# Response to Reviewer #1

We sincerely appreciate Reviewer #1 for spending his/her invaluable time to give us lots of constructive, critical and helpful comments. Most comments were carefully reflected in the revised manuscript. Our responses to individual comments are listed below.

## Major comments

1. **It is not clear whether the only difference between SAM0 and CAM5 is the UNICON scheme. Is this the case? Even so, the scheme itself seems to contain many different changes, making it difficult to isolate cause and effect. There is an awful lot of speculation in the manuscript, from attributing increases in cloud fraction and liquid in the Arctic to increased condensation rate to attributing the increase in condensation rate to poleward transport of heat and moisture. Because it's not clear what exactly is different in SAM0 compared to CAM5 without reading the references in the manuscript in detail, I recommend that the authors conduct sensitivity tests to isolate the individual effects they are speculating. For example, if the authors claim that poleward moisture and heat transports are the main factors in SAM0 that cause an increase in condensation rate in the Arctic, then they could do sensitivity tests where they increase and decrease poleward moisture and heat transports in SAM0 by varying degrees to get a sense of whether or not they are dominant factors in affecting Arctic condensation rate.**

   → First of all, we are sorry for causing the confusion admitting that we didn't provide sufficient description on the models in the original manuscript. In this study, the only difference between SAM0 and CAM5 is the UNICON scheme, which is a unified convection scheme that replaces 1) CAM5's deep and shallow convection scheme (Park, 2014a, 2014b), and 2) convective detrainment process (Park et al., 2017). Other features such as dynamic core, cloud microphysics, PBL, etc. are exactly the same for the two models. We described this on lines 80-81 in the revised manuscript.

   As the reviewer commented, the change of the convection scheme causes many different changes in the results between the two. To look at those differences more clearly, we show the evidence that SAM0 simulates the convection more strongly than CAM5, particularly in most of tropical Ocean and this is a direction to reduce bias from observation (Supplementary S7 in the revised manuscript). Several previous studies have shown that enhanced convective activity in the Tropics enhances the poleward heat and moisture transport by inducing Rossby wave trains from Tropics toward pole that promote warm and moist advection from midlatitude into the Arctic (Lee et al. 2014; Fluorny et al. 2015).

   As with those studies, SAM0 captures Rossby wave trains emanating from Tropics better than CAM5 (Supplementary S6c) and this leads to enhanced poleward heat and moisture transport in SAM0 (Figure 5 in the revised manuscript). In SAM0, the increase in the poleward moisture transport provides more water vapor source to form the cloud and the increase in the temperature by the enhanced poleward heat transport causes to product more cloud liquid condensation then cloud ice condensation in the Arctic region. All these results are consistent with the relative strengthening of convection in SAM0 (lines 230-236 in the revised manuscript).

2. **The errors of the two observational datasets and Reanalysis data used are not discussed or addressed whatsoever. Please include a detailed description of the errors and biases in all three datasets. In particular, the GOCCP dataset does not account for lidar beam attenuation, which is particularly problematic in the Arctic, where optically thick supercooled liquid clouds attenuate the beam. Precipitating ice particles underneath these layers, which are known to commonly exist, would not be detected. If comparing the results of the models to GOCCP alone in terms of cloud amount, GOCCP might underestimate the actual cloud amount. I suggest that the authors either include a ground-based observational dataset to get an idea of the potential biases involved when comparing the models to GOCCP.**

   → Thanks to the reviewer's comment, we now provide descriptions about biases and errors of the satellite observations and the two reanalysis data used in this study especially over Arctic. As reviewer mentioned, CALIPSO-GOCCP may underestimate ice clouds in the lowest levels at midlatitudes and in polar regions because it's lidar beam may not detect some ice crystals underneath the optically thick stratocumulus clouds due to its attenuation (Cesana et al., 2015). CERES-EBAF also may produce an uncertainty over the Arctic, particularly for clear-sky retrievals due to the low albedo contrast between snow and clouds (English et al., 2014). We will carefully discuss the possible biases and errors in detail on lines 107-119 in the revised manuscript.

   Regarding the use of GOCCP as a cloud amount estimate, we supplement the climatology data of long-term ground-based cloud and radiation measurements from 1998 to 2010 at the North Slope of Alaska (NSA) Barrow site (71.38N, 156.68W) from the Atmospheric Radiation Measurement (ARM) Best Estimate (ARMBE) dataset (Xie et al. 2010) for the model evaluation (Figure 2 in the revised manuscript). (lines 119-125 at the revised manuscript)

3. **Although SAM0 is able to produce more low cloud amount and cloud liquid and less cloud ice as illustrated in Figure 2, it is not clear from the figures until Figures 6-9 how the models compare against observations. It could be that SAM0 overshoots low-cloud amount/cloud liquid or undershoots cloud ice relative to the observations. I would suggest including observations in Figure 2 as well. This could be done if the authors were to e.g. run the model in single column mode and compare their results with ground-based observations from the M-PACE field campaign. This could also provide additional evidence to support the authors' claims using an**

**additional complementary ground-based observational dataset. This should also be clarified on lines 17-19 in the Abstract, where it should be specified what observational dataset the reduced biases are with respect to.**

→ Thanks to Reviewer #1's suggestion, we revised Figure 2 of the original manuscript by adding ERA-interim reanalysis cloud liquid/ice contents data (Supplementary Figure S2 in the revised manuscript). We tried to use satellite observation data, but we could not find the data processing method. We inevitably used ERA-interim data. In the result, CAM5 underestimated the total cloud condensation with underestimating both cloud liquid and ice condensation against ERA-interim data. In the SAM0, although cloud ice condensation is underestimated as much as CAM5, cloud liquid condensation is simulated closed to observation, which reduces the overall bias of total cloud condensate in CAM5. (lines 161-165 in the revised manuscript) Instead of conducting a single-column model experiment using M-PACE field campaign data, the climatology data of long-term ground-based cloud and radiation measurements from 1998 to 2010 at the North Slope of Alaska (NSA) Barrow site (71.38N, 156.68W) from the Atmospheric Radiation Measurement (ARM) Best Estimate (ARMBE) dataset (Xie et al. 2010) are used for the model evaluation (Figure 2 in the revised manuscript). In the result, the total cloud fraction (TAC) in CAM5 was simulated totally less than in the observation except for July and August, and the liquid water path (LWP) also underestimate over the entire period. Accordingly, the downward shortwave flux was overestimated, and the downward longwave flux was underestimated particularly in autumn and winter. Although TAC in SAM0 was slightly overestimated in the summertime compared to the observation, SAM0 reduced the bias of CAM5 in the rest of the period. The LWP and the surface radiation fluxes were also simulated closer to the observation than in CAM5. (lines 147-155 in the revised manuscript)

4. **Figure 3: Why these microphysical tendencies? Why not include other microphysical processes such as accretion, autoconversion, wet/dry deposition as well? This analysis may be missing processes that are more important than net condensation rate. Also, the nonlinear interactions between the model tendencies are not quantified in Figure 3; the various processes all feedback and are dependent on one another. The authors could make this analysis more rigorous by quantifying the contribution of these liquid and ice tendencies to cloud liquid and ice mass using a multiple linear regression approach.**

   → Those microphysical tendencies such as accretion are already included in the PRS (cyan lines) in figure 3 of the original manuscript (Figure 4 in the revised manuscript) and they obviously sink the cloud condensation for both liquid and ice processes. Aerosol wet/dry deposition could not be included in the budget analysis because the process is not a cloud liquid/ice condensation process.

5. **The strong negative bias in TCA seems to persist in the summer (Figure 8), yet why does there appear to be little to no SWCF bias? Is LCA more relevant than TCA?**
   → Does reviewer mean Greenland region? If so, the Greenland region in the model is an area of over 1 m of snow, and albedo is close to 1. Therefore, the area reflects most of the incoming shortwave regardless of cloud amount, and SWCF is close to zero.

## Minor comments

1. **Page 9: LCA was never explicitly defined. I'm assuming this stands for low-cloud amount. Does this include clouds from 700hPa to 1000 hPa?**
   → We are sorry for causing confusion. LCA stands for low-cloud fraction, which, as reviewer commented, means a cloud fraction between 700 hPa and 1000 hPa. The definition of LCA was added on line 263 in the revised manuscript.

2. **Section 2.1: What is the vertical resolution of the model? What was used as the spin-up time of the model? Which COSP simulator was used (e.g. was it the lidar simulator?)**
   → Both SAM0 and CAM5 have 30 vertical layers. For model experiments, we follow the standard procedure of AMIP-type experiment, which does not require spin-up time. Yes, we used the lidar simulator in the COSP We added these points on line 98 and 101 in the revised manuscript.

3. **Figure 3: Does the WBF process include snow?**
   → In both models, the WBF process only implies conversion from liquid to ice.

4. **Section 3.2: The sentences referring to the temperature inversions are written in a confusing way. It seems like the temperature inversions should be mentioned after the effect of LCA on surface fluxes, not before since it's a consequence of the clouds.**
   → We are sorry for the confusion. We changed the sentence as: "In the Arctic during winter, less LCA in CAM5 reduces FLUT over the land and the sea–ice region in the lower troposphere because the temperature in the cloudy layer is higher than that at the surface (i.e., temperature inversion). Less LCA also reduces downward LW radiation at the surface (FLDS), which leads to colder near-surface air than the observation, resulting in enhancement of the temperature inversion." (lines 276-279 in the revised manuscript)

5. **Rather than state that "most of the shaded area" is statistically significant, why not shade the statistically insignificant areas to avoid crowding the plot?**
   → In the revised manuscript, only the statistically significant areas were plotted.

## Response to Reviewer #2

We sincerely appreciate Reviewer #2 for spending his/her invaluable time to give us lots of constructive, critical and helpful comments. Most comments were carefully reflected in the revised manuscript. Our responses to individual comments are listed below.

**<u>Major comments</u>**

1. **For the link between statement 3 and 4, the authors cite Park et al. (2014): "the horizontal and vertical transports of heat and moisture are the important factors inducing the net condensation of water vapor into cloud liquid (NCD) both in SAM0 and CAM5". Are these factors also important in the Arctic regions? How dominant are these factors? Are there any other important factors? Could other modifications in SAM0 contribute to the enhancement of NCD? For example, in-cloud turbulence and precipitation from super-cooled liquid clouds.**

   **The following analysis of concurrence and correlations between advection and clouds are not definite evidence either. As a model study (instead of observational data analysis), more concrete evidence is expected for this imperative link. How about adding a budget analysis like the one for statement 2 and 3 or experiments turning on/off certain model processes?**

   → As reviewer mentioned, we examined all of the cloud liquid and ice condensate process tendencies including in-cloud turbulences and precipitation in each grid-box of the model in the Arctic region (in figure 4 in the revised manuscript). By this effort, we found that net condensation of water vapor into cloud liquid (NCD) is a single dominant process for the Arctic cloud liquid condensation compared to other physical processes (e.g., nonlocal asymmetric turbulent eddies (CON), local symmetric turbulent eddies (PBL), precipitation (PRS), conversion of cloud liquid into cloud ice (WBF), etc.). Given the cloud fraction, in the model, the NCD is explicitly calculated by the saturation equilibrium in cloud macrophysics scheme, which indicates that the NCD in a grid-box is produced more with the condition of more water vapor and lower grid-mean temperature. Assuming that the Arctic region is a cylinder, the water vapor over the Arctic region can be increased by only the two ways, those are a convergence of meridional moisture flux and a surface moisture flux. Because the difference of surface moisture flux between the two models is much smaller than that of the convergence of meridional moisture flux in Arctic region (compare supplementary S3a with S3b in the revised manuscript), we infer that the differences in the large-scale horizontal advection of moisture and temperature from sub-Arctic to Arctic are responsible for the increase in the Arctic water vapor source. The Arctic temperature can be changed by various physical and dynamical processes such as radiation, grid-scale advection, moist turbulence, etc.. In this study, although SAM0 has a higher temperature than CAM5 in the Arctic, the net condensate rate in

SAM0 is larger than in CAM5 because of relatively larger poleward moisture transport into the Arctic. This point indicates that moisture transport is a dominant factor for the generation of NCD. We explained these points clearly on lines 199-206 and lines 237-241 in the revised manuscript.

Although we agree with the Reviewer #2, however, there is a difficulty to determine which factor indeed contributes to the increase in the NCD through the budget analysis, because NCD is calculated by a complex relationship between temperature, water vapor, cloud fraction in a grid-box (i.e., saturation equilibrium). Instead of additional budget analysis, we provide more evidence that SAM0 exhibits stronger convection (Supplementary S7) and explanations on how this can be related to the enhanced poleward moisture transport. (lines 230-236 in the revised manuscript)

2. **The authors speculate that horizontal advection rather than vertical transport is responsible for the enhancement of NCD due to the identical surface boundaries. Could the authors provide some discussion instead of speculation on the role of vertical transport? Is it possible that the modification of SAM0 on the convection scheme alters the vertical structure of the atmosphere, which could also contribute to the NCD enhancement?**

   → As the reviewer #2 commented, the replacement of convection scheme (i.e., UNICON scheme) in SAM0 can change the vertical structure of atmosphere as shown in Figure 5d and 5h in the revised manuscript. As a response to the comment, we examine the relative amount of annual-mean meridional moisture flux and vertical moisture flux averaged at 65° N (Figure R1). Figure R1 shows each flux difference between SAM0 and CAM5. For a fair comparison, we converted the vertical moisture flux unit to [g kg$^{-1}$ m$^{-1}$ s$^{-1}$]. The results indicate that the horizontal moisture flux is about 1000 times larger than vertical moisture flux.

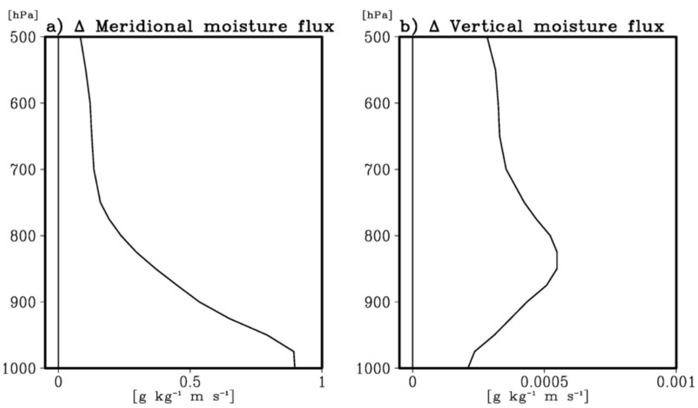


**Figure R1. Differences the zonal-mean (a) meridional moisture flux and (b) vertical moisture flux at 65° N between SAM0 and CAM5**

3. **Evaluated against ERA-Interim, SAM0 exhibits smaller biases than CAM5 in annual-mean geopotential heights simulations. However, this does not guarantee a more accurate simulation of heat and moisture advection. For example, SAM0 overestimates geopotential height at 850 hPa in tropical Pacific and underestimates in sub-Arctic Pacific, leading to larger heat transport into the Arctic. The moisture transport is also affected by the location of pathways. Could the authors evaluate the heat and moisture advection directly against observations? More importantly, this is the only way to validate the claim of "proper heat and moisture transport is the key process in simulating Arctic climate". Otherwise, the evidence could only support a claim of "enhanced heat and moisture transport improve Arctic climate simulations" because the larger advection could be an overcompensation in order to increase liquid clouds.**

→ We agree with reviewer's comments. From the additional calculation, we found that the SAM0 reduces the bias of the poleward heat and moisture transports against observation compared to the CAM5. We calculated the biases of poleward heat and moisture transports in both CAM5 and SAM0 against ERA-Interim reanalysis (Supplementary S4 and S5 in the revised manuscript). CAM5 overestimates both moisture and heat fluxes over the midlatitude region against the observation but underestimates those on the periphery (around 70° N) of the Arctic circle. Although the positive bias over the midlatitude region still remains, SAM0 reduces the biases of CAM5 on the periphery (around 70° N) of the Arctic circle. (lines 219-222 in the revised manuscript) The horizontal pattern also shows that the enhanced poleward moisture transport in SAM0 is in agreement with the observation. Figure R2 shows the vertically integrated annual mean moisture flux and its convergence from ERA-Interim and from those differences between SAM0 and CAM5. The poleward moisture flux increases particularly in the North Atlantic and North American regions where are similar to the regions with large poleward moisture transport in ERA-Interim.

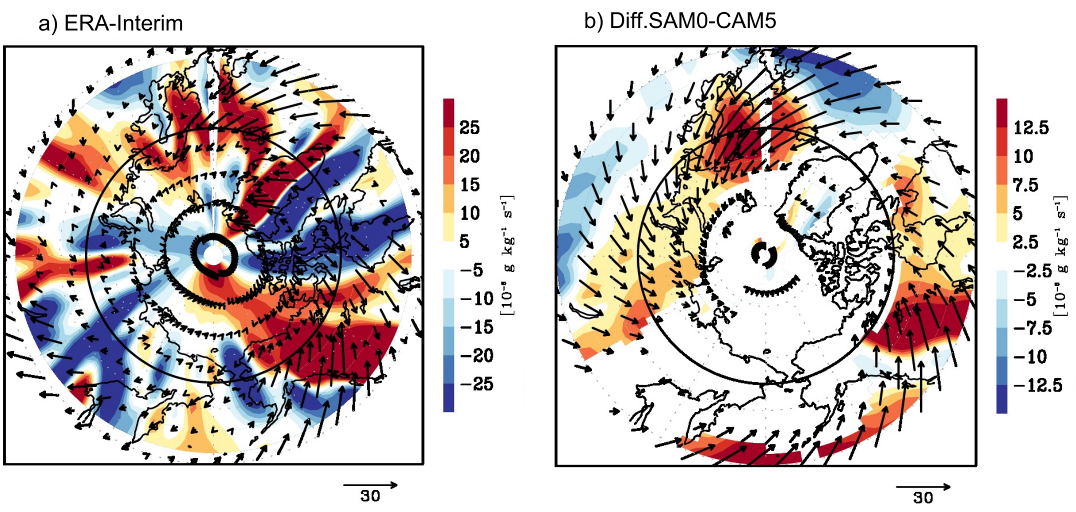

**Figure R2. Vertically-integrated annual-mean moisture flux in m g kg$^{-1}$ s$^{-1}$ (arrow) and its convergence (shaded) from (a) ERA-Interim and from (b) those differences between SAM0 and CAM5. Black contour denotes the Arctic circle (65° N).**

4. **Page 1 Line 23-26, "proper simulation of poleward heat and moisture transport is one key factor for simulating Arctic clouds" could not be wrong. However, drawing this conclusion from an uncertainty level of "association" hurts rather than lends credibility, especially in a model study. Would the authors provide more evidence to substantiate this claim? Or this manuscript could focus on the improvement of SAM0 and thoroughly evaluate all the causes.**

   → We agree with the Reviewer. Even though, in this revision, we tried to provide more pieces of evidence that poleward transports are tightly related with the increase of NCD and proper simulation of the poleward transports reduce the bias, our results are only from the comparison between specific two models. Obviously, the results cannot be generalized to other models. Accordingly, we tried to tone down the sentence and other concluding remarks in the revised manuscripts.

## Minor comments

14. **Page 6 Figure 3, have the authors looked at the seasonal breakdown? In winter, could larger moisture transport lead to more NCD to cloud ice?**

   → We examined the seasonal cycles of poleward moisture transport and NCD for both cloud liquid and ice condensate rate (Figure R3). In wintertime, NCD for cloud ice (NCD-ice) in CAM5 is larger than that in SAM0, but NCD for cloud liquid (NCD-liq) in CAM5 is less than that in SAM0 throughout the year. In both models, the poleward moisture fluxes are the largest from summer to autumn and the associated NCD-liq averaged over the Arctic region is nearly identical to the poleward moisture transport. The seasonal variability of the difference of NCD-liq averaged over the Arctic region is almost identical with that of the grid-mean RH, which explains why the Arctic liquid cloud amount increases from May to September as shown in Figure 1 in the revised manuscript. These points were described on lines 247-253 in the revised manuscript.

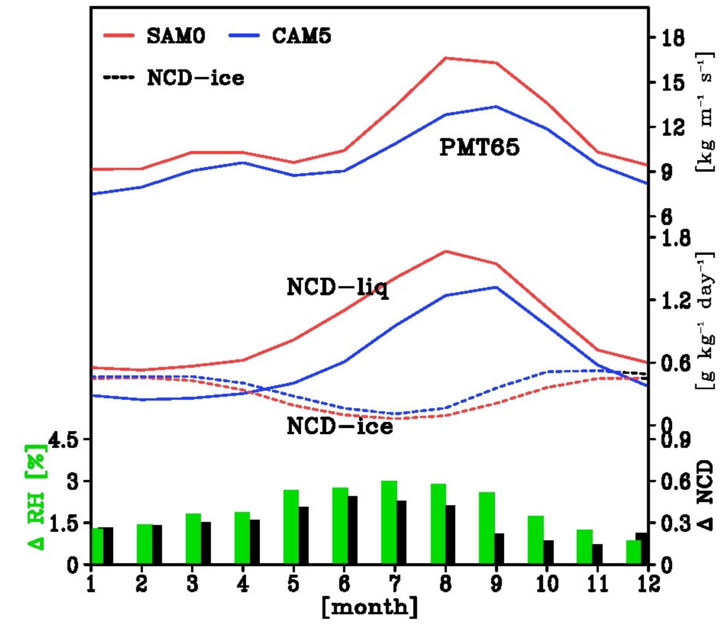


**Figure R3. Annual cycles of zonal-mean poleward moisture transport (PMT65) at 65° N, net condensation rate of water vapor into cloud liquid (NCD-liq, center solid line), and net condensation rate of water vapor into cloud ice (NCD-ice, center dashed line) averaged over the Arctic area from SAM0 (red line) and CAM5 (blue line) and the differences of NCD-liq (black bars) and relative humidity (green bars)**

**15. Page 8 Figure 4, what is the percentage of these differences relative to the absolute values of CAM5. If it's too messy to plot on the figure, a description in the text would be fine too.**

→ The difference of poleward moisture (heat) transport between SAM0 and CAM5 is about 10% (15%) of its climatology, respectively. We added this information on lines 216-217 in the revised manuscript.

**17. Page 9 Figure 5 a and b, the correlation seems to weaken in the recent years. Any reasons?**

→ We couldn't find out the reasons. We think that the issue is an interesting subject in the future work.

**20. Page 10 Figure 6c, I am confused about the unit: $10^3$ K kg $m^{-1}$ $s^{-1}$. Could it be$10^3$ K$m^{-1}$ $s^{-1}$ ?**

→ Yes. $10^3$ K $m^{-1}$ $s^{-1}$ is correct. We corrected the unit in figure 8c in the revised manuscript.

**21. Most of the paragraphs lack a topic sentence to guide readers. For example, the topic sentence for the first paragraph in Section 3 could be "SAM0 reduces the negative biases of CAM5 in liquid cloud simulations".**

→ Thanks. We entirely corrected paragraphs in the revised manuscript.

**Other minor issues**

→ We sincerely thank for reviewer's kind comments. All of the minor issues are fully considered in the revised manuscripts. In addition, some other errors are corrected.

## Response for Reviewer #3

We sincerely appreciate Reviewer 3 for spending his/her invaluable time to give us lots of constructive, critical and helpful comments. Most comments were carefully reflected in the revised manuscript. Our responses to individual comments are listed below.

**Major comments**

1. **Improvements of simulated Arctic clouds: according to Figure 1, although SAM0 cloud fraction is closer to observations, significant biases still persist, especially in winter. The improvement in PR90 is marginal. I suggest the authors to also compare the liquid and ice water path to the observations (e.g. Lenaerts et al. 2017), because they are also important for cloud radiative effects. For example, does the decrease in cloud ice mass (Figure 2c) make it closer to observations?**

   → As reviewer's suggestion, we added liquid water path (LWP) and ice water path (IWP) bias against from ERA-interim data (Supplementary S1 in the revised manuscript). Additionally, we added the vertical profile of cloud contents from ERA-interim data in the Supplementary S2 in the revised manuscript. We tried to use satellite observation data as shown in Lenaerts et al. (2017), but we could not find the data processing method, so I inevitably used ERA-interim data. Lenaerts et al. (2017) showed the LWP and IWP from CloudSat-Calipso climatology (C-C in their paper) and the difference between ERA-Interim and C-C. We could speculate the comparison between the model results and C-C, indirectly. In our result, CAM5 considerably underestimates the total cloud content with underestimating both cloud liquid and ice amount against ERA-interim data. In the SAM0, Although cloud ice condensate is underestimated as much as CAM5, cloud liquid condensate is simulated closed to observation, which reduces the overall bias of CAM5 in total cloud condensate. We mentioned the point on lines 161-165 in the revised manuscript.

2. **Relationship between meridional fluxes and increased cloud liquid:**

   **a) Is vertical advection included in the meridional transport? Heat and moisture transport into the Arctic doesn't just happen in the horizontal plane. In fact, eddies transport moisture along (moist) isentropes.**

   → We agree with the reviewer. To provide the best answer for your question, we examine the relative amount of the meridional moisture flux and vertical moisture flux averaged at 65° N (Figure R1 in response for reviewer#2). Figure R1 shows each flux difference between SAM0 and CAM5. For a fair comparison, we convert the vertical moisture flux unit to [g kg$^{-1}$ m$^{-1}$ s$^{-1}$]. The results indicate that the meridional moisture flux is about 1000 times larger than vertical moisture flux. So, we think the vertical moisture flux can be ignored in this study.

**b) Even though increased moisture flux and Arctic liquid cloud are correlated, it doesn't provide causation.**

→ We agree with the reviewer's comments. We think we do not provide sufficient explanation on the link between poleward moisture transport and the Arctic net condensation of water vapor into cloud liquid (NCD) in the original manuscript. Given the cloud fraction, in the model, the NCD is explicitly calculated by the saturation equilibrium in cloud macrophysics scheme, which indicates that the NCD in a grid-box is produced more with the condition of more water vapor and lower grid-mean temperature. Assuming that the Arctic region is a cylinder, the water vapor over the Arctic region can be increased by only the two ways, those are a convergence of meridional moisture flux and a surface moisture flux. Because the difference of surface moisture flux between the two models is much smaller than that of the convergence of meridional moisture flux in Arctic region (compare supplementary S3a with S3b in the revised manuscript), we infer that the differences in the large-scale horizontal advection of moisture and temperature from sub-Arctic to Arctic are responsible for the increase in the Arctic water vapor source. The Arctic temperature can be changed by various physical and dynamical processes such as radiation, grid-scale advection, moist turbulence, etc.. In this study, although SAM0 has a higher temperature than CAM5 in the Arctic, the net condensate rate in SAM0 is larger than in CAM5 because of relatively larger poleward moisture transport into the Arctic. This point indicates that moisture transport is a dominant factor for the generation of NCD. We explained this point clearly on lines 199-206 and lines 237-241 in the revised manuscript.

We agree that the correlation between poleward moisture transport and Arctic NCD do not explain definite causality. In the revised manuscript, in addition to the discussion prementioned above, we focused on to explain more clearly the link between poleward moisture transport and NCD with analyzing seasonal variabilities between the two models (lines 247-252 in the revised manuscript). Additionally, we provide more evidence that SAM0 exhibits stronger convection (Supplementary S7) and explanations on how this can be related to the enhanced poleward moisture transport. (lines 230-236 in the revised manuscript)

3. **The results shown here are from atmospheric only GCMs. Since the results depend on the atmospheric heat transport, ocean coupling could potentially alter the results. Have the authors looked at whether the changes in heat and moisture fluxes are still robust in coupled SMA0?**

→ Thank you for your constructive suggestion. We agree to need the additional experiment using a fully-coupled model owing to air-sea interaction. The factor may be more important in recent years when the Arctic has undergone rapid warming and Arctic sea ice has drastically declined. Currently, we do not have the present-day full-coupled experiment data set of both CAM5 and SAM0. We will try this subject in future work (line 327 in the revised manuscript).

**Minor comments**

1. **Please hatch the maps to show their significance level, instead of saying "most shaded areas exceed a 95% significance level". Since not all areas are significant, it is useful to know where it is not significant.**

   → We agree with reviewer's comment. In the revised manuscript, only the statistically significant areas were plotted.

2. **P3 L7: What microphysics scheme does SAM0 use? Is it the same for CAM5? If not, it can introduce additional sensitivity.**

   → First of all, we are sorry for causing the confusion admitting that we didn't provide sufficient description on the models in the original manuscript. In this study, the only difference between SAM0 and CAM5 is the UNICON scheme, which is a unified convection scheme that replaces 1) CAM5's deep and shallow convection scheme (Park, 2014a, 2014b), and 2) convective detrainment process (Park et al., 2017). Not only cloud microphysics but also other features such as dynamic core, PBL, etc. are exactly the same for both models. We described this on lines 80-81 in the revised manuscript.

3. **P3 L23: Are different periods from 1979 to 2015 selected to compare with the corresponding observations (CALIPSO and CERES)? If so, it should be specified, since the simulation period is much longer than what the observations cover. If not, are the results sensitive to the mismatch in periods?**

   → Yes. The integration period of both CAM5 and SAM0 is 36 years from January 1979 to February 2015 and we use the climatology of the CALIPSO-GOCCP from June 2006 to November 2010 and the climatology of CERES-EBAF from March 2000 to February 2013. The period chosen is limited by the availability of each satellite observation data. Although the period among the model outputs and the satellite observations are different, we think that the data could be comparable when using each climatology. To verification of this point, we plotted same figures (Figure 1a, Figure 9d,e,f, and Figure 10d,e,f in the revised manuscript) using model data averaged with the same period to each observation data (Figure R4 and R5). The results show almost the same as the figures averaged with whole period.

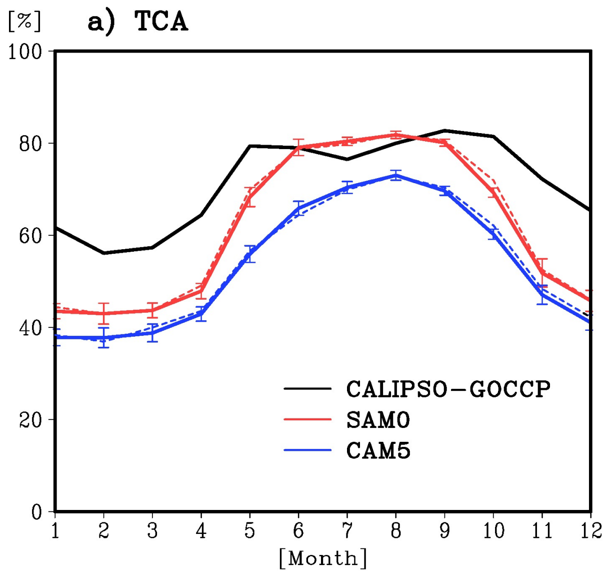


Figure R4. Identical with Figure 1 in the original manuscript except for adding the results averaged from June 2006 to November 2010 (dashed lines) for each model

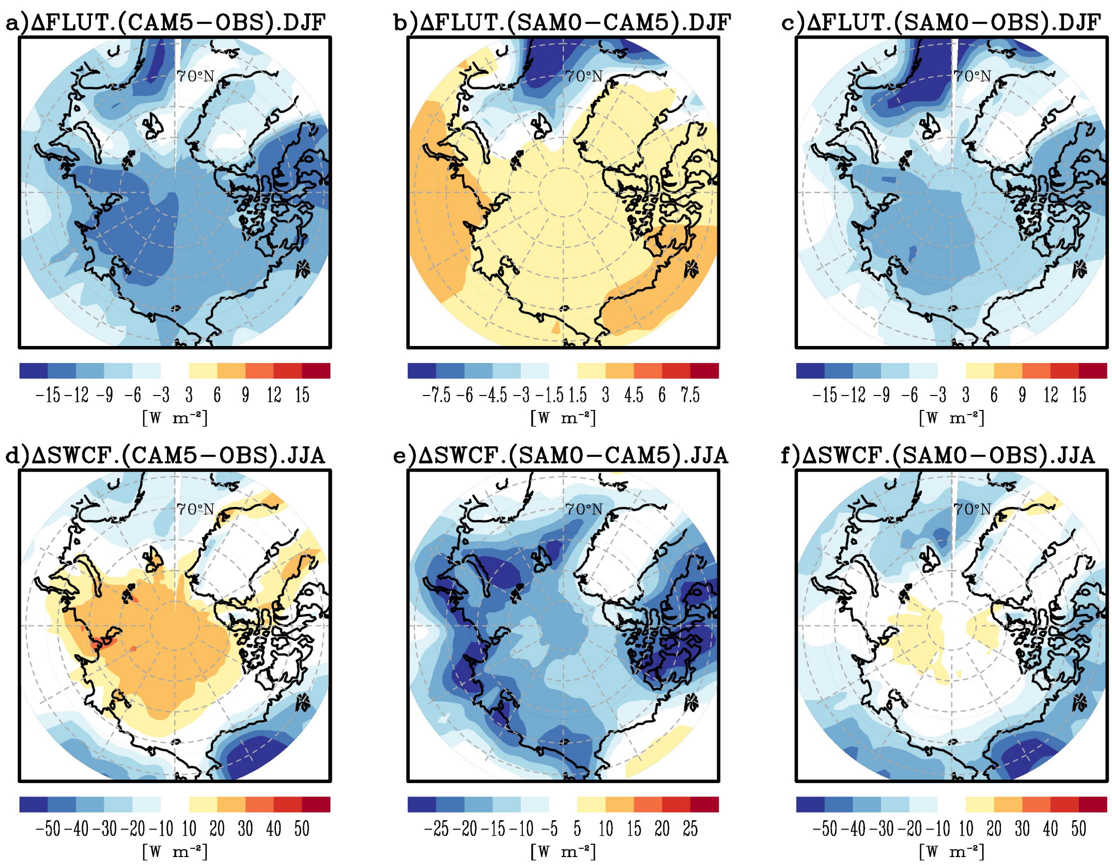


Figure 5. (a), (b), and (c) are identical with Figure 7d,e,f in the original manuscript and (d), (e), and (f) are identical with Figure 8d,e,f in the original manuscript except for using data averaged from March 2000 to February 2013 for each model

4. **P4 L14-15: The TCA bias also varies seasonally. SAM0's improvement is the most significant in summer, but less so in winter. Have the authors investigated the seasonal and spatial variability in poleward moisture transport? The seasonal cycle combined with spatial maps could shed light on why clouds are underestimated in the Arctic.**

   → We investigated the seasonal and spatial variability of poleward moisture transport and NCD for cloud liquid in figure 6 and supplementary S3a in the revised manuscript. In seasonal variability perspective, the poleward moisture transport in SAM0 is simulated more than CAM5 throughout the year (Figure 6 in the revised manuscript). In both models, the poleward moisture fluxes are the largest from summer to autumn and the associated NCD for cloud liquid averaged over the Arctic region is nearly identical to the poleward moisture transport. The seasonal variability of the difference of NCD for cloud liquid averaged over the Arctic region is almost identical with that of the grid-mean RH, which explains why the Arctic liquid cloud amount increases from May to September as shown in Figure 1 in the revised manuscript. These points were described on lines 247-253 in the revised manuscript. Supplementary S3a in the revised manuscript shows the vertically-integrated annual-mean moisture flux and its convergence from ERA-Interim and from those differences between SAM0 and CAM5. The poleward moisture flux increases particularly in the North Atlantic and North American regions where are identical with the regions with large poleward moisture transport in ERA-Interim.

5. **P6 Figure 3: Are these budgets closed? Net tendency profiles for liquid and ice from each model can be added to these figures.**

   → Actually, there was a simple mistake in calculating the NCD for the cloud liquid in Figure 3a in the original manuscript. Although a little bit more value of NCD for the cloud liquid is calculated, it did not affect the overall description for Figure 3 in the original manuscript. After we fixed it in the revised manuscript, the sum of all tendencies for both cloud liquid and ice is closed to zero because we plotted all tendencies for both cloud liquid and ice condensates. So we think that it is not necessary to add the zero line.

6. **P8 Figure 4: According to the moisture and heat flux convergence, we expect increased liquid condensation thus more liquid clouds at around 70N. Is this the case? For example, in winter the total cloud increase is quite spatially uniform over the Arctic Ocean (Fig 7b).**

   → The TCA increase in SAM0 during wintertime is relatively larger on the periphery of the Arctic circle (between 60° N and 70° N) than the Arctic inside region. The TAC increases particularly in the North Atlantic and North American regions where are identical with the regions with the greatest increase in the poleward moisture transport as shown in supplementary S3a in the revised manuscript.

7. **P8 L22-P9 L2: We all know that correlation does not mean causation. By just showing correlation, the causality is not proven. For example, it is also possible that both changes are caused by a third factor that is not in the analysis.**
   → We agree with your comment. We described this point previously in major comment 2-(b).

8. **P8 L13: LCA was never spelled out in the paper.**
   → We are sorry for the confusion. LCA stands for the low-cloud fraction. The definition of LCA has been added on line 263 in the revised manuscript.

9. **P9 L14: What makes these two models the outliers? Are there any physical reasoning to say so? One should not just pick and choose the models or discard the end members because they do not agree with your hypothesis.**
   → We would like to use all available CMIP5 models including the necessary variables. Although bcc-csm1-1-m and MPI-ESM-LR models are outliers in the relationship between the meridional moisture transport and TCA and LCA, the models show the correlation between the meridional heat transport and LWP ration.

10. **P10 Figure 6: Are the widths of black lines in (a) and (b) represent the spread of observed poleward moisture transport? If not, these lines are very misleading and unnecessary.**
    → The widths of black lines in the original manuscript Figure 6 means not "the spread of observed poleward moisture transport" but "just values of CALIPSO cloud fraction". We removed the line and pointed out the "values of CALIPSO cloud fraction" at y-axis in Figure 8a and 8b in the revised manuscript.

11. **P10 L7: Upward LW at TOA includes both clear sky and cloud effects. Have the authors look at the cloud radiative effect differences between the two models? The negative bias in upward LW at TOA in the Atlantic sector seems to get worse in SAM0. Is it because in this region, SAM0 is producing too much clouds comparing to the observations?**
    → We checked the longwave cloud radiative forcing (LWCF) during the wintertime. LWCF in SAM0 simulates a positive bias against observation in the Atlantic sector, in contrast negative bias in the land and sea-ice region because of a temperature inversion. Indeed, SAM0 produces a little bit more clouds over the Atlantic sector compared with the observation, as shown in Figure 9c in the revised manuscript. Thus increase in the cloud amount over the open-sea region reduce the FLUT in SAM0, which enhanced the negative bias of FLUT in CAM5.

12. **P10 L11: Figure 7 shows TCA, but the argument the authors give here involves LCA. Is the LCA change the same as TCA?**

    → We plotted the TCA in Figure 7 in the original manuscript for consistency in the entire manuscript. The LCA change is almost the same as TCA.

13. **P11 L7: Remove "a" before "summertime biases"**

    → Thanks. We corrected in the revised manuscript.

14. **P13 Figure 8: Does panel d) suggest that CAM5 SW cloud forcing is too weak at the surface? This would lead to a warm bias over the Arctic ocean. But g) shows a cold bias, which means that the LW cloud forcing bias (not enough warming at surface) dominates the net forcing. It would be helpful to see both LWCF and SWCF to get a fuller picture. I suggest the authors to plot LWCF and SWCF for both TOA and surface, at least to include them in the supplementary material.**

    → We agree with reviewer's comment. During summertime, the surface temperature response is not explained by only SWCF. Rather the surface temperature is determined by surface net flux of SW and LW. So we plotted the net SW radiation at the surface (FSNS) and net LW radiation at the surface (FLNS) and the sum of FSNS and FLNS in the original manuscript Figure 9. The difference of the sum of FSNS and FLNS between SAM0 and CAM5 agrees with the difference of near-surface temperature ($T_{2m}$). We add the plots of SWCF and LWCF at TOA in the Supplementary S8 in the revised manuscript.

15. **P14 L11: The wording "SAM0 remedies these problems" is too strong, given that significant cloud biases still persist.**

    → We agree with reviewer. We corrected inappropriate sentences not to describe too strongly in the revised manuscript.

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# Impact of poleward heat and moisture transports on Arctic clouds and climate simulation

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**Abstract.** Many General Circulation Models (GCMs) have difficulty in simulating Arctic clouds and climate causing a large inter-model spread. To address this issue, two Atmospheric Model Inter-comparison Project (AMIP) simulations from the Community Atmosphere Model version 5 (CAM5) and from the Seoul National University (SNU) Atmosphere Model version 0 (SAM0) with a Unified Convection Scheme (UNICON) are employed to identify the mechanism that works on improving Arctic clouds and climate simulation. Over the Arctic, SAM0 simulates more cloud fraction and cloud liquid mass than CAM5, reducing the negative Arctic clouds biases in CAM5. The analysis of cloud water condensate rates indicates that this improvement is associated with an enhanced net condensation rate of water vapor into the liquid condensate of the Arctic low-level clouds, which in turn is driven by enhanced poleward transports of heat and moisture by mean meridional circulation and transient eddies. The reduced Arctic cloud biases lead to improved simulations of surface radiation fluxes and near-surface air temperature over the Arctic throughout the year. The association between the enhanced poleward transports of heat and moisture and more liquid clouds over the Arctic is also evident not only in both models but also in the multi-model analysis. Our study demonstrated that improvement of the poleward heat and moisture transport in a model can be one of the key factors for better simulations of Arctic clouds and climate.

## 1 Introduction

With increasing greenhouse gases, the Arctic has undergone the most rapid warming on Earth. During the last decade, the warming rate of the near-surface air temperature over the Arctic has been two to three times that of the entire globe (Johannessen et al., 2016; Screen and Simmonds, 2010; Serreze and Barry, 2011). This pronounced Arctic temperature amplification, some of which is forced by the positive feedbacks among various climate components (e.g., sea ice albedo feedback (Deser et al., 2000), water vapor and cloud feedback (Lu and Cai, 2009), as well as lapse-rate feedback (Pithan et al., 2014)), is also responsible for extreme weather and climate events over mid-latitude continents (Kug et al., 2015; Screen and Simmonds, 2013; Wu and Smith, 2016). Most General Circulation Models (GCMs) struggle to properly simulate the Arctic climate, suffering from the excessive cold surface temperature. The inter-GCM spread of greenhouse-induced warming is the largest over the Arctic (Boe et al., 2009; de Boer et al., 2012; Chapman and Walsh, 2007; Karlsson and Svensson, 2013). Many studies

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reported that the GCM-simulated cold biases over the Arctic are associated with the biases of shortwave (SW) and longwave (LW) radiations at the surface, which are due to poor simulation of Arctic clouds (Barton et al., 2014; English et al., 2015; Karlsson and Svensson, 2013; Shupe and Intrieri, 2004).

Over the Arctic, many GCMs underestimate the cloud fraction (de Boer et al., 2012; Cesana and Chepfer, 2012; English et al., 2015; Kay et al., 2016) and cloud liquid mass (Cesana et al., 2015; English et al., 2014; Kay et al., 2016). Because the liquid-containing clouds (i.e., mixed-phase clouds) have a larger optical depth than pure ice clouds (King et al., 2004; Shupe and Intrieri, 2004), less cloud liquid mass causes weaker cloud radiative forcing in GCMs. Unlike in midlatitudes, the mixed-phase clouds over the Arctic can persist for several days (Morrison et al., 2011; Shupe et al., 2011). From a process perspective, cloud liquid in the mixed-phase clouds should be rapidly depleted into cloud ice within a few hours owing to the higher saturation vapor pressure over water compared with ice (i.e., the Wegener–Bergeron–Findeisen (WBF) mechanism) (Bergeron, 1935; Findeisen, 1938; Wegener, 1911). Therefore, to sustain cloud liquids for several days, a certain production mechanism needs to counteract the WBF depletion process. Morrison et al. (2011) reviewed various candidate production processes for cloud liquid in Arctic mixed-phase clouds, such as the compensating feedback between the formation and growth of cloud liquid droplets and ice crystals (Jiang et al., 2000; Prenni et al., 2007), in-cloud turbulence generated by cloud top radiative cooling (Korolev and Field, 2008; Shupe et al., 2008), and horizontal advection by large-scale flows (Sedlar and Tjernström, 2009; Solomon et al., 2011). More recent studies also noted that ice nucleation may be important for correctly simulating Arctic mixed-phase clouds. Liu et al. (2011) demonstrated that their revised ice nucleation scheme increased cloud liquid mass in the Arctic mixed-phase stratocumulus and associated downward LW flux at the surface during the Fall 2004 Mixed-Phase Arctic Cloud Experiment (MPACE). Subsequent sensitivity studies with various ice nucleation schemes reported similar results (English et al., 2014; Xie et al., 2013). These improvements are attributed to the revised ice nucleation that decelerates the WBF depletion process in the mixed-phase clouds. Even with the cloud liquid mass increase, low-level cloud fraction still decreased in simulations, such that the biases of the radiation fluxes at the surface and the top-of-atmosphere (TOA) still remained.

In an attempt to determine the factors responsible for the negative biases in GCM-simulated cloud liquid mass and cloud fraction over the Arctic, this study will compare the Arctic climate simulated by the Seoul National University Atmosphere Model version 0 with a Unified Convection Scheme (SAM0-UNICON; Park, 2014a, 2014b; Park et al., 2017; Park et al., 2019) to that of the Community Atmosphere Model version 5 (CAM5; Neale et al., 2012; Park et al., 2014). By comparing two Atmospheric Model Intercomparison Project (AMIP) simulations with CAM5 and SAM0–UNICON, we will show 1) the difference in cloud properties over the Arctic as simulated by SAM0–UNICON and CAM5, 2) the mechanisms of the improved clouds simulation, and 3) the influence of clouds simulation on the Arctic climate simulation. Model design and data used in this study will be described in Section 2. The results of the Arctic clouds simulation and related mechanism will be provided in Section 3.1. The impact of Arctic clouds on the Arctic climate simulation will be presented in Section 3.2. Finally, a summary and discussion will be provided in Section 4.

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## 2 Method

### 2.1 Model and experimental design

SAM0-UNICON (Park et al., 2019), hereinafter, SAM0, for simplicity, is an international GCM participating in the Coupled Model Intercomparison Project 6 (CMIP6) (Eyring et al., 2016). SAM0 is based on CAM5, however, adopts the Unified Convection Scheme (UNICON) (Park, 2014a, 2014b) instead of the shallow (Park and Bretherton, 2009) and deep convection schemes (Zhang and McFarlane, 1995) of CAM5; further, it has a revised treatment of the cloud macrophysics process (Park et al., 2017). Other features, such as dynamic core, cloud macrophysics and microphysics, and PBL, etc. are exactly the same for both models. UNICON is a process-based subgrid convection parameterization scheme consisting of multiple convective updrafts, convective downdrafts, and subgrid cold pools and mesoscale organized flow without relying on any equilibrium constraints, such as convective available potential energy (CAPE) or convective inhibition (CIN) closures. UNICON simulates all dry-moist, forced-free, and shallow-deep convection within a single framework in a seamless, consistent, and unified manner (Park, 2014a, 2014b). The revised cloud macrophysics scheme diagnoses additional detrained cumulus by assuming a steady state balance between the detrainment rate of cumulus condensates and the dissipation rate of detrained condensates by entrainment mixing (Park et al., 2017). The addition of detrained cumulus substantially improves the simulation of low-level clouds and the associated cloud radiative forcing in the subtropical trade cumulus regime. Park et al. (2019) showed that the global mean climate, 20th century global warming, and El Niño and Southern Oscillation (ENSO) simulated by SAM0 are roughly similar to those of CAM5 and the Community Earth System Model version 1 (CESM1; Hurrell et al., 2013); however, SAM0 substantially improves the simulations of the Madden–Julian Oscillation (MJO) (Madden and Julian, 1971), diurnal cycle of precipitation, and tropical cyclones, all of which are known to be extremely difficult to simulate in GCMs.

To evaluate the impact of SAM0 on the Arctic cloud system, we conducted five ensemble experiments of an AMIP simulation for 36 years from January 1979 to February 2015 with a horizontal resolution of 1.9° latitude x 2.5° longitude and with 30 vertical layers for both CAM5 and SAM0. The climatology from the two simulations over the Arctic are then compared. The detailed settings of the AMIP simulations are identical to those described in Park et al. (2014). For a rational comparison with satellite observation data, the model cloud fraction is calculated using lidar simulator in the Cloud Feedbacks Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP) diagnostic model. A detailed description of the COSP diagnostic model can be found in Kay et al. (2012).

### 2.2 Observational data

The observed Arctic cloud fraction and condensate phase information are obtained from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)–GCM Oriented CALIPSO Cloud Product (CALIPSO–GOCCP) from June 2006 to November 2010 (Chepfer et al., 2010). The lidar beam of CALIPSO may not detect a few ice crystals underneath the optically thick stratocumulus clouds due to its attenuation and the CALIPSO–GOCCP may slightly underestimate the ice clouds in the lowest levels at midlatitudes and in polar regions (Cesana et al., 2015). Nevertheless, CALIPSO–GOCCP currently provides the best available satellite observations of polar clouds because it can detect optically thin clouds without relying on the albedo or thermal contrast (Cesana and

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Chepfer, 2012; Kay et al., 2012). The observed TOA fluxes are obtained from the version 2.8 of the Clouds and Earth's Radiant Energy System (Wielicki et al., 1996) Energy Balanced and Filled data (Loeb et al., 2009) (CERES–EBAF) from March 2000 to February 2013. Although CERES–EBAF over the Arctic likely exceeds the global uncertainty particularly for clear sky retrievals due to the low albedo contrast between snow and clouds, it is the only available source of basin-wide TOA fluxes in the Arctic, and newer versions have advanced to distinguish clouds from underlying high-albedo sea ice and snow cover by utilizing cloud radiances from the collocated Moderate Resolution Imaging Spectroradiometer (MODIS) and sea ice concentration fields from the National Snow and Ice Data Center (NSIDC) (English et al., 2014). The climatology data of long-term ground-based cloud and radiation measurements from 1998 to 2010 at the North Slope of Alaska (NSA) Barrow site (71.38N, 156.68W) from the Atmospheric Radiation Measurement (ARM) Best Estimate (ARMBE) dataset (Xie et al., 2010) are used for the model evaluation. The Arctic near-surface air temperature at a 2 m height ($T_{2m}$), liquid water path (LWP), and ice water path (IWP) are obtained from the European Center for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis dataset from January 1979 to February 2015 (Dee et al., 2011).

### 2.3 CMIP5 models

To identify the relationship between the Arctic clouds and poleward transports of moisture and heat, we also analyzed AMIP simulations of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). We used the outputs from nine models (bcc-csm1-1-m, CanAM4, CNRM-CM5, GFDL-CM3, HadGEM2-A, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, and MPI-ESM-LR), which can be accessed from http://pcmdi.llnl.gov/. These models are selected based on the availability of the following model outputs: monthly low-cloud fraction calculated by CALIPSO COSP diagnostic model (variable name: cllcalipso), liquid water path (variable name: clwvi), ice water path (variable name: clivi), daily meridional wind (variable name: va), air temperature (variable name: ta), and specific humidity (variable name: hus).

## 3 Results

### 3.1 Arctic clouds and their relationships with poleward moisture and heat transports

SAM0 reduces the negative biases of CAM5 in cloud fraction and liquid cloud simulations. Figure 1a shows the annual cycle of the total cloud fraction (TCA) averaged over the Arctic area (north of 65° N) obtained from CAM5, SAM0, and observation. Consistent with Kay et al. (2012) and English et al. (2014), CAM5 underestimates the observed TCA throughout the year. The negative biases in the CAM5-simulated TCA are reduced in SAM0, which simulates a more realistic TCA, particularly during summer. SAM0 improves not only the cloud fraction but also the simulation of cloud phase characteristics. Cesana et al. (2015) proposed the height at which the ratio of cloud ice mass to total cloud condensate mass is 90 % (i.e., the phase ratio, PR90) as a useful indicator in assessing the model performance to simulate the cloud phase. The obtained PR90 in most GCMs is located at heights lower than that of the satellite observation, implying that most GCMs underestimate cloud liquid mass or overestimate cloud ice mass. Both CAM5 and SAM0 underestimate cloud liquid mass over the Arctic; however, SAM0 exhibits better estimates compared with CAM5 (Fig. 1b). Not only the biases against satellite observation, the biases against ground-based observation are also reduced in SAM0. Figure 2 shows the annual



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cycle of TCA, LWP, surface downward short-wave radiation (FSDS), and surface downward long wave radiation (FLDS) from CAM5, SAM0, and the observation at barrow site. TCA in CAM5 is less than that of the observation except for July and August. LWP is also underestimated over the entire period. Accordingly, the downward shortwave flux is overestimated and the downward longwave flux is underestimated particularly in autumn and winter. Although TCA in SAM0 is slightly overestimated in summertime compared with the observation, SAM0 reduces the bias of CAM5 during the other periods. The LWP and the surface radiation fluxes are also simulated closer to the observation than those in CAM5.

Figure 3 shows the annual-mean vertical profiles of grid-mean cloud condensate masses and the difference of cloud fraction between SAM0 and CAM5 averaged over the Arctic area. Compared with CAM5, SAM0 simulates more cloud liquid condensate mass in the lower troposphere but slightly less cloud ice condensate mass throughout the troposphere (Fig. 3b and 3c). Thus, the total cloud condensate mass increases (decreases) in the lower troposphere (in the mid-troposphere) from CAM5 to SAM0, respectively, which is responsible for the difference in the cloud fraction (Fig. 3a and 3d). The increase in the cloud liquid condensate mass reduces its bias against the ERA-interim reanalysis. CAM5 underestimates both cloud liquid and ice condensation against ERA-interim data (Supplementary S1b, S1e, and S2). SAM0, however, simulates the cloud liquid condensation close to the observation, although the cloud ice condensation is underestimated as much as CAM5 (Supplementary S1c, S1f and S2). These changes of cloud characteristics from CAM5 to SAM0 differ from previous report on the impact of revised ice nucleation scheme (English et al., 2014; Liu et al., 2011; Morrison et al., 2008), which simulated a smaller (larger) low-level (mid-level) cloud fraction. The increase (decrease) of cloud liquid (ice) mass is consistent with the increase of PR90 heights from CAM5 to SAM0 shown in Fig. 1b.

To

understand the physical processes responsible for the increases of cloud fraction and cloud liquid mass in the lower troposphere from CAM5 to SAM0, we plotted the annual-mean vertical profiles of the grid-mean tendencies of cloud liquid and ice condensate masses averaged over the Arctic area from various physical processes (Fig. 4). Both CAM5 and SAM0 shows two main physical processes generating Arctic cloud liquid condensate the net condensation of water vapor into cloud liquid (NCD) simulated by the cloud macrophysics scheme and the convective detrainment of cloud liquid (DET). In contrast, two main depletion processes are observed: the precipitation–sedimentation fallout of cloud condensate (PRS) and WBF conversion of cloud liquid into cloud ice (WBF) simulated by the cloud microphysics scheme. For cloud ice condensate, the main sources are the net deposition of water vapor into cloud ice (NCD), WBF, and convective detrainment of cloud ice (DET), while the main sink is PRS (Fig. 4b). With the exception within the Planetary Boundary Layer (PBL) below 950 hPa, the grid-mean tendencies due to subgrid vertical transports of cloud condensates by local symmetric turbulent eddies (PBL) and nonlocal asymmetric turbulent eddies (CON) are generally smaller than other tendencies. Near the surface, the PBL scheme operates as a strong source for cloud liquid owing to downward vertical transport of cloud liquid mass from the cloud layers above (Fig. 4a).

The largest difference between CAM5 and SAM0 is observed in NCD and DET, particularly for cloud liquid. For cloud liquid, SAM0 simulates weaker DET but much stronger NCD than CAM5, such that the sum of NCD and DET simulated by SAM0 is larger than that of CAM5 with the maximum difference of approximately 0.05 g kg$^{-1}$ day$^{-1}$ around the 850 hPa, where the differences of cloud liquid condensate mass and cloud fraction between CAM5 and SAM0 are also maximum (see Fig. 3b). This indicates that the increases of cloud fraction and cloud

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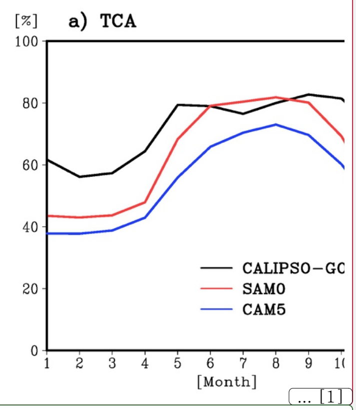


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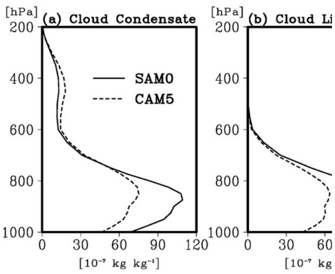
Moved down [1]: **Annual-mean vertical profiles of grid-mean (a) cloud condensate mass (cloud liquid + cloud ice), (b) cloud liquid mass, and (c) cloud ice mass averaged over the Arctic area from SAM0 (solid lines) and CAM5 (dotted lines) and (d) the difference of cloud fraction between SAM0 and CAM5.**

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liquid condensate mass from CAM5 to SAM0 are mainly caused by an enhanced NCD for cloud liquid from CAM5 to SAM0. The differences in PBL and CON between CAM5 and SAM0 are relatively small. For cloud ice, the overall production rate simulated by SAM0 is smaller than that of CAM5, mainly due to the decreases in NCD and DET slightly compensated by the increases in WBF and PRS, which leads to the decrease of cloud ice mass, as shown in Fig. 3c. The SAM0-simulated WBF tendency is slightly larger than that of CAM5 partly due to the larger cloud liquid mass in SAM0. In summary, the increases of cloud liquid mass, cloud fraction, and PR90 from CAM5 to SAM0 shown in Figs. 1 and 3 (which are improvements) are mainly caused by the enhanced NCD for cloud liquid from CAM5 to SAM0. In accordance with the stronger NCD for liquid, the liquid cloud fraction also increases to satisfy the saturation equilibrium constraint for cloud liquid (see Appendix A of Park et al. (2014)).

The question on what physical process has caused the increase of NCD for cloud liquid from CAM5 to SAM0 remained. In the both models, the NCD for cloud liquid is explicitly calculated by the saturation equilibrium in the cloud macrophysics scheme, which indicates that more NCD for cloud liquid is produced with more water vapor and lower temperature (Park et al., 2014). Assuming that the Arctic region is a cylinder, the water vapor over the Arctic region can be increased only by two ways: convergence of meridional moisture flux and surface moisture flux. Because the difference of surface moisture flux between the two models is much smaller than that of the convergence of meridional moisture flux in Arctic region (compare Supplementary S3a with S3b), we inferred that the difference in the large-scale horizontal advection of moisture from sub-Arctic to Arctic caused the increase in the Arctic water vapor source. Figure 5 shows the differences of zonal-mean meridional transports of heat and moisture in high-latitude region and vertical profiles of water vapor (Q), air temperature (T), and relative humidity (RH) averaged over the Arctic area. The zonal-mean meridional flux is calculated as Eq. 1:

$$[\overline{vX}] = [\bar{v}][\bar{X}] + [\bar{v}^{*}\bar{X}^{*}] + [\overline{v'X'}], \qquad (1)$$

where X = Q or T; v is the meridional velocity; the overbar and prime denote time-mean and departure from the time-mean, respectively; and the square bracket and asterisk denote zonal-mean and departure from the zonal-mean, respectively. The first term on the right-hand side is the flux by the mean meridional circulation, the second term is the flux by stationary eddy, and the last term is the flux by transient eddy.

In the midlatitude and subpolar regions, SAM0 simulates poleward transports of heat and moisture more than CAM5, particularly in the lower troposphere (Figs. 5a and 5e), mainly due to enhanced transports by mean meridional circulation and transient eddies (Figs. 5b–c and 5f–g). The difference of poleward moisture (heat) transport between SAM0 and CAM5 is approximately 10% (15%) of its climatology, respectively. The enhanced poleward transports of heat and moisture in SAM0 reduces its biases against observation compared with CAM5. CAM5 overestimates both moisture and heat fluxes over the midlatitude region against the observation but underestimates those on the periphery (around 70° N) of the Arctic circle (Supplementary S4). Although the positive bias over the midlatitude region still remains, SAM0 reduces the biases of CAM5 on the periphery (around 70° N) of the Arctic circle (Supplementary S5). In the northern hemisphere, SAM0 simulates higher pressure and temperature in the low-latitude region but lower pressure and temperature in the high-latitude region compared with CAM5, which is an improvement compared with the ERA-Interim observation (Supplementary S6). The circulation change in SAM0 enhances the mean meridional circulation and polar jet stream over higher latitudes (Li and Wang, 2003). The associated strengthening of zonal mean meridional wind in the midlatitude region (see the contour lines in Figs. 5b and 5f) enhances the poleward transports of heat and moisture near the

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surface. Enhanced polar jet stream (see the contour lines in Figs. 5c and 5g) strengthens the storm track activity on the periphery of the Arctic circle (between 60° N and 70° N) (Supplementary S6c and S6f) and increases the associated poleward transports of heat and moisture by transient eddies. Moreover, SAM0 simulates the convection more strongly than CAM5, particularly in most of the tropical ocean, which reduces bias from observation (Supplementary S7). Several previous studies have shown that enhanced convective activity in the Tropics enhances the poleward heat and moisture transport by inducing Rossby wave trains from Tropics toward the pole promoting warm and moist advection from midlatitude into the Arctic (Lee et al., 2014; Fluorny et al., 2015). As with those studies, SAM0 seems to capture Rossby wave trains emanating from Tropics better than CAM5 (Supplementary S5f) leading to enhanced poleward heat and moisture transport in SAM0.

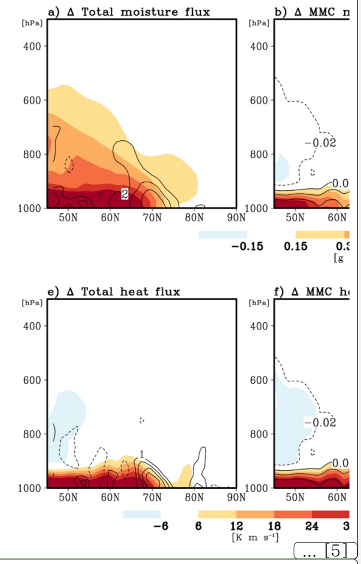
Consequently, SAM0 simulated higher Q and T than CAM5 over the Arctic (Figs. 5d and 5h). Notably, although SAM0 has a higher temperature than CAM5 in the Arctic, RH in SAM0 is higher than CAM5, which reveals that the increase in poleward moisture transport into the Arctic is relatively larger than the increase in temperature. This indicates that the poleward moisture transport into the Arctic is a dominant factor for the generation of NCD for cloud liquid. Because the liquid cloud fraction is a function of grid-mean RH in both models, cloud fraction increases in the lower troposphere (i.e., below 700 hPa), as shown in Fig. 3d. In addition, warming associated with enhanced poleward heat transport and condensation heating is likely to reduce the amount of cloud ice mass from CAM5 to SAM0, as shown in Fig. 3c; hence, reducing the ice cloud fraction in the mid-troposphere (i.e., above 700 hPa) formulated as a function of cloud ice condensate mass in both models (Fig. 2d).

The relationships between the poleward moisture transport and NCD for cloud liquid are well shown in seasonal and interannual variabilities in both models (Figs. 6 and 7). SAM0 simulates more poleward moisture transport into the Arctic than CAM5 throughout the year (Fig. 6). In both models, the poleward moisture transports at 65° N are the largest from summer to autumn, and the associated NCD for cloud liquid averaged over the Arctic region nearly agree with the poleward moisture transport. The seasonal variability of NCD difference for cloud liquid is almost coincident with that of RH, which explains the increase in the Arctic liquid cloud fraction from May to September as shown in Fig. 1. The interannual variations of the poleward moisture transport and NCD for cloud liquid in each model are also highly correlated (Figs. 7a and 7b), with the correlation coefficients of 0.84 and 0.81 for CAM5 and SAM0, respectively. In addition, in almost all years, SAM0 simulates more poleward moisture flux and higher NCD for cloud liquid over the Arctic than CAM5, and the inter-model differences of these variables are also highly correlated (Fig. 7c). In summary, the strengthened poleward moisture transport increases NCD for cloud liquid, cloud liquid mass, and cloud fraction from CAM5 to SAM0.

The close association between the Arctic cloudiness and poleward transports of heat and moisture, as shown from the analysis of CAM5 and SAM0 simulations, also exist in other climate models. Figure 8 shows the scatter plots between the annual mean meridional transports of heat and moisture at 65° N and Arctic cloudiness and the LWP ratio (i.e., the ratio of LWP to total condensate water path, LWP/(LWP+IWP)), obtained from the analysis of various AMIP simulations of CMIP5 models. Wide inter-model spread exists in the TCA, low cloud fraction (LCA, defined as those with tops between the surface and 700 hPa), LWP ratio, and poleward transports of heat and moisture. Except for a few outliers (e.g., bcc-csm1-1-m and MPI-ESM-LR), there is a clear inter-model proportional relationship between the meridional moisture transport and TCA and LCA (Fig. 8a and 8b). All models simulate consistently positive poleward moisture transport. However, some models simulate equatorward heat transport at 65° N and the corresponding LWP ratio over the Arctic tends to be smaller than those from the



contour lines in Figs. 5c and 5g4c, g… strengthens the storm track activity on the periphery of the Arctic circle (between 60° N and 70° N) (Supplementary S6c and S6f) and increases the associated poleward transports of heat and moisture by transient eddies. Moreover, SAM0 simulates the convection more strongly than CAM5, particularly in most of the tropical ocean, which reduces bias from observation (Supplementary S7). Several previous studies have shown that enhanced convective activity in the Tropics enhances the polew[... [4]]

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Moved down [2]: **Differences of zonal-mean meridional fluxes of (a, b, and c) moisture and (e, f, and g) heat by (a and e) total processes (i.e., the transported sum by mean meridional circulation, stationary eddies, and transient eddies), (b and f) mean meridional circulation (MMC), and (c and g) transient eddies (TE) between SAM0 and CAM5.**

Deleted: **Differences of annual zonal-mean vertical profiles (d) water vapor (Q, black) and relative humidity (RH, red), and (h) air**…temperature than CAM5 in the Arctic, RH in SAM0 is higher than CAM5, which reveals that the increase in poleward moisture transport into the Arctic is relatively larger than the increase in temperature. This indicates that the poleward moisture transport into the Arctic is a dominant factor for the generation of NCD for cloud liquid.**(T) averaged over the Arctic area between SAM0 and CAM5. The black lines in (a) and (e) denote th**[... [6]]

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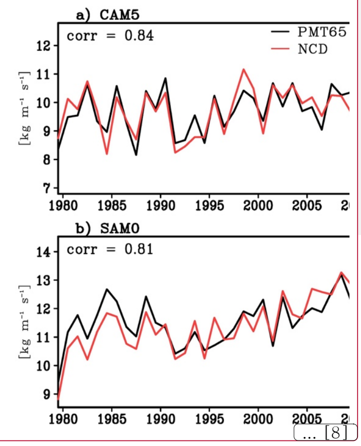


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models with poleward heat transport (Fig. 8c). The models with strong poleward moisture transport tend to have strong poleward heat transport as well. The inter-model analysis supports our conclusion that poleward moisture and heat transport is one of the key factors controlling LCA and LWP in the Arctic.

### 3.2 Impact of Arctic clouds on the Arctic climate

Clouds play a critical role in the surface radiative balance as a climate regulator in the Arctic region. Figure 9 shows biases of TCA, upward LW radiation flux at the top of the atmosphere (TOA) (FLUT), and $T_{2m}$ during wintertime obtained from CAM5 and SAM0. As shown, CAM5 suffers from the negative biases of TCA, FLUT, and $T_{2m}$ during December-January-February (DJF) (Fig. 9, left panel). In the Arctic during winter, less LCA in CAM5 reduces FLUT over the land and the sea–ice region in the lower troposphere because the temperature in the cloudy layer is higher than that at the surface (i.e., temperature inversion). Less LCA also reduces downward LW radiation at the surface (FLDS), which leads to colder near-surface air than the observation, resulting in enhancement of the temperature inversion. Compared with CAM5, SAM0 simulates more TCA, FLUT, and $T_{2m}$ over the whole Arctic (Fig. 9, center panel), such that their negative biases in CAM5 are alleviated in SAM0 (Fig. 9, right panel). Over the ocean where temperature inversion does not exist, more LCA in SAM0 results in more FLUT than CAM5 (Fig. 9e). SAM0 also simulates stronger FLDS than CAM5 over the entire Arctic, as expected (not shown).

Not only the biases during DJF, summertime biases of TCA, shortwave cloud radiative forcing at TOA (SWCF), and $T_{2m}$ are also reduced from CAM5 to SAM0 (Fig. 10). In most Arctic areas except for some portions of the northern continents, CAM5 has the negative biases of TCA (mainly LCA) during June-July-August (JJA) (Fig. 10a). SAM0 simulates more TCA than CAM5 (Fig. 10b), such that most of the negative TCA biases in CAM5 over the Arctic sea ice and open ocean areas disappear (Fig. 10c). In the Arctic during summertime, cloudiness has the opposite effect on SWCF and LWCF (Supplementary S8); thus, we need to examine the two radiations at the surface to find the impact of the Arctic cloud to Arctic climate. With more LCA than CAM5, SAM0 simulates more net LW radiation at the surface (FLNS, Fig. 11b). Owing to the high albedo of underlying sea ice and snow in the vicinity of the Arctic pole, the net SW radiation at the surface (FSNS) does not change much there; however, FSNS decreases substantially in the surrounding regions of the Arctic pole (Fig. 11a). Overall, the increase of FLNS dominates over the decrease of FSNS in the Arctic pole, while the opposite is true in the surrounding regions (Fig. 11b and 11c). The associated increase of $T_{2m}$ from CAM5 to SAM0 in the Arctic pole (Fig. 10h) decreases snow depth and surface albedo, while the opposite increases of snow depth and surface albedo occur in the surrounding continental area (Fig. 11d and 11e). The enhanced SWCF cooling near the Arctic pole in SAM0 (Fig. 10e) is the combined results of the increased LCA and decreased snow depth and surface albedo. If the Arctic sea ice fraction is allowed to change in response to the charges of overlying atmospheric conditions (e.g., coupled simulation), SAM0 is likely to simulate less sea ice fraction than CAM5 due to more LCA and warmer near-surface air temperature, which can be further accelerated by the positive surface albedo feedback (Holland and Bitz, 2003). In fact, Park et al. (2019) found that SAM0 simulates less sea ice fraction than the Community Earth System Model version 1 (CESM1, a coupled model of CAM5, Hurrell et al., 2013) over the Arctic in the 20th century coupled simulation.

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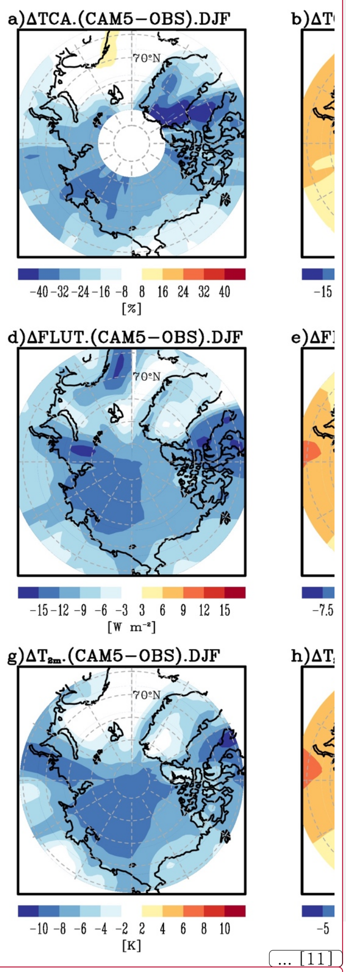


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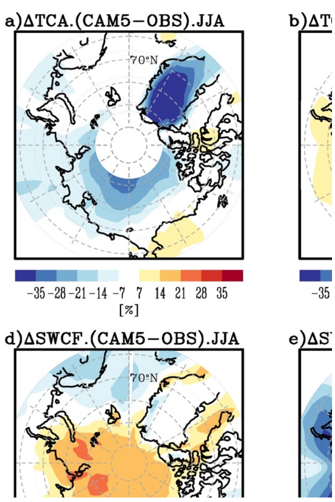

## 4. Summary and Discussion

Many GCMs suffer from the cold bias over the Arctic, which has been speculated to be caused by radiation biases associated with underestimated cloud fraction and cloud liquid mass over the Arctic. To address this issue, we compared various aspects of the Arctic clouds and climate in two different AMIP simulations generated by CAM5 and SAM0.

Similar to other GCMs and previous studies, CAM5 underestimates cloud fraction and cloud liquid mass in the Arctic lower troposphere throughout the year. SAM0 alleviates these problems, although biases still persists. Our analysis showed that this improvement in the Arctic cloud simulation with SAM0 is mainly due to stronger NCD for cloud liquid, which in turn, was due to enhanced poleward transports of heat and moisture by mean meridional circulation and transient eddies. A new unified convection scheme (UNICON) in SAM0 strengthens and shifts poleward the zonal mean meridional circulation, polar jet stream, and associated synoptic storm activity on the periphery of the Arctic circle. The proportional relationship between the Arctic cloudiness and meridional transports of heat and moisture in CAM5 and SAM0 also exists not only in both models but also in a set of CMIP5 models. In association with the deficient simulations of cloud fraction and cloud liquid mass, CAM5 suffers from the negative bias of near-surface air temperature throughout the year. With more cloud fraction and cloud liquid mass, SAM0 also alleviates the cold temperature biases in the Arctic mainly by enhancing the downward LW radiation at the surface, which is consistent with the hypotheses suggested by previous studies (Barton et al., 2014; Chan and Comiso, 2013; Klocke et al., 2011; Pithan and Mauritsen, 2014; Walsh and Chapman, 1998). Our study indicates that the improvement of poleward heat and moisture transport in a model can be one of the key factors for better simulations of Arctic clouds and climate.

Further study is in progress to investigate this hypothesis using fully coupled model. The authors are also continuously working to further reduce the remaining biases of Arctic clouds and climate by controlling convective activity simulated by UNICON and incorporating an improved ice nucleation scheme as suggested by previous studies.

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**Author Contributions**

E.-H. Baek performed the overall numerical experiments and analysis. S. Park developed and provided SAM0 and CAM5, and helped to analyze the simulation results. B.-M. Kim designed the project and helped to analyze the simulation results and the CMIP5 models. All authors contributed to conducting analyses.

**Competing interests**

The authors declare that they have no conflict of interest.

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## Figures

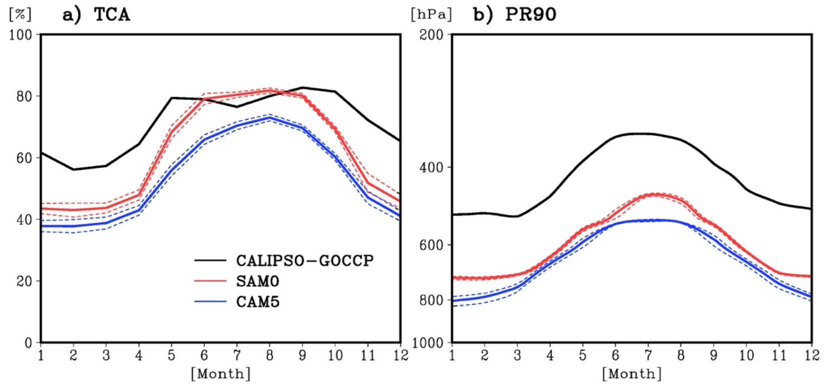


Figure 1: Annual cycles of (a) total cloud fraction (TCA) and (b) the height where the ratio of ice condensate mass to total condensate mass is 90 % (phase ratio, PR90) averaged over the Arctic area, north of 65° N from CALIPSO-GOCCP observations (black line), SAM0 (red line), and CAM5 (blue line). Dashed lines denote the standard deviation of each variable.

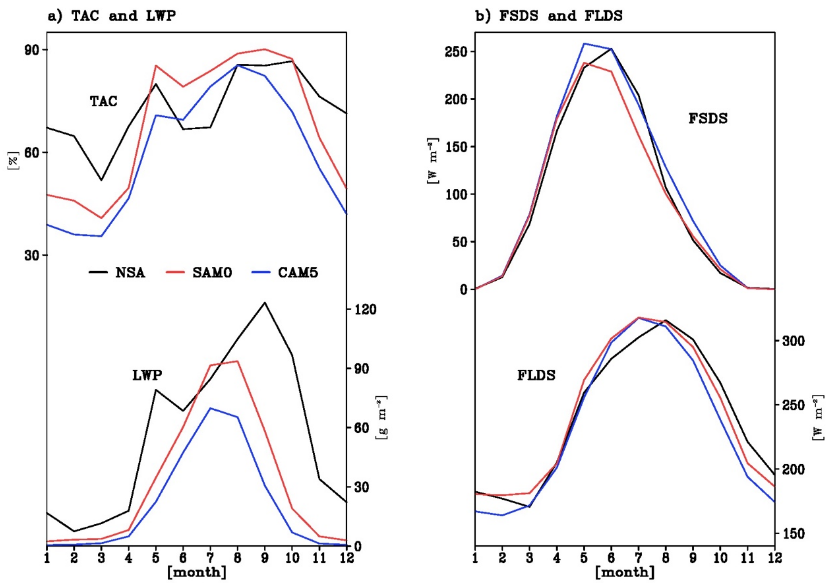


Figure 2: Annual cycles of total cloud fraction (TAC, upper in (a)), liquid water path (LWP, bottom in (a)), surface downward shortwave flux (FSDS, upper in (b)), and surface downward longwave flux (FLDS, bottom in (b)) from the

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Deleted: S1. Differences of annual-mean (upper) 500 hPa geopotential

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climatology of ground-based cloud and radiation measurements at North Slope of Alaska (NSA) Barrow site (black line), SAM0 (red line), and CAM5 (blue line).

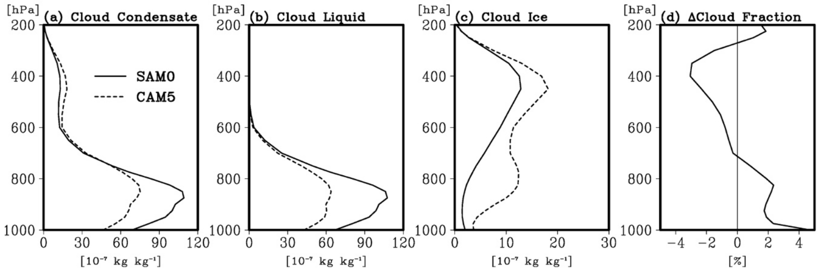


Figure 3: Annual-mean vertical profiles of grid-mean (a) cloud condensate mass (cloud liquid + cloud ice), (b) cloud liquid mass, and (c) cloud ice mass averaged over the Arctic area from SAM0 (solid lines) and CAM5 (dotted lines) and (d) the difference of cloud fraction between SAM0 and CAM5.

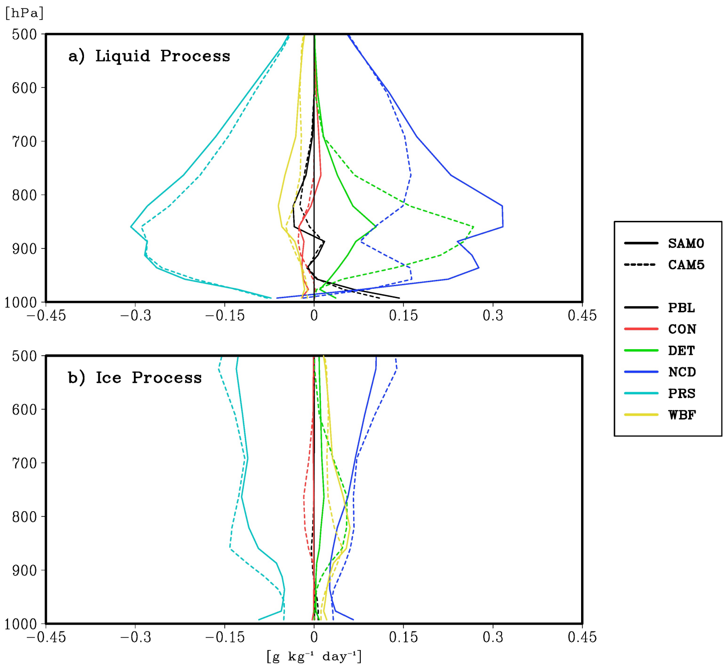


Figure 4: Annual-mean vertical profiles of the grid-mean tendencies of the (a) cloud liquid mass and (b) cloud ice mass induced by various moist physics processes from SAM0 (solid lines) and CAM5 (dotted lines). The processes shown are

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subgrid vertical transport by local symmetric turbulent eddies (PBL, black color), subgrid vertical transport by nonlocal asymmetric turbulent eddies (CON, red), convective detrainment (DET, green), net condensation of water vapor into cloud liquid and net deposition of water vapor into cloud liquid and ice (NCD, blue), precipitation-sedimentation fallout (PRS, cyan), and WBF conversion from cloud liquid mass to cloud ice mass (WBF, yellow).

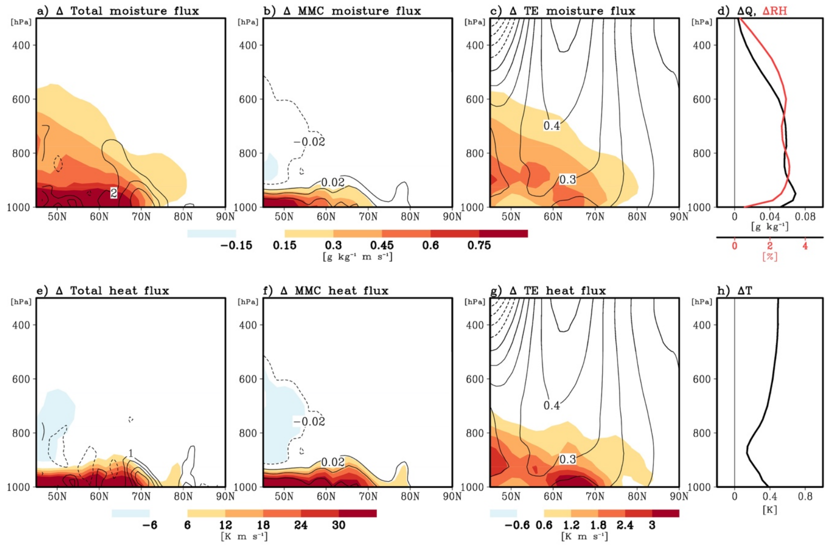


**Figure 5: Differences of zonal-mean meridional fluxes of (a, b, and c) moisture and (e, f, and g) heat by (a and e) total processes (i.e., the transported sum by mean meridional circulation, stationary eddies, and transient eddies), (b and f) mean meridional circulation (MMC), and (c and g) transient eddies (TE) between SAM0 and CAM5. Differences of the annual-mean vertical profiles (d) water vapor (Q, black) and relative humidity (RH, red), and (h) air temperature (T) averaged over the Arctic area between SAM0 and CAM5. The black lines in (a) and (e) denote the differences of zonal-mean convergence of total moisture flux in $10^{-7}$ g kg$^{-1}$ m s$^{-1}$ and total heat flux in $10^{-5}$ K s$^{-1}$. The black lines in (b) and (f) denote the differences of zonal mean meridional wind in m s$^{-1}$. The black lines in (c) and (g) denote the differences of zonal-mean zonal wind in m s$^{-1}$ between SAM0 and CAM5, respectively. Most shaded areas exceed 95 % significance level from the Student t-test.**

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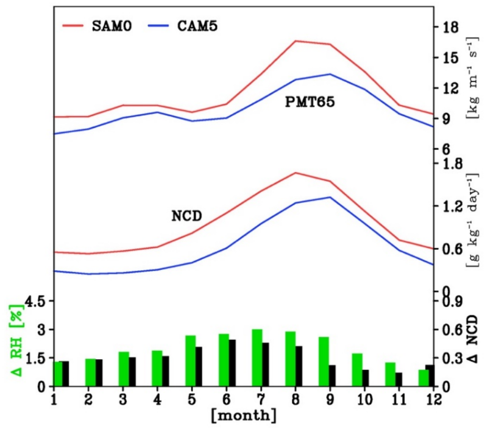


**Figure 6: Annual cycles of vertically-integrated zonal-mean poleward moisture transport in g kg$^{-1}$ m s$^{-1}$ at 65° N (PMT65) and net condensation rate of water vapor into cloud liquid in g kg$^{-1}$ day$^{-1}$ (NCD) averaged over the Arctic area from SAM0 (red line) and CAM5 (blue line).**

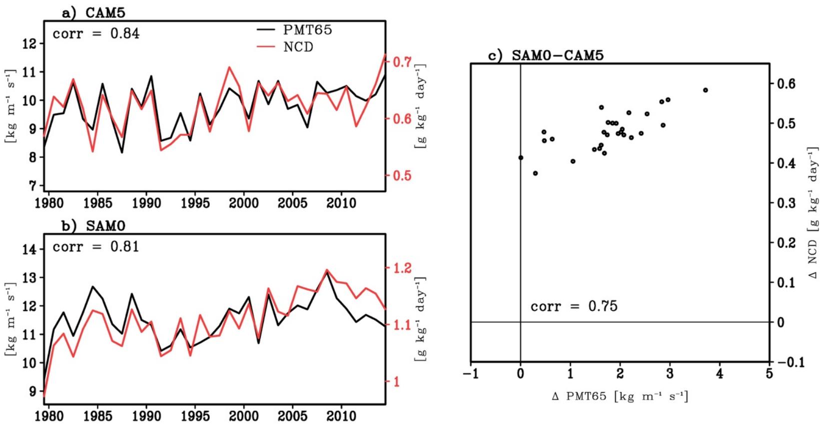


**Figure 7: Interannual time series of the vertically-integrated annual-mean poleward moisture flux at 65° N (PMT65, black line) and net condensation rate of water vapor into cloud liquid (NCD, red line) averaged over the Arctic area from (a) CAM5 and (b) SAM0, and (c) the scatter plot of the differences of annual-mean PMT65 and NCD between SAM0 and CAM5.**

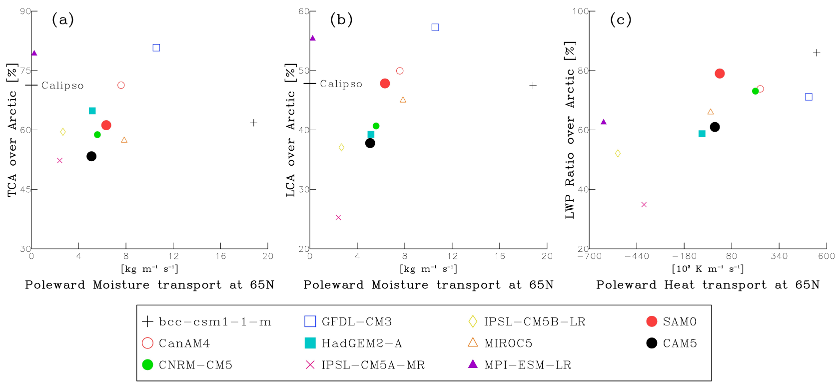


**Figure 8: Scatter plots of the annual mean poleward fluxes of moisture and heat integrated over the vertical layers (1000–7000 hPa) at 65° N, cloud fractions, and LWP ratio averaged over the Arctic area, obtained from various AMIP simulations of CMIP5 models, CAM5 and SAM0. The black lines in (a) and (b) denote the observed TCA and LCA, respectively, obtained from CALIPSO-GOCCP data.**

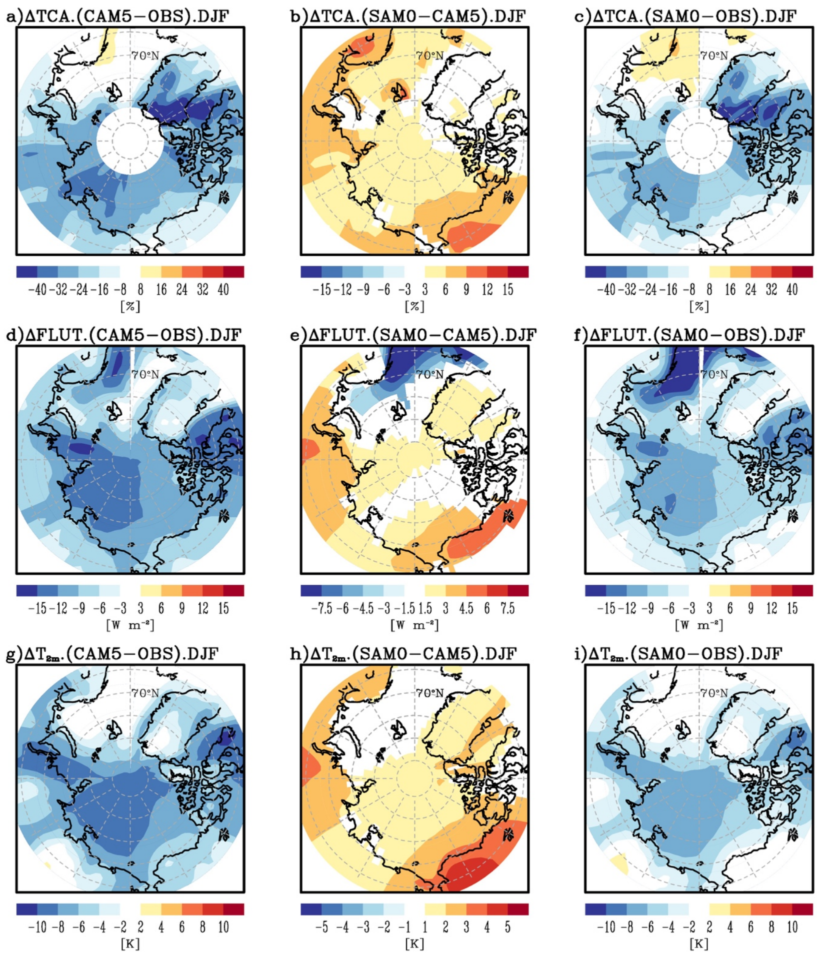


**Figure 9: Biases of (upper) TCA against the CALIPSO–GOCCP observation, (middle) upward longwave (LW) radiative flux at TOA (FLUT) against the CERES–EBAF observation, and (lower) near-surface air temperature at a 2 m height ($T_{2m}$) against the ERA-interim reanalysis during DJF obtained from (left) CAM5 and (right) SAM0, and (center) the differences of each variable between SAM0 and CAM5. Shaded areas in (b), (e), and (h) exceed 95 % significance level from the Student t-test.**

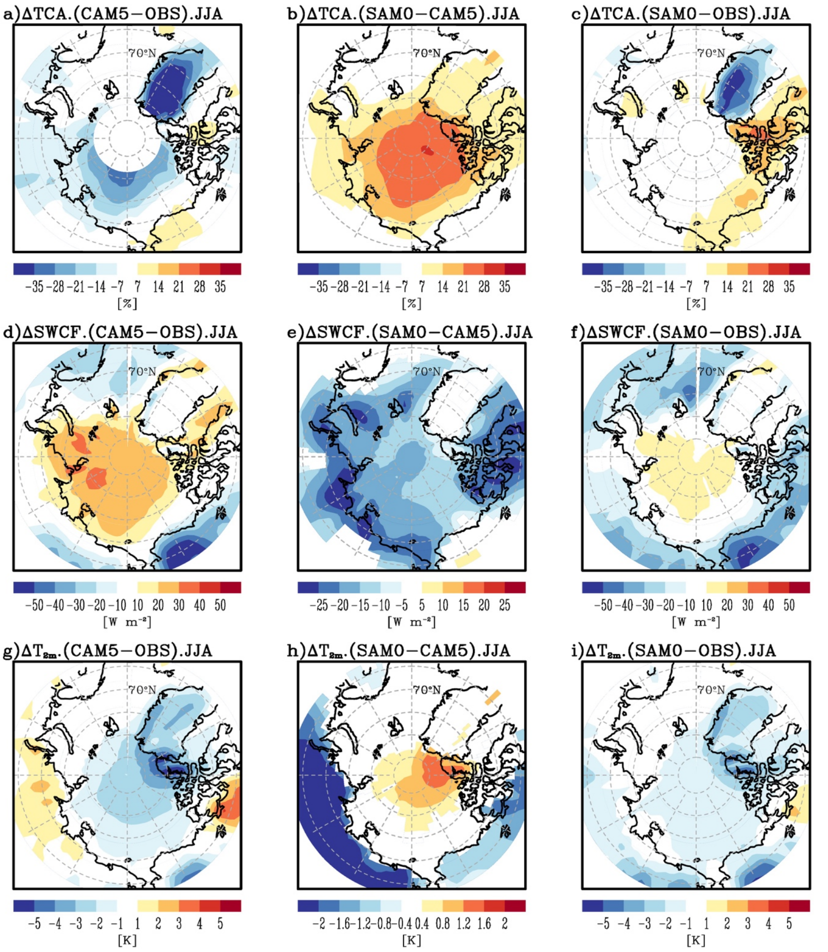


**Figure 10: Identical with Fig. 8, except for the shortwave cloud radiative forcing at TOA (SWCF) in the middle panel and during JJA. Shaded areas in (b), (e), and (h) exceed 95 % significance level from the Student t-test.**

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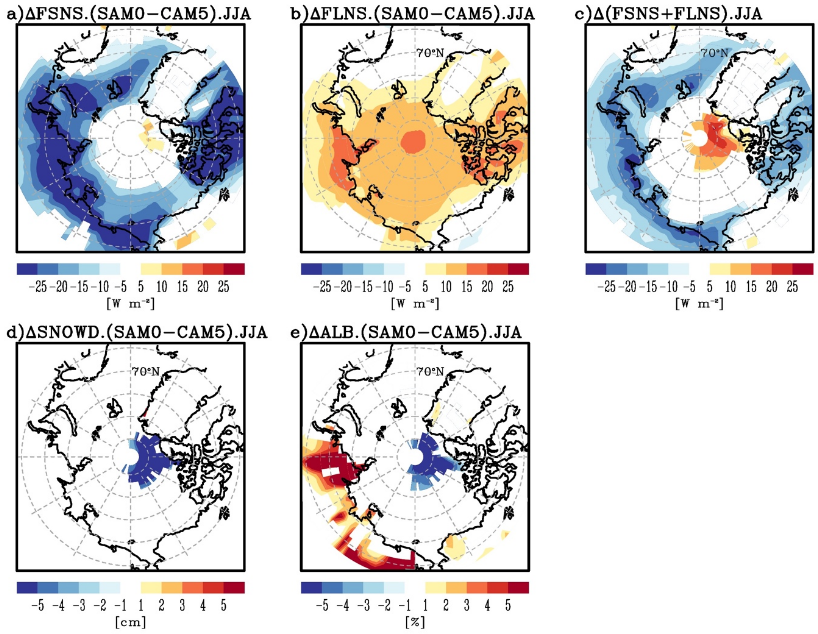


**Figure 11: Differences of (a) net SW flux at the surface (FSNS), (b) net LW flux at the surface (FLNS), (c) sum of FSNS and FLNS, (d) snow depth (SNOWD), and (e) surface albedo (ALB) during JJA between SAM0 and CAM5. Shaded areas exceed 95 % significance level from the Student t-test.**