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Key Points:
- Disabling cloud radiative feedbacks in a climate model can separate the influence of Arctic and global cloud feedbacks on greenhouse warming
- Arctic surface greenhouse warming increases due to global cloud feedbacks but is insensitive to Arctic cloud feedbacks
- The sum of noncloud feedbacks (water vapor, lapse rate, and surface albedo) is unaffected by disabling cloud feedbacks both globally and in the Arctic alone

Supporting Information:
- Supporting Information S1

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Quantifying the Influence of Cloud Radiative Feedbacks on Arctic Surface Warming Using Cloud Locking in an Earth System Model

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Abstract Understanding the influence of clouds on amplified Arctic surface warming remains an important unsolved research problem. Here, this cloud influence is directly quantified by disabling cloud radiative feedbacks or "cloud locking" within a state-of-the-art and well-documented model. Through comparison of idealized greenhouse warming experiments with and without cloud locking, the influence of Arctic and global cloud feedbacks is assessed. Global cloud feedbacks increase both global and Arctic warming by around 25%. In contrast, disabling Arctic cloud feedbacks has a negligible influence on both Arctic and global surface warming. Interestingly, the sum of noncloud radiative feedbacks does not change with either global or Arctic-only cloud locking. Notably, the influence of Arctic cloud feedbacks is likely underestimated, because, like many models, the model used here underestimates high-latitude supercooled cloud liquid. More broadly, this work demonstrates the value of regional and global cloud locking in a well-characterized model.

1. Introduction

Observations and modeling show that the Arctic surface warms more than anywhere else on the globe under increased greenhouse gas forcing (e.g., Manabe & Stouffer, 1980; Collins et al., 2013). Greater-than-global (or "amplified") Arctic warming results from local positive Arctic feedbacks not present at lower latitudes including the positive surface albedo and lapse rate feedbacks (e.g., Goosse et al., 2018; Pithan & Mauritsen, 2014; Stuecker et al., 2018). Clouds affect both Arctic and global surface greenhouse warming through their radiative feedbacks, yet clouds remain a substantial source of uncertainty in climate models (Boucher et al., 2013). Recent assessments conclude that global cloud radiative feedbacks are "likely positive" (Vial et al., 2013; Zelinka et al., 2017). In contrast, Arctic cloud feedbacks have been assessed to be small but uncertain in sign (Boucher et al., 2013), though there is observational evidence for a positive Arctic cloud-sea ice feedback in nonsummer months (Kay & Gettelman, 2009; Morrison et al., 2018; Schweiger et al., 2008). While recent progress has been made in understanding cloud influence on Arctic climate (e.g., Kay et al., 2016), quantifying the contribution of local (i.e., Arctic) and nonlocal (i.e., global) cloud radiative feedbacks to Arctic surface greenhouse warming remains an important open research question.

Disabling cloud feedbacks within models enables causal quantification of their influence on the climate system (e.g., Grise et al., 2019; Mauritsen et al., 2013; Middlemas et al., 2019; Vavrus, 2004). One such technique—often referred to as "cloud locking"—disables cloud radiative feedbacks including the interaction of cloud radiative feedbacks with noncloud climate feedbacks and atmospheric circulation. Comparing model runs with and without radiative feedbacks allows a full assessment of the impact of the feedbacks and provides an attractive strategy for quantifying cloud feedback influence on Arctic surface greenhouse warming. For example, Vavrus (2004) implemented a form of global cloud locking in an atmosphere-mixed layer ocean climate model and found that 40% of the Arctic warming in response to a carbon dioxide doubling results from global cloud feedbacks.

Cloud locking offers distinct advantages over other methods used to estimate cloud feedbacks. For example, regression (Cess et al., 1990), radiative kernels (Soden et al., 2008), and radiative perturbation technique

(Colman & McAvaney, 1997) assume that feedbacks are linearly additive and independent. Such techniques ignore interactions of cloud feedbacks with atmospheric circulation and noncloud feedbacks. Assuming that clouds are independent of circulation and other feedbacks is problematic as cloud feedbacks can be correlated with atmospheric circulation, water vapor, and lapse rate feedbacks (e.g., Mauritsen et al., 2013).

In this study, we use cloud locking experiments to understand cloud influence on Arctic surface greenhouse warming. Building on previous cloud locking work with idealized models (e.g., Langen et al., 2012; Mauritsen et al., 2013; Vavrus, 2004), we use a full complexity global coupled climate model that has been extensively vetted with observations. For the first time, we differentiate between the influence of local (Arctic, 70–90°N) and nonlocal clouds by running experiments with clouds locked both globally and in the Arctic only. Our goals are twofold. First, we quantify local and nonlocal cloud feedback influence on Arctic surface greenhouse warming. Second, we assess the influence of global and Arctic cloud locking on other noncloud radiative feedbacks including the Planck, water vapor, lapse rate, and surface albedo feedbacks.

2. Methods

We use a well-documented, state-of-the-art, and widely used climate model: Community Earth System Model (CESM) with the Community Atmosphere Model Version 5 (CESM1-CAM5) (Hurrell et al., 2013). The performance and capabilities of CESM1-CAM5 have been documented in many studies as a part of Coupled Model Intercomparison Projection Version 5 (CMIP5) (Taylor et al., 2012) and the CESM1-CAM5 large initial condition ensemble (LENS, Kay et al., 2015). Extensive evaluation with observations shows that CESM1-CAM5 ranks among the top-performing fully coupled models available. For example, CESM1-CAM5 has the best representation of global distributions of surface temperature and precipitation in CMIP5 (Figure 3; Knutti et al., 2013) and improved upon long-standing global cloud biases (e.g., the global too few, too bright bias, Kay et al., 2012).

CESM1-CAM5 has also been extensively assessed in the Arctic, providing a foundation to frame this study. For sea ice, CESM1-CAM5 reasonably reproduces the observed seasonal cycle of extent, observed thickness distribution, and the satellite-recorded aerial loss (Ding et al., 2019; Jahn et al., 2016). For clouds, CESM1-CAM5 reproduces the observed annual cycle of Arctic cloud cover (Kay et al., 2016) and the observed Arctic cloud response to sea ice variability (Morrison et al., 2019). All this said, CESM1-CAM5 exhibits high-latitude cloud biases that are important for this work. Specifically, CESM1-CAM5 has insufficient supercooled cloud liquid and opaque cloud cover at high latitudes, including in the Arctic (e.g., Morrison et al., 2019; Tan & Storelvmo, 2019).

Cloud locking has been implemented and scientifically validated within CESM1-CAM5 (Middlemas et al., 2019). To "lock" the clouds in CESM1-CAM5, 10 cloud parameters are prescribed in the radiation calculations of the atmospheric model. As described in Middlemas et al. (2019), these prescribed cloud parameters are taken at every 2 hr (i.e., every other radiation time step) from a year with neutral El Niño–Southern Oscillation conditions (year 1366) of the CESM1-CAM5 LENS preindustrial control run. That year of cloud parameters is then passed into the radiative transfer calculations of the "locked" integration, matching time of day and day of year and is repeated every year. In other words, in all cloud-locked simulations, the clouds and associated cloud radiative forcing is "locked" to year 1366 from the preindustrial control and cannot respond to changes in the climate system. Locking turns off the ability of cloud radiative heating rate to evolve with the climate (Andrews et al., 2015). In other words, cloud radiative feedbacks are disabled, but the rest of the climate freely evolves. Due to the decorrelation of cloud radiative effects and climate, cloud locking induces small mean state changes in preindustrial simulations (e.g., <0.2-K differences in global mean temperature). Following previous cloud locking studies (e.g., Ceppi & Hartmann, 2016; Langen et al., 2012; Mauritsen et al., 2013; Middlemas et al., 2019; Radel et al., 2016; Voigt & Shaw, 2015), we assume that these small mean state differences have a negligible influence.

In this study, we compare three types of simulations: (1) control simulations with cloud feedbacks active everywhere ("CNT"), (2) global cloud locking simulation with cloud feedbacks disabled everywhere ("GCL"), and (3) Arctic-only cloud locking simulation with cloud feedbacks disabled in the Arctic (70–90 N) only ("ACL"). By differencing a preindustrial simulation and a corresponding simulation in which atmospheric carbon dioxide concentrations were instantaneously doubled, we find the 2xCO_2 climate system response for each simulation type. Following experimental protocol for recent model intercomparison

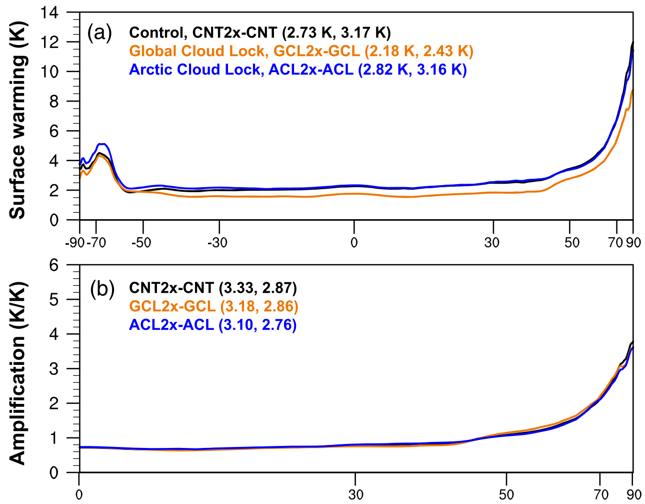

Figure 1. Zonal mean response to a carbon dioxide doubling for control (CNT), global cloud locking (GCL), and Arctic cloud locking (ACL): (a) surface warming and (b) amplification. The *x* axes are area weighted. Plotted amplification values are the zonal mean warming divided by the Northern Hemisphere warming. Values in parentheses for (a) are the global and Northern Hemisphere warming, respectively. Values in parentheses for (b) are the Arctic amplification normalized by the global mean and the Northern Hemisphere warming, respectively. To minimize the influence of internal generated variability, all calculations use 50-year averages taken from the end of each overlapping 150 years.

projects using fully coupled models (Good et al., 2016; Webb et al., 2017), we ran 150 years of each $2xCO_2$ simulation. While idealized, instantaneous $2xCO_2$ experiments are ubiquitous because climate response differences can be easily diagnosed with a known timescale (Good et al., 2016). By comparing the three simulation types, we identify the influence of global cloud feedbacks and Arctic cloud feedbacks on the $2xCO_2$ climate system response. While the preindustrial simulations had varying lengths (CNT 1,000 years, GCL 300 years, and ACL 200 years), we compared the overlapping 150 years of the preindustrial and $2xCO_2$ simulations.

To complement cloud locking, we also diagnose feedbacks using radiative kernels constructed for CESM1-CAM5 (Pendergrass et al., 2018). Comparing cloud locking and kernel-based feedback analysis provides distinct and complementary information for cloud feedbacks. While kernel-based cloud feedbacks quantify cloud radiative feedbacks alone (Soden et al., 2008), cloud locking enables estimation of all but the cloud radiative feedback. Indeed, subtracting simulations with and without cloud locking quantifies the cloud radiative feedback and its interactions with other feedbacks and circulation. Combining cloud locking and radiative kernels also enables assessment of cloud feedback influence on noncloud feedbacks. When cloud feedbacks are locked, other radiative feedbacks, like the lapse rate or water vapor feedbacks, can change in strength. For example, Mauritsen et al. (2013) found that locking global clouds weakened tropical upper tropospheric warming leading to weaker positive water vapor and negative lapse rate feedbacks. Here, we assess the influence of clouds on noncloud feedbacks by comparing kernel-based noncloud feedbacks in simulations with and without cloud locking.

3. Results

3.1. The Influence of Global and Arctic Cloud Locking on Surface Warming

We first assess the influence of global cloud feedbacks on the surface temperature response to an instantaneous CO_2 doubling (Figure 1a). For years 100-150, global surface warming is +0.74 K larger with cloud feedbacks active globally (2.73 K) than with global cloud feedbacks locked (2.18 K). This finding indicates that CESM1-CAM5 has an overall positive cloud feedback that amplifies global warming and is also consistent with positive global longwave and shortwave cloud feedbacks diagnosed using radiative kernels in CESM1-CAM5 (Gettelman et al., 2012, 2013; Table 1). Zonal mean comparisons show that disabling global cloud feedbacks decreases surface greenhouse warming at almost all latitudes. One exception is over the high-latitude Southern Ocean where disabling cloud feedbacks does not affect surface greenhouse warming.

Unlike global cloud feedbacks, Arctic cloud feedbacks have a negligible influence on global and Arctic surface greenhouse warming (Figure 1a). Global surface greenhouse warming is nearly identical in simulations with and without Arctic cloud radiative feedbacks (2.73 vs. 2.82 K) (Figure 1a). Notably, disabling Arctic cloud feedbacks has a negligible influence on Arctic and Northern Hemisphere surface greenhouse warming (Figure 1). In fact, disabling Arctic cloud feedbacks has a negligible influence on zonal mean surface warming at all latitudes compared to CTL except at high southern latitudes. Finding a small influence of Arctic cloud locking on Arctic warming is consistent with a small total Arctic cloud feedback diagnosed using radiative kernels in CESM1-CAM5 (Table 1).

We next assess the influence of cloud radiative feedbacks on Arctic amplification, here defined as local warming normalized by warming at all northern latitudes (0–90°N). To avoid introducing signal from the high southern latitudes, we focus on Arctic amplification relative to the Northern Hemisphere mean. Interestingly, Arctic amplification is within 5% for all three configurations: control (2.87 K), global cloud locked (2.86 K), and Arctic cloud locked (2.76 K). Additionally, zonal mean amplification is similar at all Northern Hemisphere latitudes in all three configurations (Figure 1a).

Table 1
Climate Feedbacks (Units W m^{-2} K^{-1}) Diagnosed Using Radiative Kernels

	Global			Arctic (70–90°N)		
	CNT	GCL	ACL	CNT	GCL	ACL
Planck feedback	−3.31	−3.32	−3.32	−2.58	−2.58	−2.58
Surface albedo feedback	0.33	0.33	0.34	1.64	1.64	1.66
Lapse rate feedback	−0.72	−0.50	−0.70	0.95	0.96	0.91
Water vapor feedback	1.78	1.58	1.77	0.29	0.26	0.29
Total noncloud feedback	−1.92	−1.91	−1.91	0.30	0.28	0.28
Longwave cloud feedback	0.10	—	—	0.16	—	—
Shortwave cloud feedback	0.46	—	—	−0.18	—	—
Total cloud feedback	0.56	—	—	−0.02	—	—

Note. Feedbacks were calculated for 2xCO_2 using the last 50 years of the control (CNT), global cloud-locked (GCL), and Arctic cloud-locked (ACL) simulations. All feedbacks are normalized by global surface temperature. Uncertainties due to temporal sampling lead to individual feedback differences of less than 0.04 W m^{-2} K^{-1} (see Table S2).

Having compared annual mean warming responses, we next address seasonality. Arctic surface greenhouse warming has large seasonality resulting from well-established interactions between sea ice loss and upper ocean heat storage (e.g., Manabe & Stouffer, 1980). Our simulations show that cloud feedbacks, whether global or local to the Arctic, do not alter the seasonality of Arctic surface greenhouse warming and amplification in CESM1-CAM5 (Figure 2). For example, disabling global cloud feedbacks reduces warming in all months but still results in less warming in summer than in the late fall and winter.

3.2. Cloud Influence on and Response to Arctic Surface Fluxes

The results presented thus far show that Arctic cloud radiative feedbacks have negligible influence on Arctic surface warming and Arctic amplification in CESM1-CAM5. With this context, we next document the underlying processes and assess if they are physically reasonable through an analysis of Arctic surface fluxes (Figure 3). As expected, Arctic surface downwelling longwave radiation (DLR) increases under 2xCO_2 (Figure 3a) following the seasonality of the 2xCO_2 Arctic warming (Figure 2). Also as expected, Arctic latent and sensible heat fluxes from the ocean to the atmosphere increase under 2xCO_2, especially in nonsummer months (Figures 3b and 3c). The flux response in the experiment with cloud feedbacks active globally is consistent with well-established understanding of Arctic flux changes under increased greenhouse gas concentrations and therefore provides the necessary baseline to address a fundamental question: What is the influence of cloud radiative feedbacks on the Arctic surface flux response to GHG forcing?

We start with DLR. In comparison to the control simulations, the global cloud locking simulations have smaller DLR increases with 2xCO_2 (Figure 3b). This weaker 2xCO_2 response is consistent with less warming found in the global cloud locking simulations than in the control simulations. That a DLR difference results from a large warming difference is unsurprising, but can we detect evidence for Arctic clouds directly affecting longwave fluxes? A cloud influence is expected because in addition to increased atmospheric temperature, increased atmospheric emissivity increases DLR, and increased liquid-containing clouds increase atmospheric emissivity, especially in a cold atmosphere. Comparing Arctic-only cloud locking and control simulations presents an opportunity to assess Arctic cloud influence on DLR because of their similar warming. Despite their similar overall warming (Figure 1), DLR increases less in the Arctic-only cloud locking simulations than in the control

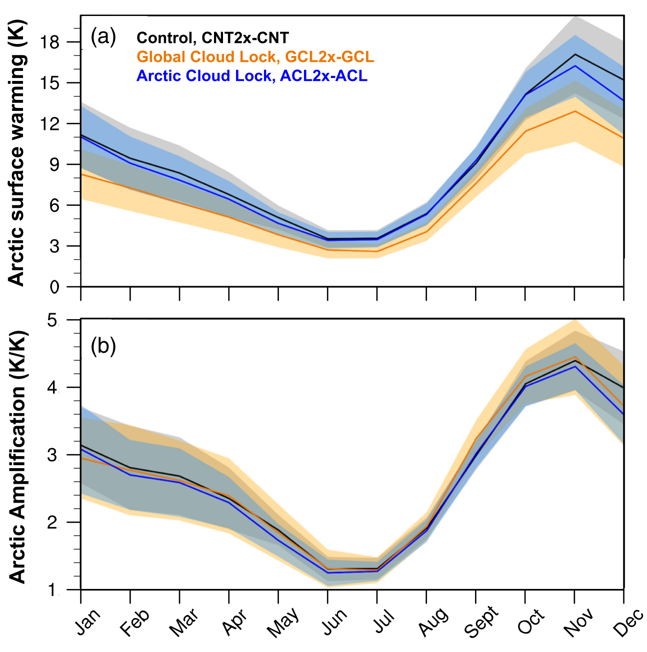

Figure 2. Seasonal Arctic response to a carbon dioxide doubling: (a) surface warming and (b) amplification. Amplification is calculated as the Arctic mean warming divided by the Northern Hemisphere mean warming. The Arctic is defined as 70–90°N. Shading indicates one standard deviation. To minimize the influence of internal generated variability, all calculations use 50-year averages taken from the end of each model run.

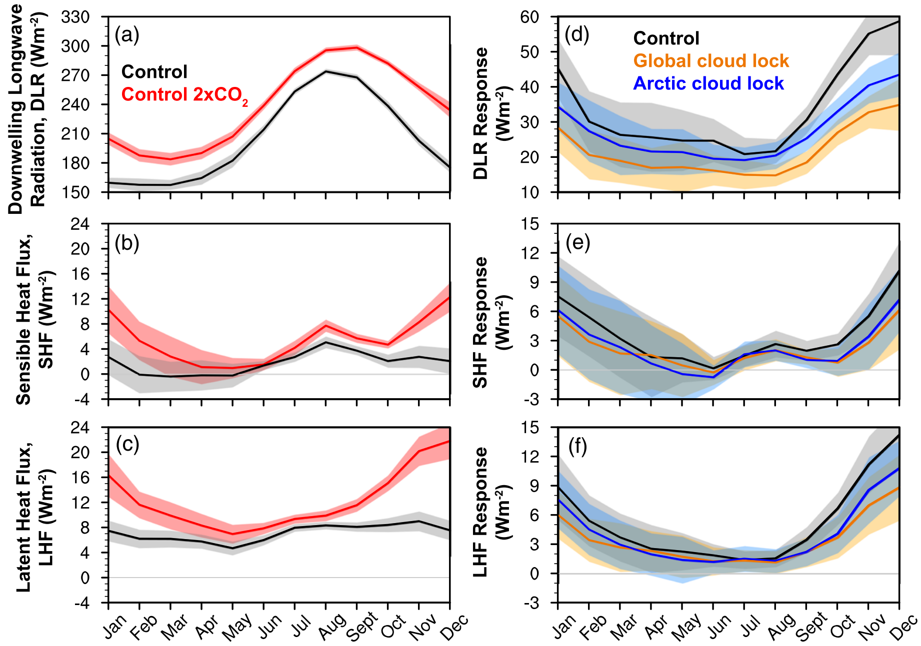

Figure 3. Seasonality of Arctic surface fluxes: (a) downwelling longwave flux for control (CNT) and control 2xCO_2 (CNT2x), (b) sensible heat flux for CNT and CNT2x, (c) latent heat flux for CNT and CNT2x, and (d–f) as in (a)–(c) but for the response to a carbon dioxide doubling for control (CNT2x-CNT), global cloud lock (GCL2x-GCL), and Arctic cloud lock (ACL2x-ACL). To minimize the influence of internal generated variability, all calculations use 50-year averages taken from the end of each model run. Shading shows the standard deviation in year-to-year values.

simulations. In other words, Arctic cloud feedbacks increase the downwelling longwave flux under 2xCO_2 in CESM1-CAM5. While a cloud influence on DLR is detectable, it is interesting that it does not affect the surface warming response to 2xCO_2 forcing.

We next examine Arctic sensible and latent heat fluxes. Increased 2xCO_2 turbulent heat fluxes from the ocean to the atmosphere explain the Arctic cloud feedback in response to sea ice loss in CESM1-CAM5 during nonsummer months (Morrison et al., 2019). While the increased turbulent heat fluxes occur in all simulation types, they only change the clouds in the simulations with active cloud feedbacks. Interestingly, the 2xCO_2 turbulent heat fluxes increase more when Arctic cloud feedbacks are active than when Arctic cloud feedbacks are disabled. Arctic cloud feedbacks enhance the vertical gradients of temperature and moisture that drive turbulent fluxes providing evidence for a positive feedback between the clouds and the turbulent fluxes that drive them. Yet turbulent heat flux increases in both of the cloud locking simulation types suggest that this turbulent heat flux difference results primarily from Arctic cloud feedbacks and not from differences in surface warming.

3.3. Influence of Cloud Feedbacks on Heat Transport, Circulation, and Noncloud Feedbacks

We first assess the influence of cloud radiative feedbacks on heat transport and atmospheric circulation. Total heat transport by the atmosphere and ocean into the Arctic exhibits only small changes (~0.02 PW) with cloud locking (supporting information Table S1). While cloud locking does affect the atmospheric circulation, sea-level pressure pattern differences do not explain surface warming pattern differences (Figures S1–S3). In sum, we do not find evidence that heat transport and atmospheric circulation explain surface warming differences resulting from cloud locking.

Leveraging the complementary information gained from radiative kernels and cloud locking, we next assess the influence of cloud feedbacks on noncloud feedbacks. We compare kernel-derived noncloud feedbacks in simulations with and without cloud locking. Through these comparisons, we quantify the influence of cloud locking on the noncloud feedbacks: the Planck, lapse rate, surface albedo, and water vapor feedbacks (Table 1).

The sum of global noncloud kernel-assessed feedbacks is unaffected by cloud locking (Table 1). The global Planck and surface albedo feedbacks are unaffected by cloud locking whether it is applied globally or just in the Arctic. The global water vapor and lapse rate feedbacks are unaffected by Arctic cloud locking but are strongly affected by global cloud locking. Disabling global cloud feedbacks weakens both the negative global lapse rate feedback from −0.72 to −0.50 W m^{-2} K^{-1} and the positive global water vapor feedback from 1.78 to 1.58 W m^{-2} K^{-1}. That said, the combined change in the global water vapor and lapse rate feedbacks with global cloud locking is negligible (less than 0.01 W m^{-2} K^{-1}). Weakening global lapse rate and water vapor feedbacks with cloud locking is consistent with Mauritsen et al. (2013), a study that emphasizes the coupling between clouds, water vapor, and lapse rates in a deepening tropical troposphere.

Cloud locking also has a small influence on Arctic noncloud feedbacks (Table 1). While small, disabling global cloud feedbacks weakens the Arctic water vapor feedback from 0.29 to 0.26 W m^{-2} K^{-1}. Disabling Arctic cloud feedbacks slightly weakens the positive Arctic lapse rate feedback from 0.95 to 0.91 W m^{-2} K^{-1} and strengthens the Arctic surface albedo feedback from 1.64 to 1.66 W m^{-2} K^{-1}.

4. Discussion

Separating the influence of local and nonlocal cloud feedbacks on Arctic surface greenhouse warming in a fully coupled state-of-the-art climate model is an important and novel advance of this work. We find that Arctic warming responds much more to disabling global cloud feedbacks than to disabling Arctic cloud feedbacks. In other words, there is a substantial influence of nonlocal cloud feedbacks on Arctic greenhouse warming. Meanwhile, Arctic *amplification* is insensitive to disabling both global and Arctic-only cloud feedbacks. Previous studies have not been able to discriminate between the influence of local and nonlocal cloud feedbacks on Arctic greenhouse warming. For example, Vavrus (2004) found that global cloud feedbacks increased surface Arctic warming by 40% but could not separate the influence of global and Arctic cloud feedbacks on this increased warming. Additionally, Tan and Storelvmo (2019) found Arctic amplification enhancement by changing microphysical parameters to produce more liquid-containing clouds in CESM1-CAM5. However, Tan and Storelvmo (2019) did not distinguish between the effects of changing liquid-containing clouds in the Arctic alone versus in other parts of the globe, like the Southern Ocean, where the representation of cloud phase feedbacks has been shown to have large impacts on equilibrium global surface greenhouse warming (Frey & Kay, 2017; Tan et al., 2016). The findings of the present study highlight the value of regional cloud locking in the Arctic.

Another novel aspect of this study is combining cloud locking and kernel-diagnosed radiative feedbacks to assess the influence of cloud radiative feedbacks on climate. Though they provide different information, kernels (just the cloud radiative feedback) and cloud locking (all but the cloud radiative feedback) show consistent results for CESM1-CAM5 cloud influence on greenhouse warming. Namely, global cloud feedbacks increase surface greenhouse warming, but Arctic cloud feedbacks have negligible impact on surface greenhouse warming. We also found that the cloud radiative feedback influence on net noncloud feedbacks overall is small. When combined with consistent diagnosis of a positive cloud radiative feedback from kernels (just the cloud radiative feedback) and cloud locking (cloud radiative feedback including interactions with noncloud feedbacks and circulation), this result implies that cloud-circulation coupling does not change the sign of the global cloud radiative feedback.

Illustrating the scientific value of isolating Arctic cloud feedbacks, we find a negligible influence of Arctic clouds on noncloud Arctic feedbacks. Arctic cloud feedbacks do slightly weaken the Arctic lapse rate feedback (Table 1), a result consistent with a positive longwave cloud feedback in CESM1-CAM5 (Morrison et al., 2019) and cloudy Arctic states having weaker temperature inversions (e.g., Morrison et al., 2011; Pithan et al., 2014).

Using a single model is both a limitation and a strength of this study. Implementing cloud locking requires code modifications and computationally expensive experiments beyond CMIP (Webb et al., 2017). Therefore, it is challenging to implement and verify cloud locking in multiple models for intercomparison. Fortunately, as described in section 3.1, CESM1-CAM5 has been widely used and scrutinized, including intensive study of the Arctic. Thus, by combining our results with previous work, we can assess limitations of conclusions drawn from cloud locking in this one model. Previous work suggests that Arctic cloud feedbacks are underestimated in CESM1-CAM5 (Morrison et al., 2019; Tan & Storelvmo, 2019), because the clouds in CESM1-CAM5 contain insufficient supercooled liquid water, and thus, cloud influence on radiative fluxes is underestimated (e.g., Cesana et al., 2012). Consistent with previous work using CESM1-CAM5 (Morrison et al., 2019), we find evidence for a positive Arctic cloud-sea ice feedback in non-summer months, which is supported by observations. Arctic DLR decreases when Arctic cloud feedbacks are disabled. That said, insufficient supercooled liquid in these clouds may explain why this cloud-sea ice feedback does not illicit a change in the modeled Arctic greenhouse surface warming. Many climate models share this insufficient supercooled liquid bias in the Arctic, with implications for underestimation of positive longwave cloud feedbacks but also positive lapse rate feedbacks (e.g., Pithan et al., 2014). Future work should identify the influence of insufficient supercooled liquid biases on the results presented here. In particular, the hypothesis that cloud locking in a model with more supercooled Arctic cloud water may reveal an increased role for Arctic cloud feedbacks in amplifying Arctic warming could be tested. In any case, understanding the importance of cloud properties for cloud feedbacks is an important and interesting open research question.

5. Conclusions

Quantifying the contribution of cloud radiative feedbacks to Arctic surface greenhouse warming has been a challenging and long-standing problem. In this study, we employed cloud locking, which decorrelates cloud radiative forcing from atmospheric circulation, to isolate cloud radiative feedbacks. We applied cloud locking separately in the Arctic and across the globe to quantify the roles of local and nonlocal cloud feedbacks for the first time. Consistent with diagnostic kernel techniques (Gettelman et al., 2012), we find that global cloud radiative feedbacks warm the Arctic while the effect of Arctic cloud feedbacks is negligible. This consistency and complementary diagnostic kernel feedback analysis suggests that for global and Arctic averages, cloud feedbacks do not affect the sum of noncloud feedbacks and are unaffected by cloud-circulation coupling. Methodologically, this study provides a new path to understanding cloud contribution to Arctic warming. That said, the specific conclusions reached here should be further tested in vetted, state-of-the-art coupled models with improved representation of cloud processes, particularly the supercooled liquid in high-latitude clouds.

Data Availability Statement

Computing and data storage resources were provided by the Computational and Information Systems Laboratory (CISL) at NCAR, including the Cheyenne supercomputer (doi:10.5065/D6RX99HX). The CESM data used in this study are available on Globus Collection NCAR GLADE (/glade/p/univ/ucub0064/clocking.output).

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