Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL081871

# Evidence of Strong Contributions From Mixed-Phase Clouds to Arctic Climate Change

**Ivy Tan**[1,2] and **Trude Storelvmo**[3,4]

[1]Earth Sciences Division, NASA GSFC, Greenbelt, MD, USA, [2]Universities Space Research Association, Columbia, MD, USA, [3]Department of Geosciences, University of Oslo, Oslo, Norway, [4]School of Business, Nord University, Bodø, Norway

**Key Points:**
- Partitioning of cloud phase in a climate model impacts Arctic amplification via longwave radiation as a consequence of the cloud phase feedback
- The strength and magnitude of the impact of cloud phase on Arctic amplification depend on the microphysical characteristics of the clouds

**Correspondence to:**
I. Tan,
ivy.tan@nasa.gov

**Citation:**
Tan, I., & Storelvmo, T. (2019). Evidence of strong contributions from mixed-phase clouds to Arctic climate change. *Geophysical Research Letters*, *46*, 2894–2902. https://doi.org/10.1029/2018GL081871

Received 29 DEC 2018
Accepted 20 FEB 2019
Accepted article online 25 FEB 2019
Published online 9 MAR 2019
Corrected 5 APR 2019

This article was corrected on 5 APR 2019. See the end of the full text for details.



**Abstract** Underestimation of the proportion of supercooled liquid in mixed-phase clouds in climate models has called into question its impact on Arctic climate change. We show that correcting for this bias in the CESM model can either enhance or reduce Arctic amplification depending on the microphysical characteristics of the clouds as a corollary to the cloud phase feedback. Replacement of ice with liquid in the cloud phase feedback results in more downward longwave radiation, which is effectively trapped as heat at the surface in the Arctic due to its unique stable stratification conditions, and this ultimately leads to a more positive lapse rate feedback. The larger the ice particles are to begin with, the stronger Arctic amplification becomes due to the lower precipitation efficiency of liquid droplets compared to ice crystals. Our results emphasize the importance of realistic representations of microphysical processes in mixed-phase clouds, particularly in the Arctic.

**Plain Language Summary** Warming of Earth's Arctic at a faster pace relative to the rest of the globe is referred to as “Arctic amplification.” Mixed-phase clouds consisting of both liquid droplets and ice crystals are ubiquitous in Earth's Arctic. The ratio of liquid to ice in mixed-phase clouds is typically underestimated in climate models and has been shown to lead to underestimates in global warming by underestimating the strength of the “cloud phase feedback.” Replacement of cloud ice with liquid as Earth warms results in more reflected sunlight to space. Therefore, a low cloud liquid bias results in a global overestimate of the negative cloud phase feedback. In this study, we find that correcting this low bias can simultaneously reduce Arctic amplification by reducing longwave radiation to the surface that is trapped as heat in the Arctic. However, the effect is highly sensitive to the size of the cloud particles. Ice particles typically precipitate faster than liquid droplets so replacement of larger ice particles with liquid results in longer-lived clouds that radiate more longwave radiation to the surface, which ultimately leads to enhanced Arctic amplification. The results of this study emphasize the importance of realistic representations of mixed-phase cloud microphysics in climate models.

## 1. Introduction

Earth's Arctic is warming at a faster rate than the global average. Although this accelerated warming, referred to as Arctic amplification, is a well-established phenomenon, there is nonetheless a lack of consensus on the main physical mechanisms that are responsible for it. Early studies have primarily attributed Arctic amplification to the sea ice albedo feedback (Manabe & Wetherald, 1975), a positive feedback that amplifies initial warming predominantly through the melting of sea ice, which decreases the reflectivity of Earth's surface to sunlight. Many other studies have since confirmed the important role of the sea ice albedo feedback in Arctic amplification (Holland & Bitz, 2003; Screen & Simmonds, 2010; Taylor et al., 2013). However, the lapse rate feedback (Graversen et al., 2014), poleward energy transport (Hwang et al., 2011) and cloud feedbacks (Cronin & Tziperman, 2015; Taylor et al., 2013; Vavrus, 2004) have also been shown to play important roles in Arctic amplification. Unfortunately, the extent to which the myriad of possible climate feedbacks influences Arctic amplification is currently plagued with uncertainty. This is especially the case for cloud feedbacks, which continue to be the leading cause of uncertainty in climate projections (Stocker et al., 2013). While some studies have indicated that cloud feedbacks exert a substantial influence on Arctic climate change (Cronin & Tziperman, 2015; Kay et al., 2016; Taylor et al., 2013; Vavrus, 2004) as well as sea ice formation (Burt et al., 2015; Cao et al., 2017; Kay et al., 2008), the impact of cloud feedbacks on Arctic amplification

**Table 1**
*Summary of the Five Pairs of Simulations in Tan et al. (2016) That Are Analyzed in This Study, Which Focuses on the Arctic Processes in the Simulations*

| Name of simulation | Description |
|---|---|
| Low-SLF | INP increased by a factor of 75 |
| Control | Default model configuration |
| CALIOP-SLF1 | Constrained to better agree with satellite observations by modifying the cloud microphysical parameters displayed in Table 2 |
| CALIOP-SLF2 | Constrained to better agree with satellite observations by modifying the cloud microphysical parameters displayed in Table 2 |
| High-SLF | Free of INP |

*Note*. INP = ice nucleating particles.

was shown to be small in the ensemble of climate models participating in the fifth phase of the Cloud Model Intercomparison Project (Pithan & Mauritsen, 2014).

An outstanding aspect of the fifth phase of the Cloud Model Intercomparison Project models, however, is the low bias they possess in the fraction of supercooled liquid in liquid- and ice-containing mixed-phase clouds in comparison to satellite observations (Cesana et al., 2015; Komurcu et al., 2014; McCoy et al., 2016). Tan et al. (2016) showed that when the low bias in supercooled liquid fraction (SLF) in version 5.1 of the National Center for Atmospheric Research's Community Atmosphere Model (CAM5.1; Neale et al., 2010) was constrained by global satellite observations from the National Aeronautics and Space Administration's Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument (Winker et al., 2009), the equilibrium climate sensitivity (ECS) of the fully coupled version of the model increased by up to 1.3 °C. The increase in ECS was attributed to a weakened negative "cloud phase feedback" (Mitchell et al., 1989; Tsushima et al., 2006)—increasing the average SLF of the model prior to atmospheric $CO_2$ doubling reduced the amount of ice-to-liquid transitions that occurred in response to a warmer and deeper troposphere after atmospheric $CO_2$ doubling. Since liquid droplets tend to be both more abundant and smaller in size compared to their solid counterparts (Pruppacher & Klett, 1997), fewer ice-to-liquid transitions in clouds equate to smaller increases in cloud optical depth post-$CO_2$ doubling which ultimately causes ECS to increase by reducing the shortwave radiation reflected back to space. When the same version of the model was instead coupled to a thermodynamic mixed-layer ocean model, ECS was increased by a comparable amount of 1.5 °C, largely due to a weakened cloud phase feedback (Frey & Kay, 2017).

This study revisits the simulations of Tan et al. (2016) with a focus on the implications of cloud thermodynamic phase partitioning on Arctic climate change. The low bias in SLF in climate models is particularly relevant to the Arctic (Liu et al., 2011; Xie et al., 2013), where there exist unique thermodynamic and dynamic conditions that are conducive to producing the ubiquitous and resilient mixed-phase clouds (Morrison et al., 2012) that are observed year-round in the local boundary layer (Cesana et al., 2012; Hu et al., 2010). Section 2 briefly reviews the simulations in Tan et al. (2016), and section 3 reports and analyzes the results of the simulations as they specifically pertain to Arctic climate change. Finally, the results are discussed and conclusions are drawn in section 4.

## 2. Methods

To determine the impact of SLF on Arctic climate, we analyzed the same five pairs of simulations with both present-day (henceforth referred to as the "initial state") and doubled $CO_2$ concentrations that span a wide range of SLF (Table 1) in Tan et al. (2016). In the global warming simulations, atmospheric $CO_2$ was instantaneously doubled at the start of the simulations.

In increasing order of SLF, one pair of simulations ("Low-SLF") had unrealistically low SLFs, which was achieved by increasing the number of ice nucleating particles (INP) in the model by a factor of 75. The simulation containing the second-lowest SLF was the "Control" simulation, which was run with the default model configuration. Next, two pairs of simulations ("CALIOP-SLF1" and "CALIOP-SLF2") were constrained by modifying six cloud microphysical parameters (Table 2) such that the root-mean-square errors of the initial-state SLF relative to global observations obtained by CALIOP was <0.050 on the −10, −20, and

**Table 2**
*Summary of Cloud Microphysical Parameter Values Used in Three of the Simulations in Tan et al. (2016) That Are Also Analyzed in This Study With a Focus on the Arctic Processes in the Simulations*

| Microphysical parameter modified | Control | CALIOP-SLF1 | CALIOP-SLF2 |
|---|---|---|---|
| Fraction of dust aerosol active as INP | 1 | 0.49 | 0.19 |
| WBF time scale retardation factor for growth of ice | 1 | 0.024 | 0.80 |
| WBF time scale retardation factor for growth of snow | 1 | 0.024 | 0.80 |
| Fraction of aerosols scavenged in stratiform clouds | 1 | 0.96 | 0.99 |
| Fraction of aerosols scavenged in convective clouds | 0.40 | 0.72 | 0.97 |
| Ice crystal fall speed parameter | 700 $s^{-1}$ | 354 $s^{-1}$ | 371 $s^{-1}$ |
| Net impact of parameters on $\overline{r_{\mathrm{eff}}}$ at 860 hPa | 91.5 $\mu$m | 64.6 $\mu$m | 184.3 $\mu$m |

*Note*. The Wegener-Bergeron-Findeisen (WBF) process refers to the process whereby ice crystals grow at the expense of supercooled liquid when the ambient vapor pressure is in between the saturation vapor pressure over ice and liquid (Bergeron, 1935; Findeisen, 1938; Wegener, 1911). The bottom row indicates the net impact of the six microphysical parameters on the mean Arctic effective radii at the 860-hPa pressure level in the initial state of the default model, CALIOP-SLF1 and CALIOP-SLF2. CALIOP = Cloud-Aerosol Lidar with Orthogonal Polarization; INP = ice nucleating particles.

−30°C isotherms. These six cloud microphysical parameters were selected on the basis of their importance for the partitioning of cloud thermodynamic phase and net radiative flux at the top of the atmosphere as described in further detail in Tan and Storelvmo (2016). In lieu of utilizing a satellite simulator approach, consistent comparisons of SLF between CALIOP and CAM5 were instead obtained by sampling only cloud tops in CAM5 unless the optical depth of the cloud, $\tau$ <3, in which case underlying clouds were also sampled. The observed SLF was defined as the ratio of the number of liquid to the total number of liquid and ice footprints in CALIOP's level 2 Vertical Feature Mask product on fixed isotherms obtained from NCEP-DOE Reanalysis II data following Tan et al. (2014). SLFs were calculated using mixing ratio in place of lidar footprint counts in CAM5. In addition to the perturbations to the cloud microphysical parameters in these two simulations, two other modifications were implemented. First, the default cloud ice nucleation scheme (Meyers et al., 1992), which computes the ice number concentration as a function of temperature and supersaturation for these two simulations, was also replaced with the DeMott et al. (2015) ice nucleation scheme. This scheme takes into account the number of prognostically predicted large dust aerosol particles that act as INP from the modal aerosol module with three lognormal modes (MAM3; Liu et al., 2012) in the computation of ice number concentration. Implementation of an earlier version (DeMott et al., 2010) of the DeMott et al. (2015) ice nucleation scheme in CAM5 has previously been shown to improve comparisons of Arctic low clouds (Liu et al., 2011) but overestimate the midlevel cloud fraction with observations (Xie et al., 2013). Second, the convective detrainment parameterization in the model was modified so that ice was only detrained when temperatures were less than −35°C. Finally, the simulation at this other extreme that had unrealistically high SLFs ("High-SLF") was achieved by eliminating all INP in the model and also implementing the same convective detrainment scheme used in CALIOP-SLF1 and CALIOP-SLF2. The small amount of ice produced in High-SLF was derived from ice sedimentation from cirrus clouds and from ice detrainment from convection at temperatures below −35°C.

All 10 simulations were run with version 1.06 of the fully coupled version of the model, Community Earth System Model (CESM1.06; Hurrell et al., 2013), which included dynamical ocean, sea ice, and land components. All averages in the analysis were computed using the last 50 years of simulation (henceforth referred to as the "mean state") after equilibrium (defined as the point when the incoming shortwave and outgoing longwave radiation balanced at the top of the atmosphere to within 0.3 $W/m^2$).

The lapse rate feedback calculations were computed using the radiative kernels developed by Shell et al. (2008). The lapse rate feedback was computed as

$$\lambda_{LR} = \frac{\partial R}{\partial T}\frac{\mathrm{d}T}{\mathrm{d}\bar{T}_{as}} - \frac{\partial R}{\partial T}\frac{\mathrm{d}T_s}{\mathrm{d}\bar{T}_{as}}, \quad (1)$$

where $R$ is the net radiative flux at the top of the atmosphere excluding forcing, $T$ is atmospheric temperature, $\bar{T}_{as}$ is global mean surface air temperature, and $T_s$ is surface temperature. In equation (1), $\frac{\partial R}{\partial T}$ is the radiative kernel and all changes were computed in response to atmospheric $CO_2$ doubling.

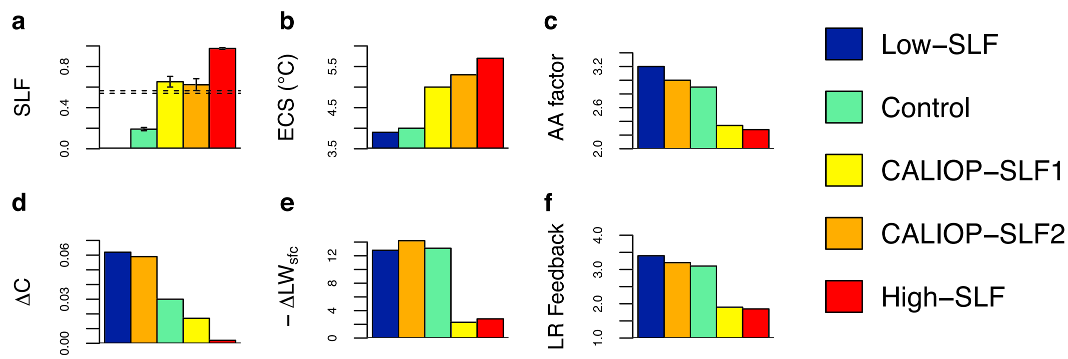


**Figure 1.** (a) Initial-state mean SLF averaged over the Arctic at the −10°C isotherm. The observational range (standard error straddling the mean) derived from CALIOP is indicated by the dashed lines. (b) ECS. (c) Arctic amplification factor, defined as the change in mean-state Arctic surface air temperature normalized by ECS. (d) Change in mean state in low cloud fraction (760 to 990 hPa) in response to $CO_2$ doubling. (e) Change in mean-state net longwave cloud radiative forcing at the surface in response to $CO_2$ doubling (downward direction is defined as positive). (f) Lapse rate feedback computed using radiative kernels. Note that CALIOP-SLF2 in panels (c), (d), and (e) has been rearranged. CALIOP = Cloud-Aerosol Lidar with Orthogonal Polarization; ECS = equilibrium climate sensitivity; SLF = supercooled liquid fraction.

## 3. Results

The mean initial-state Arctic (henceforth defined as north of 75°N) SLFs at the −10°C isotherm for each of the five pairs of simulations are displayed in Figure 1a. Their corresponding increases in ECS, defined as the change in global mean equilibrated surface temperature after doubling of atmospheric $CO_2$, shown in Tan et al. (2016) are redisplayed in Figure 1b. While Tan et al. (2016) showed that a weakened cloud phase feedback was responsible for the increase in ECS when initial-state SLF was increased, the *local* response in the Arctic is the simultaneous decrease in surface air temperature relative to ECS, quantified by the "Arctic amplification (AA) factor," with the exception of CALIOP-SLF2 (Figure 1c). Here we have computed the AA factor as the "ratio of means," but a computation of the AA factor as the "mean ratio" (Hind et al., 2016) confirms statistically significant differences in the AA factor between all simulations.

The opposite impact that correcting for the low bias in SLF has on the Arctic compared to the rest of the globe can be explained as follows: ice-to-liquid replacement upon atmospheric $CO_2$ doubling in the cloud phase feedback implies a decrease in average hydrometeor size relative to the initial state since ice crystals tend to be larger than liquid droplets (Pruppacher & Klett, 1997). The smaller size of liquid droplets also renders them less efficient at precipitating compared to ice crystals, which ultimately prolongs cloud lifetime and hence cloud cover relative to the initial state (Figure 1d). The change in precipitation efficiency is consistent with theory, observations, and climate models (Ceppi et al., 2016; Pruppacher & Klett, 1997; Senior & Mitchell, 1993; Zamora et al., 2018) and is more pronounced the stronger the cloud phase feedback, as reflected by the relatively larger increase in grid mean total water content in Low-SLF compared to High-SLF (Figure 2). At the same time, a larger increase in low cloud fraction implies an increase in downward longwave radiation to the surface in the annual mean (Matus & L'Ecuyer, 2017) (Figure 1e). In the Arctic, the unique stably stratified conditions in the lower troposphere trap this additional heat from the longwave radiation near the surface (Bintanja et al., 2011). The trapping of heat near the surface combined with increased atmospheric longwave cooling due to increased cloudiness in turn causes the lapse rate feedback to become more positive (Figure 1f), which ultimately explains Arctic amplification in the model. Thus, while the negative cloud phase feedback is a global phenomenon that cools Earth's surface through increased reflection of shortwave radiation back to space, the Arctic is a special case with unique conditions that ultimately counteract this cooling via cloud-induced trapping of longwave radiation that heats the surface. The processes driving the impact of SLF on Arctic amplification are summarized in Figure 3, and the mechanism has been verified to be insensitive to the latitude used to define the lower threshold of the Arctic (not shown).

At first glance, CALIOP-SLF2 appears to be an exception to the proposed Arctic amplification mechanism described above; rather than exhibiting a decrease in Arctic amplification relative to Control, it instead exhibits an increase in Arctic amplification. This seemingly unexpected behavior of CALIOP-SLF2 arises from the fact that it contains ice particles that are much larger in size in its initial state (bottom row, Table 2).

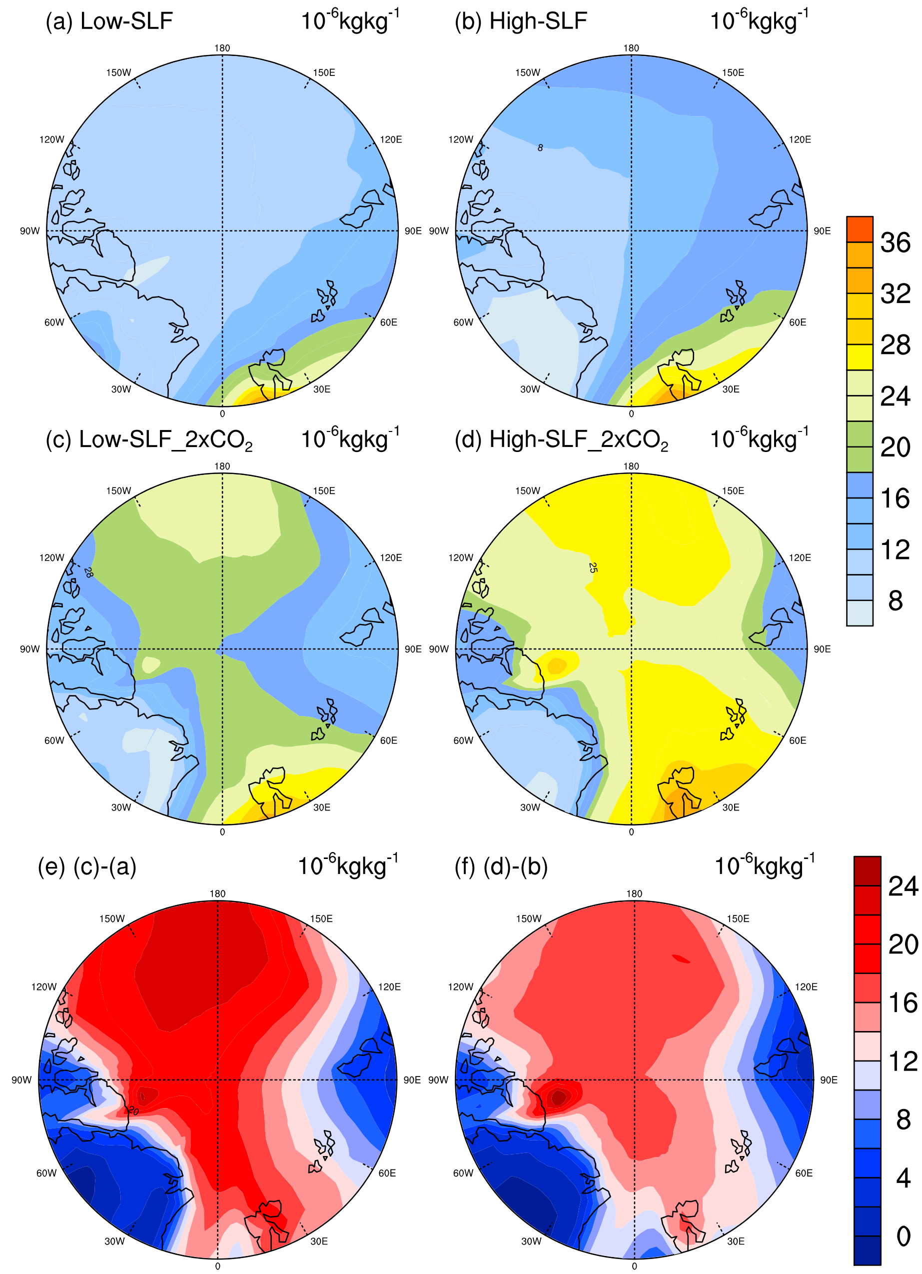


**Figure 2.** Polar projections of vertically averaged mean-state total grid mean water content between 760 and 990 hPa for (a) Low-SLF and (b) High-SLF prior to $CO_2$ doubling and (c) Low-SLF and (d) High-SLF after $CO_2$ doubling. The increase in grid mean total water content in Low-SLF post-$CO_2$ doubling (e) is greater than that in High-SLF (f), supporting that longer-lived clouds persist in response to global warming in simulations with lower initial-state SLFs. SLF = supercooled liquid fraction.

In particular, the mean Arctic ice crystal effective radius in the initial state of CALIOP-SLF2 is approximately 200 $\mu$m, which is more than twice as large as that of the other simulations. The larger ice particle sizes in CALIOP-SLF2 can be traced to the fact that it has a combination of fewer INP available for ice crystal formation, a slower ice crystal terminal fall speed, and a faster Wegener-Bergeron-Findeisen process (Table 2). With larger initial-state mean ice particle sizes, the ice-to-liquid replacement in the cloud phase feedback of CALIOP-SLF2 results in a more dramatic decrease in average hydrometeor size relative to the initial state compared to the other simulations. This ultimately exaggerates the Arctic amplification mechanism described above to the extent that Arctic amplification in CALIOP-SLF2 is greater than that of Control. A noteworthy consequence is that the Arctic warms by as much as 19 °C in response to $CO_2$ doubling in

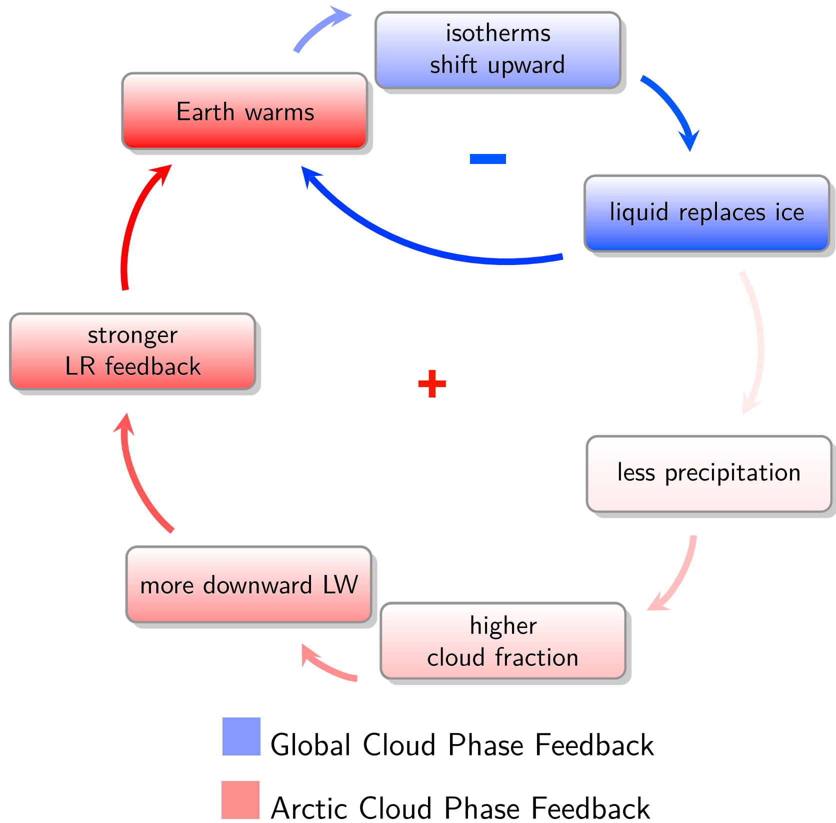


**Figure 3.** Flowchart summarizing the mechanisms that ultimately lead to reduced Arctic amplification. After initial warming induced by doubling of atmospheric $CO_2$ concentrations, the negative cloud phase feedback (displayed in blue) counteracts the initial warming globally. However, the warming is reinforced locally in the Arctic by a positive feedback (displayed in red) and is triggered by an increase in local cloud coverage through the cloud lifetime effect. The increase in cloud coverage increases longwave radiation emitted to the surface that is trapped as heat as a result of local stable stratification conditions in the Arctic, causing the lapse rate feedback to become more positive. Both feedbacks are stronger when the initial-state supercooled liquid fraction is lower.

CALIOP-SLF2. However, the question as to which simulation contains the most realistic ice particle sizes is difficult to evaluate since the definition of ice crystal effective radius differs substantially among models and observations (McFarquhar & Heymsfield, 1998). Further complicating matters, observations of ice crystal effective radii in the Arctic are scarce.

## 4. Discussion and Conclusions

Analysis of the Arctic region of the simulations originally presented in Tan et al. (2016) reveals that the Arctic tends to warm less relative to the global average when the low bias in initial-state SLF is removed, but with the caveat that the temperature change in the Arctic relative to the global average is highly sensitive to the microphysical characteristics of the mixed-phase clouds. In particular, larger ice particles in Arctic mixed-phase clouds could ultimately enhance rather than reduce Arctic amplification due to the larger decrease in average hydrometeor size that will arise from ice-to-liquid replacement in the cloud phase feedback. The larger decrease in average hydrometeor size manifests as an increase in cloud fraction since smaller liquid droplets tend to precipitate less efficiently compared to larger ice particles, and this increases downwelling longwave radiation at the surface from clouds, which ultimately enhances Arctic amplification.

While Arctic amplification is generally a phenomenon observed only during boreal winter (Lu & Cai, 2009; Sejas et al., 2014), the mechanism presented (Figure 3) operates on the annual average possibly due to the unique stable stratification conditions that tend to exist year-round (Tjernström & Graversen, 2009) in the Arctic. However, the impact of SLF on the melting of Arctic sea ice, which exhibits a strong seasonal dependence is well correlated ($R = 0.94$) with absolute temperature change in the Arctic (Figure 4). Thus,

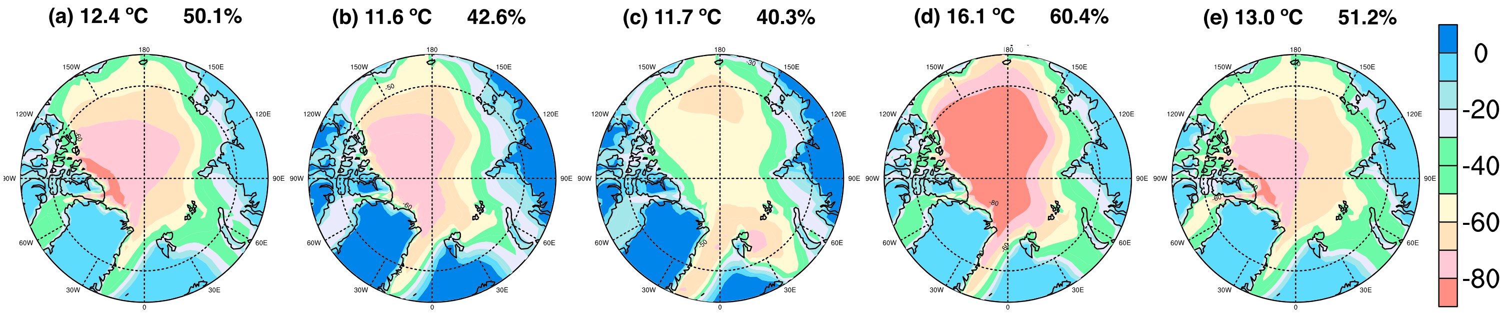


**Figure 4.** Change in annual mean percentage of surface covered by sea ice in response to $CO_2$ doubling for (a) Low-SLF, (b) Control, (c) CALIOP-SLF1, (d) CALIOP-SLF2, and (e) High-SLF. The average increase (decrease) in average Arctic surface temperature (sea ice cover) is displayed in the top left (right) corner. CALIOP = Cloud-Aerosol Lidar with Orthogonal Polarization; SLF = supercooled liquid fraction.

the mechanism presented in this study is a corollary to the long-term cloud phase feedback in contrast to previous studies that have attributed greater Arctic surface warming in the current climate as a direct consequence of short-term enhanced downward longwave radiation to the surface (Bennartz et al., 2013).

We note that the conclusions drawn from the analysis of the results in this study were based on a single climate model and the extent to which our results hold across different climate models has not yet been tested. A recent study investigating the impact of cloud thermodynamic phase partitioning on ECS using the ECHAM6.3-HAM2.3 model found that the importance of the cloud phase feedback on ECS may be model-dependent (Lohmann & Neubauer, 2018). We also point out that we focus on the long-term (century and longer time scale) impact of SLF on Arctic climate change in our study that occurs after ocean heat adjustment. While SLF has been shown to dramatically influence global climate change, quantified by the single ECS metric through the cloud phase feedback, the influence of SLF on short-term (21st century) warming may be muted by ocean heat uptake (Frey et al., 2017). Therefore, by extension, the impact of SLF on Arctic climate change may be comparatively small on the decadal time scale.

The need for improving cloud microphysical processes that influence thermodynamic phase is underscored by the impact of these processes on Arctic amplification. Given the tendency of most climate models to underestimate the proportion of supercooled liquid in mixed-phase clouds, eliminating this low bias in climate models by correcting the cloud microphysical processes at the root of the issue should be a priority, as it would not only potentially increase climate sensitivity estimates (Frey & Kay, 2017; Tan et al., 2016) but also simultaneously impact Arctic amplification estimates. CALIOP-SLF2 in particular demonstrates that attention to details in the cloud microphysical processes that influence SLF can be critical, especially in the Arctic, where mixed-phase clouds are ubiquitous and unique thermodynamic conditions interact with the microphysical processes (Morrison et al., 2012). Indispensable to these endeavors are improved observations of the microphysical properties of mixed-phase clouds, particularly in the Arctic. Our analysis suggests that although global satellite observations from CALIOP have been ground-breaking and critical for improving our understanding of the impact of clouds on climate change, remote sensing observations alone, whether active or passive, are insufficient for constraining ice cloud microphysical properties as they require several assumptions to obtain them (Heymsfield et al., 2005; King et al., 2004). On the other hand, in situ observations targeted toward documenting the microphysical properties of ice crystals in Arctic mixed-phase clouds, although sparse in spatial coverage, are more direct (Korolev et al., 2017) and could provide a potential complementary path to addressing the issues associated with cloud thermodynamic phase and its influence on Arctic amplification. Improvements in the way observations are combined with our theoretical understanding and implementation of the processes in models are also critical for progress in better predicting Arctic climate change (Kay et al., 2016).

**Acknowledgments**
Observations retrieved from CALIPSO are available online at NASA Langley's Atmospheric Science Data Center's website. NCEP-DOE Reanalysis II data are available online at the website (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html). Model output can be downloaded online at the website (https://osf.io/r3qch/files/). The effort of I. T. was supported by the NASA Postdoctoral Program at NASA GSFC administered by University Space Research Association under contract with NASA. The effort of T. S. was supported by the European Research Council through grant number 758005. The authors also acknowledge high-performance computing support from Yellowstone provided by National Center for Atmospheric Research's Computational and Information Systems Laboratory, sponsored by NSF under grant 1352417.

## References

Bennartz, R., Shupe, M. D., Turner, D. D., Walden, V. P., Steffen, K., Cox, C. J., & Pettersen, C. (2013). July 2012 Greenland melt extent enhanced by low-level liquid clouds. *Nature*, *496*, 83–86.

Bergeron, T. (1935). On the physics of clouds and precipitation. *Procès Verbaux de l'Association de Météorologie*, 156–178.

Bintanja, R., Graversen, R. G., & Hazeleger, W. (2011). Arctic winter warming amplified by the thermal inversion and consequent low infrared cooling to space. *Nature Geoscience*, *4*, 758–761.

Burt, M. A., Randall, D. A., & Branson, M. D. (2015). Dark warming. *Journal Climate*, *29*, 705–719.

Cao, Y., Liang, S., Chen, X., He, T., Wang, D., & Cheng, X. (2017). Enhanced wintertime greenhouse effect reinforcing Arctic amplification and initial sea-ice melting. *Scientific Reports*, *7*, 8462.

Ceppi, P., Hartmann, D. L., & Webb, M. J. (2016). Mechanisms of the negative shortwave cloud feedback in middle to high latitudes. *Journal Climate*, *29*, 139–157.

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., Waliser, D. E., Jiang, X., & Li, J. L. (2015). Multimodel evaluation of cloud phase transition using satellite and reanalysis data. *Journal of Geophysical Research: Atmospheres*, *10*, 7871–7892. https://doi.org/10.1002/2014JD022932

Cronin, T. W., & Tziperman, E. (2015). Low clouds suppress Arctic air formation and amplify high-latitude continental winter warming. *Proceedings of the National Academy of Sciences*, *112*, 11,490–11,495.

DeMott, P. J., Prenni, A. J., Liu, X., Kreidenweis, S. M., Petters, M. D., Twhoy, C. H., & Rogers, D. C. (2010). Predicting global atmospheric ice nuclei distributions and their impacts on climate. *Proceedings of the National Academy of Sciences*, *107*, 11,217–11,222.

DeMott, P. J., Prenni, A. J., McMeeking, G. R., Sullivan, R. C., Petters, M. D., Tobo, Y., & Kreidenweis, Z. W. S. M. (2015). Integrating laboratory and field data to quantify the immersion freezing ice nucleation activity of mineral dust particles. *Atmospheric Chemistry and Physics*, *15*, 393–409.

Findeisen, W. (1938). Die kolloidmeteorologischen Vorgänge bei der Niederschlagsbildung. *Meteorologische Zeitschrift*, *55*, 121–133.

Frey, W. R., & Kay, J. E. (2017). The influence of extratropical cloud phase and amount feedbacks on climate sensitivity. *Climate Dynamics*, *50*, 3097–3116.

Frey, W. R., Maroon, E. A., Pendergrass, A. G., & Kay, J. E. (2017). Do Southern Ocean cloud feedbacks matter for 21st century warming? *Geophysical Research Letters*, *44*, 12,447–12,456. https://doi.org/10.1002/2017GL076339

Graversen, R. G., Langen, P., & Mauritsen, T. (2014). Polar amplification in CCSM4: Contributions from the lapse rate and surface albedo feedbacks. *Journal Climate*, *27*, 4433–4450.

Heymsfield, A. J., Winker, D. M., & van Zadelhoff, G. J. (2005). Extinction-ice water content-effective radius algorithms for CALIPSO. *Geophysical Research Letters*, *32*, L10807. https://doi.org/10.1029/2005GL022742

Hind, A., Zhang, Q., & Brattström, G. (2016). Problems encountered when defining Arctic amplification as a ratio. *Scientific Reports*, *6*, 30469.

Holland, M. M., & Bitz, C. M. (2003). Polar amplification of climate change in coupled models. *Climate Dynamics*, *21*, 221–232.

Hu, Y., Rodier, S., Xu, K. M., Sun, W., Huang, J., Lin, B., & Josset, D. (2010). Occurrence, liquid water content, and fraction of supercooled water clouds from combined CALIOP/IIR/MODIS measurements. *Journal of Geophysical Research*, *115*, D00H34. https://doi.org/10.1029/2009JD012384

Hurrell, J. W., Gent, M. M. H. P. R., Ghan, S., Kay, J. E., Kushner, P. J., Lamarque, J. F., & Lipscomb, W. H. (2013). The Community Earth System Model: A framework for collaborative research. *Bulletin of the American Meteorological Society*, *94*, 1339–1360.

Hwang, Y. T., Frierson, D. M. W., & Kay, J. E. (2011). Coupling between Arctic feedbacks and changes in poleward energy transport. *Geophysical Research Letters*, *38*, L17704. https://doi.org/10.1029/2011GL048546

Kay, J. E., L'Ecuyer, T., Chepfer, H., Loeb, N., Morrison, A., & Cesana, G. (2016). Recent advances in Arctic cloud and climate research. *Current Climate Change Reports*, *2*, 159–169.

Kay, J. E., L'Ecuyer, T., Gettelman, A., Stephens, G., & O'Dell, C. (2008). The contribution of cloud and radiation anomalies to the 2007 Arctic sea ice extent minimum. *Geophysical Research Letters*, *35*, L08503. https://doi.org/10.1029/2008GL033451

King, M. D., Platncik, S., Yang, P., Arnold, G. T., Gray, M. A., Riédi, J., & Liou, K. N. (2004). Remote sensing of liquid water and ice cloud optical thickness and effective radius in the Arctic: Application of airborne multispectral MAS data. *Journal of Atmospheric and Oceanic Technology*, *21*, 857–875.

Komurcu, M., Storelvmo, T., Tan, I., Lohmann, U., Yun, Y., Penner, J. E., & Takemura, T. (2014). Intercomparison of the cloud water phase among global climate models. *Journal of Geophysical Research: Atmospheres*, *119*, 3372–3400. https://doi.org/10.1002/2013JD021119

Korolev, A., McFarquhar, G. M., Field, P. R., Franklin, C., Lawson, P., Wang, Z., & Wendisch, M. (2017). Mixed-phase clouds: Progress and challenges. *Meteorological Monographs*, *58*, 5.1–5.50.

Liu, X., Easter, R. C., Ghan, S. J., Zaveri, R., Rasch, P., Shi, X., & Conley, A. (2012). Toward a minimal representation of aerosols in climate models: Description and evaluation in the Community Atmosphere Model CAM5. *Geoscientific Model Development*, *5*, 709–739.

Liu, X., Xie, S., Boyle, J., Klein, S. A., Shi, X., Wang, Z., & Zelenyuk, A. (2011). Testing cloud microphysics parameterizations in NCAR CAM5 with ISDAC and M?PACE observations. *Journal of Geophysical Research*, *116*, D00T11. https://doi.org/10.1029/2011JD015889

Lohmann, U., & Neubauer, D. (2018). The importance of mixed-phase and ice clouds for climate sensitivity in the global aerosol-climate model ECHAM6-HAM2. *Atmospheric Chemistry and Physics*, *18*, 8807–8828.

Lu, J., & Cai, M. (2009). Seasonality of polar surface warming amplification in climate simulations. *Geophysical Research Letters*, *36*, L16704. https://doi.org/10.1029/2009GL040133

Manabe, S., & Wetherald, R. T. (1975). The effect of doubling the $CO_2$ concentration on the climate of a general circulation model. *Journal of the Atmospheric Sciences*, *32*, 3–15.

Matus, A., & L'Ecuyer, T. S. (2017). The role of cloud phase in Earth's radiation budget. *Journal of Geophysical Research: Atmospheres*, *122*, 2559–2578. https://doi.org/10.1002/2016JD025951

McCoy, D. T., Tan, I., Hartmann, D. L., Zelinka, M. D., & Storelvmo, T. (2016). On the relationships among cloud cover, mixed-phase partitioning, and planetary albedo in GCMs. *Journal of Advances in Modeling Earth Systems*, *8*, 650–668. https://doi.org/10.1002/2015MS000589

McFarquhar, G. M., & Heymsfield, A. J. (1998). The definition and significance of an effective radius for ice clouds. *Journal of the Atmospheric Sciences*, *55*, 2039–2052.

Meyers, M. P., DeMott, P. J., & Cotton, W. R. (1992). New primary ice-nucleation parameterizations in an explicit cloud model. *Journal of Applied Meteorology and Climatology*, *31*, 708–721.

Mitchell, J. F. B., Senior, C. A., & Ingram, W. J. (1989). $CO_2$ and climate: A missing feedback. *Nature*, *341*, 132–134.

Morrison, H., de Boer, G., Feingold, G., Harrington, J., Shupe, M. D., & Sulia, K. (2012). Resilience of persistent Arctic mixed-phase clouds. *Nature Geoscience*, *5*(1), 11–17.

Neale, R. B., Chen, C. C., Gettelman, A., Lauritzen, P. H., Park, S., Williamson, D. L., & Marsh, D. (2010). Description of the NCAR community atmosphere model (CAM 5.0). NCAR Tech. Note NCAR/TN-486+ STR.

Pithan, F., & Mauritsen, T. (2014). Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nature Geoscience*, *7*, 181–184.

Pruppacher, H. R., & Klett, J. D. (1997). Microphysics of clouds and precipitation, (2ed.). In R. D. Rosen (Ed.), *Reprinted 1980* (Vol. 18, pp. 10–73). Dordrecht, Netherlands: Kluwer Academic Publishers.

Screen, J. A., & Simmonds, I. (2010). The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature*, *464*, 1334–1337.

Sejas, S., Cai, M., Hu, A., Meehl, J., Washington, W., & Taylor, P. C. (2014). On the seasonality of polar warming amplification. *Journal Climate*, *27*, 5653–5669.

Senior, C. A., & Mitchell, J. F. B. (1993). Carbon dioxide and climate. The impact of cloud parameterization. *Journal Climate*, *6*, 393–418.

Shell, K. M., Kiehl, J. T., & Shields, C. A. (2008). Using the radiative kernel technique to calculate climate feedbacks in NCAR's Community Atmospheric Model. *Journal Climate*, *21*, 2269–2282.

Stocker, T. F., Qin, D., Plattner, G.-K., Alexander, L. V., Allen, S. K., Bindoff, N. L., et al. (2013). Technical summary: Climate change 2013: The physical science basis. Fifth assessment report of the intergovernmental panel on climate change. *Computational Geometry*, *18*, 95–123.

Tan, I., & Storelvmo, T. (2016). Sensitivity study on the influence of cloud microphysical parameters on mixed-phase cloud thermodynamic phase partitioning in CAM5. *Journal of the Atmospheric Sciences*, *73*, 709–728.

Tan, I., Storelvmo, T., & Choi, Y. S. (2014). Spaceborne lidar observations of the ice-nucleating potential of dust, polluted dust, and smoke aerosols in mixed-phase clouds. *Journal of Geophysical Research: Atmospheres*, *119*, 6653–6665. https://doi.org/10.1002/2013JD021333

Tan, I., Storelvmo, T., & Zelinka, M. D. (2016). Observational constraints on mixed-phase clouds imply higher climate sensitivity. *Science*, *352*, 224–227.

Taylor, P. C., Cai, M., Hu, A., & Meehl, J. (2013). A decomposition of the feedback contributions to polar warming amplification. *Journal Climate*, *26*, 7023–7043.

Tjernström, M., & Graversen, R. G. (2009). The vertical structure of the lower Arctic troposphere analysed from observations and the ERA-40 reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *135*, 431–443.

Tsushima, Y., Emori, S., Ogura, T., Kimoto, M., Webb, M. J., Williams, K. D., & Andronova, N. (2006). Importance of the mixed-phase cloud distribution in the control climate for assessing the response of clouds to carbon dioxide increase: A multi-model study. *Climate Dynamics*, *27*, 113–126.

Vavrus, S. (2004). The impact of cloud feedbacks on Arctic climate under greenhouse forcing. *Journal Climate*, *17*, 603–615.

Wegener, A. (1911). Thermodynamik der Atmosphäre. JA Barth.

Winker, D. M., Vaughan, M. A., Omar, A., Hu, Y., Powell, K., Liu, Z., & Young, S. A. (2009). Overview of the CALIPSO mission and CALIOP data processing algorithms. *Journal of Atmospheric and Oceanic Technology*, *26*(11), 2310–2323.

Xie, S., Liu, X., Zhao, C., & Zhang, Y. (2013). Sensitivity of CAM5-simulated Arctic clouds and radiation to ice nucleation parameterization. *Journal Climate*, *26*, 5981–5999.

Zamora, L. M., Kahn, R. A., Huebert, K. B., Stohl, A., & Eckhardt, S. (2018). A satellite-based estimate of combustion aerosol cloud microphysical effects over the Arctic Ocean. *Atmospheric Chemistry and Physics*, *18*, 14,949–14,964.

## Erratum

In the originally published version of this article, two values in the "Control" column of Table 2 appeared incorrectly, with "0" in the place of the correct "1" in both cases. This error has since been corrected, and the present version may be considered the authoritative version of record.