Earth and Space Science

RESEARCH ARTICLE
10.1029/2019EA001029

Key Points:
- Global climate model underestimates liquid cloud fraction and overestimates ice cloud fraction at high, medium, and low levels.
- The misclassification of cloud phase causes that 50% supercooled liquid fraction line is 15°C warmer than observation.
- Model produces excessive ice cloud in extratropics and insufficient liquid cloud in tropics in mixed-phase levels.

Correspondence to:
Y. Peng,
pjyiran@tsinghua.edu.cn

Citation:
Guo, Z., Wang, M., Peng, Y., & Luo, Y. (2020). Evaluation on the vertical distribution of liquid and ice phase cloud fraction in Community Atmosphere Model version 5.3 using Spaceborne Lidar Observations. Earth and Space Science, 7, e2019EA001029. https://doi.org/10.1029/2019EA001029

Received 1 DEC 2019
Accepted 10 FEB 2020
Accepted article online 20 FEB 2020

Abstract Cloud partition between liquid and ice phases and their vertical distributions are crucial to energy budget and global climate. Liquid and ice cloud fractions simulated by Community Atmosphere Model version 5.3 and Cloud Feedback Model Intercomparison Project Observational Simulator Package version 1.4 are evaluated by comparing to satellite retrieval data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation. Model underestimates liquid cloud by 3.3%, 5.5%, and 3.1% and overestimates ice cloud by 1.5%, 6.3%, and 4.6% in high, medium, and low levels, respectively. The misclassification of liquid cloud to ice cloud occurs in all model levels, leading to an overall underestimation of supercooled liquid fraction (SLF) globally and a shift of 50% SLF line from about −20°C in observation to −5°C in model. Specifically, model produces excessive ice cloud in extratropics and insufficient liquid cloud in tropics at mixed-phase levels with temperature between 0 and −40°C.

Plain Language Summary Cloud contains water droplets and ice crystals. In temperature between 0 and −40°C, supercooled water can coexist with ice particles. The ratio of liquid phase to total cloud amount and its vertical distribution could modulate the solar energy reaching the Earth’s surface and impact on the global climate. We ran a global climate model and compared the liquid fraction of cloud with satellite measurements. The model produces more ice, but less liquid cloud in all vertical levels thus underestimates the liquid fraction of cloud. The bias is significant in the levels with coexisted ice and supercooled water clouds and in tropical and high-latitude regions. The deficiencies in cloud calculation scheme in model are discussed and that could shed a light on future model improvement.

1. Introduction

Clouds modify the Earth’s energy budget by reflecting the incoming solar radiation and absorbing and emitting infrared radiation. Clouds are usually assumed as pure ice below around −40°C and as pure liquid above 0°C (Pruppacher et al., 1998) for simulation with global climate models (GCMs) or for satellite retrieval algorithms (e.g., Gettelman et al., 2010; Shupe, 2011). Mixed-phase cloud is defined as a type of cloud that liquid and ice coexist in a range of temperature between 0 and −40°C, which occupies globally and largely in midlatitude and high latitude (Choi et al., 2010; Shupe, 2011; Zhao & Wang, 2010). The partition of liquid and ice in mixed-phase cloud involves complex processes, such as ice nucleation (Meyers et al., 1992), Wegener–Bergeron–Findeisen (WBF) process (Bergeron, 1935; Findeisen, 1938; Wegener, 1911), deposition (Meyers et al., 1992), and riming (Hallett & Mossop, 1974). The ratio of liquid cloud fraction to total (sum of liquid and ice) cloud fraction between the temperature of −40°C to 0°C is defined as supercooled liquid fraction (SLF) in cloud. The optical properties of liquid and ice cloud depend on the size and number of water droplets or ice crystals, as well as the cloud water/ice content. Liquid cloud mainly influences on the shortwave radiation, while ice cloud on the longwave radiation (Matus & L’Ecuyer, 2017; Pruppacher et al., 1998). The vertical structure of liquid and ice cloud fraction (Cesana & Chepfer, 2012; Wang & Rossow, 1998), and SLF (Matus & L’Ecuyer, 2017; Tan et al., 2016) strongly affects the radiative property of mixed-phase cloud. Therefore, an evaluation on vertical distribution of mixed-phase cloud in GCM is essential for better understanding the physical processes in cloud and for accurately constraining the model results for climate projection.
Early measurement of cloud phase was derived from brightness temperature that was indirectly acquired by passive satellite, such as Moderate Resolution Imaging Spectroradiometer (Barnes et al., 1998; Platnick et al., 2003) and International Satellite Cloud Climatology Project (Rossow & Schiffer, 1999), which could provide 2D map of cloud phase information. In year 2006, Cloud-Aerosol Lidar with Orthogonal Polarization on board the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite (Winker et al., 2007) was launched. It was the first spaceborne lidar that could retrieve the vertical structure of cloud properties from the relationship between backscattered and depolarized returned lidar signal (Hu, 2007; Hu et al., 2009).

Cloud product of CALIPSO provided the respective occurrence frequency of liquid and ice cloud (Chepfer et al., 2010), while GCMs predicted the cloud water contents of liquid and ice phases, thus leading to a gap in comparison between them (Komurcu et al., 2014; McCoy et al., 2015; Tan et al., 2016). Some researchers used the temperature at a specific ratio between liquid and total water content to evaluate the model performance (e.g., 50% in McCoy et al., 2016; 10% in Cesana et al., 2015), but the information of vertical structure was somehow lost. Cesana and Chepfer (2013) proposed a method enabling an apple-to-apple comparison between model results and satellite retrievals for cloud phase, which calculated the backscattered and depolarized returned lidar signal using GCM output and applied a same cloud phase detecting threshold as used in CALIPSO retrieval algorithm. This method was included in the new version of Cloud Feedback Model Intercomparison Project Observational Simulator Package version 1.4 (COSP1.4) in Community Atmosphere Model version 5.3 (CAM5.3), providing a global view of cloud distribution with phase information (Kay et al., 2016). CALIPSO retrieval and the corresponding COSP have been used for cloud evaluation in global models. For example, the vertical structure of cloud fraction in some Coupled Model Intercomparison Project 5 models (Cesana & Chepfer, 2012; Wang et al., 2014) was validated with CALIPSO data. Kay et al. (2016) exhibited 2D global map of cloud phase from CALIPSO retrieval and reduced the cloud phase biases in Southern Ocean by adjusting the shallow convection scheme in CAM5. However, the cloud phase information in vertical layers always lacks in previous model evaluations. In this study, we will combine the vertical distributions of cloud fraction and cloud water-ice partition from CALIPSO retrieval, for comprehensively evaluating the cloud phase simulation in CAM5.3 by utilizing COSP1.4. The cloud product from CALIPSO and detailed calculations in COSP1.4 are described in Section 2. Results of the evaluation are shown in Section 3. Discussions and possible indications for future model improvements are summarized in Section 4.

2. Data and Methods

2.1. CALIPSO-GOCCP Data

CALIPSO satellite (Winker et al., 2007) was launched in April 2006. The polarization lidar was onboard for aerosol and cloud measurements and gathered profiles every 330 m along the satellite flight track with a vertical resolution of 30 m below 8 km in altitude and 60 m above 8 km. The GCM-Oriented CALIPSO Cloud Product (CALIPSO-GOCCP hereafter) (Chepfer et al., 2010) is designed for comparing the GCM-simulated cloud fraction and microphysical properties with satellite observation by utilizing the corresponding simulator with a horizontal resolution of 2° × 2° (Chepfer et al., 2008). This data set provided the vertical distribution of cloud data and was widely used for model evaluation (Cesana et al., 2012; Chepfer et al., 2008; Wang et al., 2014; Yin et al., 2015). To obtain CALIPSO-GOCCP product, the cloud detection was determined by scattering ratio (SR) of total attenuated backscattered (ATB) signal to gas molecular ATB (aerosol was not considered, Chepfer et al., 2008) from level 1 product of CALIPSO. Pixels with SR larger than 5 was flagged as cloudy, SR between 0.01 and 1.2 as clear, SR less than 0.01 as fully attenuated, and SR between 1.2 and 5 as unclassified. The cloud fraction in each vertical level (or in a range of vertical levels) is defined as the number of cloudy pixels divided by total number of pixels measured (fully attenuated pixels are excluded). The cloud fraction (CF) on each layer is calculated following:

\[
CF = \frac{N_{\text{cloudy}}}{N_{\text{cloudy}} + N_{\text{clear}} + N_{\text{unclassified}}};
\]

where \(N_{\text{cloudy}}\), \(N_{\text{clear}}\), and \(N_{\text{unclassified}}\) indicate the number of pixels flagged as cloudy, clear, and unclassified,
respectively. Note that the total CF in a whole atmospheric column does not necessarily equal to the sum of CF in low, medium, and high levels.

For cloud phase discrimination, Cesana and Chepfer (2013) suggested a phase discrimination method according to the relationships between ATB and polarized ATB ($ATB_\perp$) for cloud phase classification in satellite retrievals. The cloudy pixels located below an optically thick cloud with SR larger than 30, or pixels with ATB higher than 1 or less than 0, or pixels high ATB but with $ATB_\perp$ close to 0 are classified as undefined (because of the unrealistic ATB values). CF is divided into three parts as liquid cloud fraction ($CF_{\text{liq}}$), ice cloud fraction ($CF_{\text{ice}}$), and undefined cloud fraction ($CF_{\text{undef}}$) as followed:

$$CF = CF_{\text{liq}} + CF_{\text{ice}} + CF_{\text{undef}}.$$  \hfill (2)

The liquid (ice) cloud fraction is defined as the number of pixels classified as liquid (ice) divided by pixels classified as cloudy and then multiply by cloud fraction as followed:

$$CF_{\text{liq}} = \frac{N_{\text{cloudy, liq}}}{N_{\text{cloudy}}} \times CF,$$  \hfill (3)

$$CF_{\text{ice}} = \frac{N_{\text{cloudy, ice}}}{N_{\text{cloudy}}} \times CF.$$  \hfill (4)

By using the temperature profile from Global Modeling and Assimilation Office (GMAO) data (Bey et al., 2001), CALIPSO-GOCCP provided global cloud fraction and cloud phase information in altitudinal and isothermal layers, respectively. CALIPSO-GOCCP data have a vertical resolution of 480 m from surface to 19.2 km; and the data in isothermal layers are with the temperature interval of 3°C. High, medium, and low cloud was defined at the levels below 3.36 km, between 3.36 and 6.72 km, and above 6.72 km, respectively.

About 10% of the clouds identified in CALIPSO-GOCCP data set were classified as undefined phase, and these clouds are under relatively high reflective clouds (SR > 30) (Cesana & Chepfer, 2013). In this study, we take liquid, ice, and total cloud fractions and SLF from CALIPSO-GOCCP data set and average from 2007 to 2011 for model evaluation. Chepfer et al. (2010) found much noisier data at clear-sky day time than night, and 30% of the profiles are abandoned in data quality check. The difference of day and night data is within 1% in global scales; thus, the night data from CALIPSO retrieval are selected for avoiding lidar noises.

### 2.2. COSP1.4 in CAM5.3

The Cloud Feedback Model Intercomparison Project Observational Simulator Package (COSP) (Bodas-Salcedo et al., 2011) is a simulator embedded in GCM. It calculates cloud properties mimicking the way that satellite observes cloud so that the model output of simulated clouds can be comparable to satellite retrievals. COSP1.3 was the first simulator for CALIPSO satellite and implemented in CAM4 and CAM5 (Kay et al., 2012). In COSP for CALIPSO, ATB and $ATB_\perp$ were calculated with model output of pressure, temperature, cloud liquid (ice) mixing ratio, number concentration, and effective radius of cloud droplet (ice/snow particle) size distribution, following the method in Chepfer et al. (2008) and Cesana and Chepfer (2013). The cloud phase discrimination method proposed by Cesana and Chepfer (2013) was added to the new version of COSP1.4, and the simulator calculated SR, ATB, and $ATB_\perp$ for discriminating cloud fraction between liquid and ice phases in isothermal and altitudinal layers, respectively. COSP1.4 is called every 3 time steps in CAM5.3. In-cloud snow is accounted for ice phase (English et al., 2014; Kay et al., 2012).

Here, we discuss about the uncertainty of simulated ATB in COSP1.4. According to Chepfer et al. (2008), the threshold of SR and multiple scattering coefficients of liquid cloud particles were proven to have little impact on the simulated ATB profile. However, the cloud microphysical scheme in CAM5.3 assumed spherical ice crystals and no subgrid vertical variation even with the coarse vertical resolution in high altitudes of model (Morrison & Gettelman, 2008). This hypothesis could specifically affect the scattering coefficients of ice particles in high and thin ice clouds, leading to a mean bias in ATB of $-0.01$ to $-0.006$ (Chiriaco et al., 2006). Overall, the bias of ATB simulated in COSP1.4 is negligible.

CAM5.3 (Neale et al., 2012) is one of the most widely used GCMs for atmospheric research and has participated in the Coupled Model Intercomparison Project 5 (Taylor et al., 2012). The model applied a
two-moment microphysics scheme for large-scale cloud simulation that predicted mass mixing ratio and number concentration of liquid and ice particles in cloud (Gettelman et al., 2010; Morrison & Gettelman, 2008). The macrophysics scheme for cloud fraction diagnosis was designed by Park et al. (2014). The 3-mode Modal Aerosol Module was utilized for aerosol simulation (Liu et al., 2012). In this study, we run CAM5.3 by prescribing the observed sea surface temperature and sea ice fraction. The experiment is conducted with horizontal resolution of 0.9° × 1.25° and lasts for 11 years (2002–2012). The first year is for spin-up, and model output in the last 10 years is taken for analysis.

3. Results

3.1. Global Distribution

The simulated total cloud fraction and the partition between liquid and ice clouds (Figures 1d–1f) have consistent distribution with the results in Kay et al. (2016). Comparing to CALIPSO retrievals (Figures 1a–1c), CAM5.3 underestimates the total cloud fraction, producing less liquid cloud but more ice cloud in midlatitude and high-latitude ocean areas. The high (Figures 1g–1l), medium (Figures 1m–1r), and low (Figures 1s–1x) cloud fractions and their respective partition between liquid and ice clouds are compared with satellite observations, taking from the same range of vertical levels as CALIPSO data (Section 2.1). Generally speaking, CAM5.3 captures the global pattern but underestimates the sum of liquid and ice cloud fraction in all levels especially in subtropical ocean areas as in Kay et al. (2012). Hannay et al. (2009) and Medeiros et al. (2012) pointed out that a too shallow planetary boundary layer depth with moist bias could explain the deviation of low and medium cloud fractions. CAM5.3 underestimates the liquid cloud fraction by 3.3%, 5.5%, and 3.1% for high, medium, and low clouds, respectively. The insufficient water clouds are mainly in subtropical and midlatitude ocean areas. The ice cloud fractions for high, medium, and low clouds are overestimated by 1.5%, 6.3%, and 4.6%, respectively. The superfluous ice clouds are mainly in high latitudes and in poles. The insufficient liquid cloud lead to a warming bias in shortwave radiation at top of the atmosphere (TOA), allowing for more solar radiation to surface in high latitudes as shown in Kay et al. (2014).

3.2. Zonal Mean

Figure 2 shows the zonal means of liquid/ice cloud fraction and SLF at different levels. The underestimation of liquid cloud fraction is mostly attributed to the biases in low and medium clouds in all latitudes (Figure 2a). However, the overestimation of ice cloud is significant in extra tropical areas especially around 60°N and 60°S (Figure 2b). CAM5.3 underestimates SLF in all levels (Figure 2c) due to the misclassification of liquid cloud to ice cloud, which is serious for medium and high clouds in tropics and for low and medium clouds in high latitudes. Cesana and Chepfer (2013) have obtained the similar bias in SLF with another GCM LMDZ5B, indicating that the two GCMs may have common problems in cloud phase partition and in the relevant cloud physical schemes.

3.3. Distribution in Isothermal Levels

Figure 3 demonstrates zonal mean cloud fraction and SLF in isothermal layers from −80°C to 20°C. The discontinuous contours in high levels over tropics (Figures 3e and 3g) are similar as that in Cesana and Chepfer (2013) and mainly due to the different vertical resolution between CALIPSO-GOCCP and COSP simulator. The CALIPSO-GOCCP isothermal data were interpolated from CALIPSO level 1 data (with 30/60 m vertical resolution, see Section 2.1) to each isothermal level by using the temperature profile in GMAO, leading to the smooth contour. However, the COSP simulator applied the vertical resolution of CAM5.3, which had 30 pressure levels and much coarser resolution in high altitudes. Therefore, model results in certain isothermal levels are lacking of valid values and show discontinuities.

CAM5.3 underestimates liquid cloud fraction in the levels warmer than 0°C in midlatitude areas (Figures 3b and 3f). It is possibly resulted from the relatively lower sea surface temperature observed by Hadley Center (Rayner et al., 2003) and used in current simulation, comparing to the GMAO temperature used in CALIPSO-GOCCP data. The lower SST and narrower isothermal lines in midlatitudes (see Figure 4) suggest that low-level temperature is generally colder in model and thus inhibit the formation of liquid clouds and result in the lower liquid cloud fraction than in CALIPSO-GOCCP data.
Figure 1. Global Distribution of Cloud Fraction (unit is %): (a, g, m, s) observations from CALIPSO-GOCCP data set for total, high, medium, and low clouds; (b, h, n, t) for total liquid, high, medium, and low liquid clouds; (c, i, o, u) for total ice, high, medium, and low ice clouds; (d, j, p, v) simulation results from CAM5.3 for total, high, medium, and low clouds; (e, k, q, w) for total liquid, high, medium, and low liquid clouds; and (f, l, r, x) for total ice, high, medium, and low ice clouds. Global mean values are indicated in upper right corner of each panel.
In the mixed-phase layers with temperature between 0°C and −40°C, model produces more ice clouds but insufficient liquid clouds, which biases are more evident in levels between 0 and −20°C (Figures 3b, 3c, 3f, and 3g). Tan and Storelvmo (2016) reported the similar bias in lower part of mixed-phase cloud layers and attributed that mainly to possible misrepresentation of WBF process in model. Because WBF process dominated in levels with relatively warmer temperature around −15°C and with ample supercooled water,

Figure 2. Zonal mean cloud fraction (unit is %) for (a) liquid cloud, (b) ice cloud, and (c) SLF. Solid and dash curves represent CAM5.3 simulation and CALIPSO-GOCCP observation, respectively. Black, red, blue, and green curves represent total cloud, low, medium, and high clouds, respectively. Note that the sum of liquid and ice cloud fractions is not necessarily 100% (see Equations (1)–(4)). The shading represents one standard deviation of the zonal average.

Figure 3. Zonal mean distribution in isothermal layers: (a, b, c, d) CALIPSO-GOCCP observation of cloud fractions for total cloud, liquid, and ice clouds and SLF (unit is %); (e, f, g, h) CAM5.3 simulation of cloud fractions for total cloud, liquid, and ice clouds and SLF. The solid black line represents the level with 50% SLF.
while homogeneous freezing dominated in higher levels with temperature below at least \(-35^\circ\text{C}\). The insufficient liquid cloud and excessive ice cloud in levels between 0 and \(-20^\circ\text{C}\) were also identified in CAM5 by Gettelman et al. (2010). From the aspect of satellite observation, Kay et al. (2016) explained that CALIPSO might misclassify some snowing and optically thin clouds in midlatitudes as liquid clouds, which could be another reason for the bias.

Excessive ice and insufficient liquid clouds lead to a noticeable bias in SLF, which also make a shift of 50% SLF line from around \(-20^\circ\text{C}\) in observation to \(-5^\circ\text{C}\) in model (Figures 3d and 3h). Cesana et al. (2015) showed a similar shift by using the constant water mass ratio line in comparison with CALIPSO satellite data. Tan and Storelvmo (2016) found that the time scale of WBF process to convert cloud liquid water to ice water plays a significant role in modifying the simulated cloud partition between liquid and ice phases.

Figure 4. Zonal mean temperature (Unit: \(^{\circ}\text{C}\)) in pressure levels from GMAO reanalysis (for CALIPSO retrieval use) and from CAM5.3 simulation for 2003–2012.

Figure 5. Global distribution in \(-20^\circ\text{C}\) isothermal level: (a, b, c, d) CALIPSO-GOCCP observation of cloud fractions for total cloud, liquid, and ice clouds and SLF (unit is \(\%\)); (e, f, g, h) CAM5.3 simulation of cloud fractions for total cloud, liquid, and ice clouds and SLF. Global mean values are indicated in upper right corner of each panel.
Figure 6. Global distribution of CALIPSO-GOCCP observation for (a) total cloud and (b) ice cloud fractions and CAM5.3 simulations for (c) total cloud and (d) ice cloud fractions in −60°C isothermal level; CALIPSO-GOCCP observation for (e) total cloud and (f) liquid cloud fractions and CAM5.3 simulations for (h) total cloud and (i) liquid cloud fractions in 10°C isothermal level. Global mean values are indicated in upper right corner of each panel.
It might be the major reason for large bias in extra tropics and high latitudes, where the vertical mixing is relatively weak and microphysical processes have dominant impact on liquid-ice partition in large-scale cloud. On the other hand, Li et al. (2017) pointed that SLF could be affected by meteorological parameters (such as relative humidity and vertical velocity) and aerosol loadings. More aerosols, especially dust acting as the ice nuclei, would cause stronger glaciation and a lower SLF (Li et al., 2017; Tan et al., 2014). SLF could decrease with enhanced vertical velocity for a strong mixing between liquid and ice particles or strong WBF process (Storelvmo et al., 2008).

Figure 5 demonstrates the global distribution of cloud fractions and SLF at −20°C isothermal level for a further investigation on spatial patterns. CAM5.3 overestimates the total cloud fraction especially in extra tropics and high latitudes, which is largely attributed to the excessive ice clouds. The secondary reason could be the insufficient liquid clouds in tropical land regions and over Southern Ocean. The biases of both liquid and ice cloud fractions lead to an overall underestimation of SLF globally. Komurcu et al. (2014) calculated the fraction of supercooled cloud water to total cloud water mass at −20°C isothermal level using CAM5.1 with the aerosol module MAM7, gaining a global mean of ~10% that is consistent with our result in Figure 5h (8.2% of global mean SLF). Additionally, D’Alessandro et al. (2019) compared CAM5 results with in situ observation over Southern Ocean and found that the calculation of water saturation for ice and liquid mixture is inaccurate when liquid water mass fraction is low in model, which could also contribute to the SLF bias.

The global distribution of cloud fraction in −60°C isothermal level is shown in Figure 6, where the model bias is mostly due to pure ice cloud. The underestimates of ice cloud fraction mainly occur in South East Asia, Amazon, and Central Africa (Figures 6a and 6c). It is possibly related to the insufficient humidity in homogeneous freezing process. On the contrary, model bias in 10°C isothermal level is mostly due to insufficient liquid clouds in extra tropical ocean areas (Figures 6e and 6g). The underestimates of liquid cloud in subtropical regions (e.g., in the west coast of South America) are consistent with the large low cloud bias in CAM5, which was attributed to the macrophysics cloud scheme for marine stratocumulus cloud in model (Park et al., 2014; Xiao et al., 2014).

4. Summary and Discussion

In this study, we evaluated the vertical distribution of liquid and ice cloud fractions simulated by CAM5.3 and COSP1.4, in comparison with CALIPSO satellite retrievals. The model underestimates liquid cloud fractions by 3.3%, 5.5%, and 3.1% but overestimates ice cloud fractions by 1.5%, 6.3%, and 4.6% in high, medium and low levels, respectively. The misclassification of liquid cloud to ice cloud leads to an overall underestimation of SLF in all vertical levels. Regarding the cloud fraction in isothermal levels, the 50% SLF line shifts from around −20°C in satellite observation to −5°C in model, which is likely attributed to the insufficient liquid clouds and the excessive ice clouds simulated in the mixed-phase layers (with temperature between 0°C and −20°C).

Our results indicated that the phase partition in cloud physical schemes in CAM5.3 still has potential problems, as recognized in some previous studies (e.g., Gettelman et al., 2010; Liu et al., 2011). First, regarding to cloud macrophysics scheme, CAM5.3 and some GCMs diagnosed the partition between liquid and ice cloud fraction as a function of temperature only (Cesana et al., 2015). This led to noticeable discrepancies in cloud fraction with different phases and in cloud radiative forcing (e.g., over Southern Ocean as mentioned in Flato et al., 2013). The statistical scheme assuming subgrid-scale distribution of water specific humidity or relevant variables/moments (e.g., Tompkins, 2002) and consistent treatment on macrophysics and microphysics schemes could help to simulate the cloud fraction more realistically (e.g., Qin et al., 2018) in GCM.

Second, inadequate assumptions or simplified treatments in cloud microphysics scheme might cause to potential uncertainties. (1) Regarding the generation of ice particles, ice nucleation is one of the key processes for cloud partitioning between ice and liquid phases (Wang et al., 2018). However, the ice nucleation scheme (Meyers et al., 1992) in CAM5.3 largely overestimates the number of ice crystals than observation (Prenni et al., 2007). Both homogenous and heterogeneous ice nucleation schemes in CAM5.3 (Liu & Penner, 2005) are sensitive to aerosol parameters, which could result in a large uncertainty in ice cloud simulation (Liu & Shi, 2018; Shi & Liu, 2018). (2) Regarding the liquid-ice conversion, the model assumed a uniformly mixture of liquid and ice that strongly overestimates the conversion of liquid to ice with WBF process.
The uniform mixing assumption is only valid on the scale as small as tens of meters (Tan & Storelvmo, 2016); thus, a treatment on WBF process suitable for GCM scale should be under consideration. On the other hand, Gettelman et al. (2010) indicated that an instantaneous freezing of all supercooled rain drops at temperature below −5°C could cause to high number concentration of snow and excessive cloud ice. (3) Regarding the growth of ice particles, the accurate simulation of depositional growth, riming and aggregation are limited by coarse representations of size distribution and segmentation of ice particles (CAM5.3 has two types of frozen particles, ice and snow, but ignoring graupel) (Gettelman et al., 2010). More physically based treatment on ice phase processes could be helpful (e.g., Zhao et al., 2017).

According to the results and analysis in this study, we suggest an urgent improvement for WBF process, which is most likely responsible for the bias in liquid-ice partition of cloud fraction in the mixed-phase layer in CAM5.3. In a recent study, Zhang et al. (2019) modified the WBF process in CAM5 and showed remarkable improvements in the cloud phase simulation by comparing with the long-term ground-based multisensor measurements in field campaign. We believe the evaluation with CALIPSO-GOCCP data on a global scale could provide further indications for improving the cloud simulation in GCMs.

Author Contributions

Z. Guo designed the research, conducted model modification and simulation, and analyzed the results. Y. Peng helped with the model works and manuscript refinement. Y. Luo and M. Wang helped with the result analysis.

Acknowledgments

The source code and input data sets of CAM5.3 and COSP1.4 applied in this study are available at https://svn.ccm3-models.cgd.ucar.edu/. The CALIPSO-GOCCP data can be downloaded in https://climserv.ipsl.polytechnique.fr/cfmip/CALIPSO... The GMAO reanalysis data can be downloaded in https://disc.gsfc.nasa.gov/. We thank Dr. Kay for helps with the code of COSP1.4 in CAM5.3. This study was supported by National Important Project of the Ministry of Science and Technology in China (grant No. 2017YFC1501044) and National Natural Science Foundation of China (grant No. 41690106, 41775137, and 71690243).

References

Barnes, W. L., Pagano, T. S., & Salomonson, V. V. (1998). Prelaunch characteristics of the Moderate Resolution Imaging Spectroradiometer (MODIS) on EOS-AM1. IEEE Transactions on Geoscience and Remote Sensing, 36, 1088–1100. https://doi.org/10.1109/36.700993

Bergeron, T. (1935). On the physics of clouds and precipitation. In Proces Verbaux de l'Association de Meteorologie (pp. 156–178). Paris: Int. Union of Geodesy and Geophys.

Bey, I., Jacob, D. J., Yantosca, R. M., Logan, J. A., Field, B. D., Fiore, A. M., et al. (2001). Global modeling of tropospheric chemistry with Bodas-Salcedo, A., Webb, M., Bony, S., Chepfer, H., Dufresne, J., Klein, S., et al. (2011). COSP: Satellite simulation software for model assessment. Bull. Amer. Meteor. Soc., 92, 1023–1043. https://doi.org/10.1175/2011BAMS2856.1

Cesana, G., & Chepfer, H. (2012). How well do climate models simulate cloud vertical structure? A comparison between CALIPSO-GOCCP satellite observations and CMIP5 models. Geophysical Research Letters, American Geophysical Union, 39(20), L20803. https://doi.org/10.1029/2012GL053153

Cesana, G., & Chepfer, H. (2013). Evaluation of the cloud thermodynamic phase in a climate model using CALIPSO-GOCCP. Journal of Geophysical Research: Atmospheres, 118, 7922–7937. https://doi.org/10.1002/jgrd.50376

Cesana, G., Kay, J. E., Chepfer, H., English, J. M., & de Boer, G. (2012). Ubiquitous low-level liquid-containing Arctic clouds: New observations and climate model constraints from CALIPSO-GOCCP. Geophysical Research Letters, 39, L20804. https://doi.org/10.1029/2012GL053385

Cesana, G., Walliser, D. E., Jiang, X., & Li, J.-L. F. (2015). Multimodel evaluation of cloud phase transition using satellite and reanalysis data. Journal of Geophysical Research: Atmospheres, 120, 7871–7892. https://doi.org/10.1002/2014JD022932

Chepfer, H., Bony, S., Winker, D., Cesana, G., Dufresne, J. L., Minnis, P., et al. (2010). The GCM-Oriented CALIPSO Cloud Product (CALIPSO-GOCCP). Journal of Geophysical Research, 115, D00H16. https://doi.org/10.1029/2009JD012251

Chepfer, H., S. Bony, D. Winker, M. Chiriaco, J.-L. Dufresne, & G. Seze. (2008). Use of CALIPSO lidar observations to evaluate the cloudiness simulated by a climate model. Geophysical Research Letters, 35, L15704 https://doi.org/10.1029/2008GL034207.

Chiriaco, M., Vautard, R., Chepfer, H., Haefelin, M., Wanherdrick, Y., Morille, Y., et al. (2006). The ability of MM5 to simulate thin ice clouds: Systematic comparisons with lidar/radar and fluxes measurements. Monthly Weather Review, 134, 897–918.

Choi, Y. S., Lindzen, R. S., & Kim, H. J. (2010). Space observations of cold-cloud phase change. Proceedings of the National Academy of Sciences of the United States of America, 107(25), 11211–11216. https://doi.org/10.1073/pnas.1006341107

D’Alessandro, J. J., Diao, M., Wu, C., Liu, X., Jensen, J. B., & Stephens, B. B. (2019). Cloud Phase and Relative Humidity Distributions over the Southern Ocean in Austral Summer Based on In Situ Observations and CAM5 Simulations. Journal of Climate, 32(10), 2781–2805. https://doi.org/10.1175/JCLI-D-18-0232.1

English, J. M., Kay, J. E., Gettelman, A., Liu, X., Wang, Y., Zhang, Y., & Chepfer, H. (2014). Contributions of clouds, surface albedos, and mixedphase ice nucleation schemes to Arctic radiation biases in CAM5. Journal of Climate. https://doi.org/10.1175/JCLI-D-13-00606.1

Findeisen, W. (1938). Koloid-meteorologische Vorgange bei Niederschlags-bildung. Meteorologische Zeitschrift, 55, 121–133.

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W., et al. (2013). Evaluation of climate models, in Climate Change 2013. In The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker et al. (pp. 741–866). Cambridge, UK, and New York: Cambridge University Press.

Gettelman, A., Liu, X., Ghan, S. J., Morrison, H., Park, S., Conley, A. J., et al. (2010). Global simulations of ice nucleation and ice supersaturation with an improved cloud scheme in the Community Atmosphere Model. Journal of Geophysical Research, 115, D18216. https://doi.org/10.1029/2009JD013797

Hallett, J., & Mysak, S. C. (1974). Production of secondary ice particles during the riming process. Nature, 249(5452), 26. https://doi.org/10.1038/249026a0
Tan, I., Storelvmo, T., & Zelinka, M. D. (2016). Observational constraints on mixed-phase clouds imply higher climate sensitivity. *Science, 352*(6282), 224–227. https://doi.org/10.1126/science.aad5300

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society, 93*, 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1

Tompkins, A. M. (2002). A prognostic parameterization for the subgrid-scale variability of water vapor and clouds in large-scale models and its use to diagnose cloud cover. *Journal of the Atmospheric Sciences, 59*(12), 1917–1942. https://doi.org/10.1175/1520-0469(2002)059<1917:APPFTS>2.0.CO;2

Wang, F., Xin, X., Wang, Z., Cheng, Y., Zhang, J., & Yang, S. (2014). Evaluation of cloud vertical structure simulated by recent BCC_AGCM versions through comparison with CALIPSO-GOCCP data. *Advances in Atmospheric Sciences*, 31(3), 721–733.

Wang, J., & Rossow, W. B. (1998). Effects of cloud vertical structure on atmospheric circulation in the GISS GCM. *Journal of Climate, 11*(11), 3010–3029. https://doi.org/10.1175/1520-0442(1998)011<3010:EOCVSO>2.0.CO;2

Wang, Y., Zhang, D., Liu, X., & Wang, Z. (2018). Distinct contributions of ice nucleation, large-scale environment, and shallow cumulus detrainment to cloud phase partitioning with NCAR CAM5. *Journal of Geophysical Research: Atmospheres, 123*, 1132–1154. https://doi.org/10.1002/2017JD027213

Wegener, A. (1911). *Thermodynamik der Atmosphäre*. Barth, Leipzig, Poland: J. A.

Xiao, H., Mechoso, C. R., Sun, R., Han, J., Pan, H.-L., Park, S., et al. (2014). Diagnosis of the marine low cloud simulation in the NCAR community earth system model (CESM) and the NCEP global forecast system (GFS)-modular ocean model v4 (MOM4) coupled model. *Climate Dynamics, 43*(3-4), 737–752. https://doi.org/10.1007/s00382-014-2067-y

Yin, J., Wang, D., Xu, H., & Zhai, G. (2015). An investigation into the three-dimensional cloud structure over East Asia from the CALIPSO-GOCCP Data. *Science China Earth Sciences, 58*(12), 2236–2246.

Zhang, M., Liu, X., Diao, M., D’Alessandro, J. J., Wang, Y., Wu, C., et al. (2019). Impacts of representing heterogeneous distribution of cloud liquid and ice on phase partitioning of Arctic mixed-phase clouds with NCAR CAM5. *Journal of Geophysical Research: Atmospheres, 124*, 13,071–13,090. https://doi.org/10.1029/2019JD030502

Zhao, M., & Wang, Z. (2010). Comparison of Arctic clouds between European Center for Medium-Range Weather Forecasts simulations and Atmospheric Radiation Measurement Climate Research Facility long-term observations at the North Slope of Alaska Barrow site. *Journal of Geophysical Research, 115*, D23202. https://doi.org/10.1029/2010JD014285

Zhao, X., Lin, Y., Peng, Y., Wang, B., Morrison, H., & Gettelman, A. (2017). A single ice approach using varying ice particle properties in global climate model microphysics. *Journal of Advances in Modeling Earth Systems, 9*, 2138–2157. https://doi.org/10.1002/2017MS000952