It is clearly shown in Figure 2b and 2f that cloud liquid water tends to distribute separately from cloud ice water in modeled clouds. Figure 5d shows that the increasing SLF pattern with normalized cloud height is well captured by UW 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 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 of Alaska coast and brought cooled air to the Barrow site, largely decreasing surface temperature during 9 October (Verlinde et al., 2007). The overestimated cloud ice mass shown in UW may be explained by the inadequate representation of this transition in the UW schemes. In contrast to UW, UW_MG1, which replaced MG2 with MG1, does not capture the increasing pattern of simulated SLF on 10 and 12 October, indicating
the use of MG2 microphysics is able to improve the SLF vertical distribution of modeled single-layer mixed-phase clouds.

4. Mass budget analysis

To better understand which cloud microphysical processes play the most important role in the changes of model behavior in simulating mixed-phase cloud phases in EAMv1 compared to CAM5, in this section we further analyze the 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 - 11 October. The budget terms are the vertical integrals of microphysical process tendencies over the selected time period.

4.1. Impact of heterogeneous ice nucleation

Figure 6a shows that liquid water condensation constitutes the majority of cloud liquid water source 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 three 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 suggests that different heterogeneous ice nucleation schemes have minimal impacts on the liquid water formation.
It is interesting to notice that even though cloud ice and snow mass mixing ratios are negligible in the single-layer mixed-phase clouds between 9 and 11 October in CTL, ice phase associated microphysical processes remains 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 MEYERS to CTL, with the 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 largely increased, which leads to the 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, substantially inhibiting the accretion of liquid droplets by rain drops (Figure 6b). This further increases the ratio of ice water mass mixing ratio to liquid water mass mixing ratio. Therefore, the number concentration of ice particles generated from heterogeneous ice production is important for the Arctic single-layer mixed-phase clouds. The heterogeneous 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 production 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 significantly small. This is because the mass of newly formed ice crystals is so small that they 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 the ice particle number concentration impacts cloud ice growth processes such as WBF.

4.2. Impact of CLUBB

Comparing UW to CTL, the change of cloud physical processes in the simulated mixed-phase clouds due to the use of CLUBB can be analyzed. In the UW experiment, the 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, it is no longer able to diagnose the detrainment and condensation processes 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 the importance of the
initial amount of cloud ice (either from shallow convection detrainment or from heterogeneous ice nucleation) here, because one prerequisite for the ice mass growth is that it requires the modeled clouds to contain sufficient cloud ice at the beginning. As noted in section 2.1, ice phase related processes are currently not explicitly treated in CLUBB’s PDF method. Instead, ice mass mixing ratio is transported to CLUBB through an eddy diffusion scheme. Such an eddy diffusion transport, however, is found to be inactive in the examined low-level boundary layer mixed-phase clouds (shown in Figure 6c). Without the initial ice from shallow convection when CLUBB is used, the further increase of cloud ice mass mixing ratio is substantially weaker in CTL when compared to UW, such as the WBF process 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 stratiform cloud microphysical parameterization, ice depositional growth is parameterized as two separate processes. The WBF process is one of them, which represents the conversion of cloud liquid water to ice (and snow) assuming homogeneous mixing between liquid and ice (and snow) in each grid cell at subfreezing temperatures. Since the MG microphysics does not treat the evaporation of cloud liquid water, the real WBF process that liquid droplets evaporate first and then water vapor deposits on ice crystals is not numerically represented. When abundant cloud ice coexists with cloud liquid in mixed-phase clouds, the WBF process will first be activated to consume available liquid water in the MG microphysics. Under the circumstance that cloud liquid water is totally consumed within one model time step (5 minutes, 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 invoked
as ice depositional growth in the MG microphysics. Therefore, the indication of ice deposition in UW implies that all available liquid water in the simulated single-layer mixed-phase clouds is completely consumed at certain levels or at certain time steps, but such a total consumption never occurs in CTL because of the weak growth rate of ice particles. Furthermore, because of the larger source for ice mass mixing ratio in UW, snow water also becomes more abundant via autoconversion of cloud ice. Accretion of rain and ice by snow particles is enhanced, which further increases the amount of ice phase cloud condensates in modeled mixed-phase clouds.

Therefore, in CTL modeled single-layer low-level mixed-phase clouds, the CLUBB parameterization significantly underestimates one source of cloud ice water that is represented in Park and Bretherton (2009). Such underestimation of cloud ice largely reduces the initial amount of ice particles that grow through the following cloud microphysical processes. Increases of cloud ice and snow mass mixing ratios are then substantially inhibited, resulting in an underestimation of total ice mass mixing ratio.

4.3. Impact of MG2

The impact of cloud microphysical parameterization change from MG1 to MG2 can be examined by comparing UW and UW_MG1 experiments. In general, 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, as well as the snow accretion of liquid droplets become substantially weaker in UW than UW_MG1. These changes can be mostly attributed to the prognostic treatment of precipitation hydrometeors (rain and snow) in the MG2
microphysics. Another important aspect in MG2 modeled clouds lies in the higher accretion rate of liquid droplets by rain drops as shown in Figure 6a and 6b. Although total cloud ice mass mixing ratio is largely reduced in the simulated mixed-phase clouds with MG2 microphysics, there is no significant change in the formation of initial cloud ice amount. 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 parameterization changes. Nevertheless, as noted in Gettelman et al. (2014), 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 modeled high-latitude single-layer mixed-phase clouds in the U.S. DOE E3SM atmospheric model (EAMv1) compared to its predecessor, CAM5. The hindcast approach allows us to isolate model deficiencies in its physical parameterizations and to compare model results directly to field campaign observations. A series of short-term hindcasts with EAMv1 are conducted for the DOE ARM Mixed-Phase Arctic Cloud Experiment (M-PACE) field campaign period when well-defined single-layer mixed-phase clouds were observed during 9 - 14 October 2004 at the ARM NSA site. Day-2 hindcast results are utilized to compare with observational data collected during M-PACE. We
find that the simulated single-layer boundary layer mixed-phase clouds are overly dominated by supercooled liquid water in the default EAMv1. Such a model behavior is dramatically different from CAM5. Compared to CAM5, EAMv1 has adopted a few major changes in the physical parameterizations, and these parameterizations can largely alter the model performance on the mixed-phase cloud phase partitioning. In this study, three parameterizations are targeted, including the use of CNT heterogeneous ice nucleation scheme; the CLUBB scheme which unifies shallow convection, PBL turbulence, and cloud macrophysics in a unified framework; as well as the MG2 cloud microphysics which prognostically treats the number and mass mixing ratios of precipitation hydrometeors. Three sensitivity experiments are performed to isolate the individual effect of the aforementioned schemes on simulated single-layer mixed-phase cloud properties.

The hindcast results show that too little total ice water mass mixing ratio is produced in the default EAMv1 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 the CNT ice nucleation scheme, CLUBB parameterization, and MG2 cloud microphysics all tend to decrease cloud ice mass mixing ratio, respectively. When all three schemes are combined together, the decreased cloud ice resulted from individual scheme change tends to add up, leading to a significant decrease of cloud ice amount and a significant increase of cloud liquid amount in modeled single-layer Arctic mixed-phase clouds. The detailed budget analysis of cloud microphysical process tendencies indicates that the initial ice particles are critical for the increase of total ice mass in the following cloud microphysics. Two important processes, the
heterogenous ice nucleation and the detrainment of cloud ice from shallow convection, produce a minimal number of initial ice particles when EAMv1 uses CNT and CLUBB to respectively replace the Meyers et al. ice nucleation scheme and the UW shallow convection and turbulence parameterizations used in CAM5. As the mass growth rate of ice crystals depends sensitively on the number concentration of ice particles in cloud microphysics, cloud ice mass is largely reduced. For example, the WBF process with respect to ice is much weaker in CTL compared with 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. As the use of MG2 does not impact the initial ice crystals, the MG2 cloud microphysics should not be a primer reason for the underestimation of cloud ice. However, the introduction of MG2 significantly reduces the WBF process with respect to both ice and snow, and the snow accretion of liquid, which also results in a lower total ice mass.

We note that the issue analyzed in this paper is more 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 be passed to the modeled mixed-phase clouds. EAMv1, like many other GCMs, underestimates the dust transport from mid-latitude sources and Arctic local dust sources, and neglects biological aerosols. This leads to the substantial underestimation of INP number concentrations over the Arctic (Shi & Liu, 2019). Such biases in modeled aerosols and INPs contribute to the biased phase partitioning of high latitude mixed-phase clouds in EAMv1. To address the issue in the CLUBB parameterization, including the phase partitioning
of CLUBB condensed cloud water in a similar approach as Park and Bretherton (2009) may help to increase the initial ice that passes to the MG2 microphysics. Ice phase should also be considered in the CLUBB’s PDF parameterization in order to develop a unified framework for shallow convection, PBL turbulence, and cloud macrophysics for cold clouds. Moreover, other cloud microphysical processes important for the increase of cloud ice mass may not be parameterized in the MG2 cloud microphysics. For example, the secondary ice production is too weak in the current modeled mixed-phase clouds.

Although this study is based on an analysis of the M-PACE field campaign at one single location, the overly dominated cloud liquid water tends to be a common phenomenon beyond this ARM site in EAMv1 modeled mixed-phase clouds (figures not shown). Results from a global evaluation of EAMv1 simulated mixed-phase clouds will be reported in a separate paper. As indicated in earlier studies, mixed-phase cloud feedback and climate sensitivity can be strongly influenced by the mixed-phase cloud phase partitioning (Tan & Storelvmo, 2019; Tan et al., 2016). How the biased phase partitioning of condensed cloud water in low-level mixed-phase clouds identified in this study would impact the cloud feedback and climate sensitivity estimated by E3SM is of interest to understand in the future study. Due to the ubiquitous distribution of this type of clouds in mid- and high latitudes, how to improve the mixed-phase cloud phase partitioning simulated in GCMs is still an open question for the community. Attempts can be either from the aerosol aspect or cloud microphysics aspect to address the outstanding problems.
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Table 1. **Summary of Physical Parameterizations in EAMv1 Simulations**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Configurations</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL</td>
<td>Parameter “berg_eff_factor” change to 1.0</td>
<td>Same as default EAMv1, but use the value 1.0 for the parameter that controls the WBF rate.</td>
</tr>
<tr>
<td>MEYERS</td>
<td>Same as CTL, but replace the CNT ice nucleation scheme (Wang et al., 2014) with Meyers et al. (1992)</td>
<td>Examine the effect of heterogeneous ice nucleation. Note that the Meyers scheme generally produces higher INP number concentrations than CNT.</td>
</tr>
<tr>
<td>UW</td>
<td>Same as CTL, but replace CLUBB with the CAM5 UW shallow convection, PBL turbulence, and cloud macrophysical schemes (Park and Bretherton, 2009; Bretherton and Park 2009; Park et al. 2014)</td>
<td>Examine the effect of CLUBB.</td>
</tr>
<tr>
<td>UW_MG1</td>
<td>Same as UW, except using the MG1 microphysics</td>
<td>Examine the effect of updated cloud microphysics.</td>
</tr>
</tbody>
</table>
Table 2. Summary of M-PACE Observations Used in This Study

<table>
<thead>
<tr>
<th>Observation</th>
<th>Quantity</th>
<th>Source and reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACRED</td>
<td>LWC/LWP and IWC/IWP</td>
<td>ARM cloud retrieval ensemble dataset (ACRED; Zhao et al., 2012)</td>
</tr>
<tr>
<td>ARSCL</td>
<td>Cloud fraction</td>
<td>Active Remotely Sensed Clouds Locations (ARSCL) algorithm (Clothiaux et al., 2000)</td>
</tr>
<tr>
<td>UND Citation</td>
<td>LWC and IWC</td>
<td>University of North Dakota (UND) Citation aircraft (McFarquhar et al., 2007)</td>
</tr>
</tbody>
</table>

Figure 1. Time-pressure cross sections of cloud fraction at the NSA Barrow site during the M-PACE field campaign. (a) Observed frequency of occurrence of clouds from the Active Remotely Sensed Clouds Locations (ARSCL) algorithm. (b) Simulated cloud fraction from CTL. (c)-(e) are the differences in simulated cloud fraction between (c) CTL and MEYERS, (d) CTL and UW, and (e) UW and UW_MG1. Unit: %. Note that CTL utilizes CLUBB, MG2, and CNT parameterizations, while three sensitivity experiments have changes of Meyers et al. (1992) ice nucleation (MEYERS), UW shallow convection, PBL turbulence, and cloud macrophysics parameterizations (UW), and both UW schemes and MG1 cloud microphysics (UW_MG1), respectively.

Figure 2. Time-pressure cross sections of simulated total cloud liquid water mass mixing ratio (including rain water mass; upper panel), total cloud ice water mass mixing ratio (including snow water mass; middle panel), and supercooled liquid fraction (lower panel) during the M-PACE field campaign from CTL, MEYERS, UW, and UW_MG1 (from left to right). (a)-(d) are for
cloud liquid water, (e)-(h) are for cloud ice water mass, and (i)-(l) are for supercooled liquid fraction. Contours represent the ambient temperature in the unit of °C.

Figure 3. Time-pressure cross sections of simulated grid mean cloud ice number concentrations for the M-PACE. (a) CTL, (b) MEYERS, (c) UW, and (d) UW_MG1. Contours represent the ambient temperature in the unit of °C.

Figure 4. Time series of liquid water path (including rain; upper panel) and ice water path (including snow; lower panel) from the EAMv1 and the ARM ACRED dataset. CTL is presented by red solid line, MEYERS green solid line, UW blue solid line, and UW_MG1 brown solid line. For the ACRED dataset, red star is the MICROBASE observation. Green plus is the retrieval from Shupe (2007). Purple cross represents the retrieval products from Wang et al., (2004). Dark blue circle is from Dong and Mace (2003), and orange triangle is from Deng and Mace (2006). Grey lines represent the one standard deviation for each data point.

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, 12 October which correspond to the same time period as the measurements.
Figure 6. Budgets of vertically integrated cloud physical process tendencies of (a) cloud liquid, (b) rain, (c) cloud ice, and (d) snow hydrometeors from the short-term hindcast day-2 results of CTL (red bars) and three sensitivity experiments, which are MEYERS (green bars), UW (blue bars), and UW_MG1 (brown bars). The vertically integrated process rates are averaged over 3-day period between 9 and 11 October 2004 during the M-PACE field campaign.
References


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Figure 2.
Figure 4.
Figure 5.
Figure 6.