Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL090452

Larger Sensitivity of Arctic Precipitation Phase to Aerosol than Greenhouse Gas Forcing

Shifeng Pan[1], Tingfeng Dou[2], Lei Lin[3,4], Jiao Yang[5], Feng Zhang[6], Mingkeng Duan[1], Chuanfeng Zhao[7,8], Hong Liao[1], and Cunde Xiao[7]

[1]Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD)/Key Laboratory of Meteorological Disaster, Ministry of Education (KLME)/Joint International Research Laboratory of Climate and Environment Change (ILCEC), Nanjing University of Information Science and Technology, Nanjing, China, [2]College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, China, [3]School of Atmospheric Sciences, Sun Yat-sen University, Guangzhou, China, [4]Key Laboratory of Tropical Atmosphere-Ocean System, Ministry of Education, and Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China, [5]State Key Laboratory of Cryospheric Sciences, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China, [6]Institute of Atmospheric Sciences, Fudan University, China/Shanghai Qi ZhiInstitute, China, [7]State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing, China, [8]College of Global Change and Earth System Science, Beijing Normal University, Beijing, China

Key Points:
- Warming forced by global aerosol reduction and increased GHG emission leads to a solid-to-liquid precipitation transition in the Arctic
- The sensitivity of Arctic precipitation phase to the aerosol forcing is approximately three times that to the GHG forcing
- The most sensitive phase changes of Arctic precipitation to the aerosol forcing are observed in Greenland and the eastern Arctic Ocean

Correspondence to:
T. Dou,
doutf@ucas.ac.cn

Citation:
Pan, S., Dou, T., Lin, L., Yang, J., Zhang, F., Duan, M., et al. (2020). Larger sensitivity of Arctic precipitation phase to aerosol than greenhouse gas forcing. *Geophysical Research Letters*, *47*, e2020GL090452. https://doi.org/10.1029/2020GL090452

Received 20 AUG 2020
Accepted 11 NOV 2020
Accepted article online 20 NOV 2020

Abstract The sensitivity of the Arctic precipitation phases (solid and liquid) to the forcings from greenhouse gases (GHGs) and aerosols over 2016–2080 was investigated by using the Community Earth System Model Version 1. Results show that the warming caused by the two forcings results in an increasing trend in total precipitation and a solid-to-liquid precipitation transition in the Arctic. Under RCP8.5 scenario, the increased rate of Arctic mean precipitation with global warming forced by aerosol reduction (7.7%/°C) is twice greater than that by increased GHG emission (3.5%/°C). The sensitivity of rainfall to precipitation ratio (RPR) to various forcings is much higher than that of total precipitation in the Arctic. The increased rate of RPR due to global aerosol forcing (8.4%/°C) is approximately 3 times that due to GHG forcing (2.9%/°C) in the Arctic, the differences even larger over Greenland and the eastern Arctic Ocean, resulting in more rainfall in these areas.

Plain Language Summary The precipitation phase is extremely sensitive to temperature changes, especially in the Arctic. Solid and liquid precipitation have almost the opposite effect on the ground energy budget. The changes in precipitation phase can greatly affect snow and ice mass balance, regulating the regional hydrological cycle. The transition from solid precipitation to liquid precipitation can even promote carbon release over the permafrost through changing the rate of snow melting. We evaluated the impacts of the two most important anthropogenic forcing agents (greenhouse gases [GHGs] and aerosols) on the changes of precipitation phases in the Arctic using a state-of-the-art Earth system model. We found that the warming forced by global aerosol reduction and increased GHG emission leads to a solid-to-liquid precipitation transition and therefore more rainfall events in the Arctic. Under RCP8.5 scenario, the sensitivity of Arctic precipitation phase to global aerosol forcing is approximately 3 times that to the GHG forcing, and the most sensitive phase changes of Arctic precipitation to the aerosol forcing are observed in Greenland and the eastern Arctic Ocean. Understanding the impact of human activities on the changes in the Arctic precipitation phase will help formulate reasonable emission reduction policies and better adapt to the rapid Arctic climate changes in the future.

1. Introduction

The changes in Arctic precipitation play an important role in the Arctic freshwater budget and evolution of the ecological environment (Zhang et al., 2013). The projected long-term trend in Arctic precipitation is projected to reach 2–3 times the global mean with climate warming (Bintanja & Selten, 2014; Trenberth, 2011). Increased Arctic precipitation can reduce the salinity of the surface water in the Arctic Ocean, which in turn affects the Atlantic meridional overturning circulation (Bintanja, 2018; Caesar et al., 2018; Davies et al., 2014; Kattsov & Walsh, 2000; Yang et al., 2016). In addition to the total precipitation amount, the changes in precipitation phases (solid and liquid) can also greatly influence the freeze-thaw process of snow and ice,

regulating the regional hydrological cycle. Solid and liquid precipitation have very different and even opposite effects on the ground energy budget and snow and ice mass balance. Snowfall prevents the melting of snow and ice and makes a positive contribution to the mass balance of snow cover, while rainfall promotes the ablation of snow and ice by reducing the thickness of snow (Screen & Simmonds, 2012) and lowering the surface albedo (Dou et al., 2019; Perovich et al., 2017).

Previous studies showed that rainfall will be the dominant form of Arctic precipitation in the high emission scenario (RCP8.5) (Bintanja & Andry, 2017). Rainfall can accelerate the mass loss of the Greenland ice sheet by promoting surface ablation (Oltmanns et al., 2019; Shepherd et al., 2020). Liquid precipitation facilitates the release of methane over permafrost areas by accelerating the melting of overlying snow (Neumann et al., 2019). In addition, rainfall events occurring over snow-covered regions in winter can form a thick layer of ice on the snow surface, preventing reindeer from foraging and resulting in a high mortality of reindeer (Forbes et al., 2016).

The Arctic region is undergoing rapid climate change under forcing from greenhouse gases (GHGs), aerosols, and other climate drivers (Stjern et al., 2019). GHGs and aerosols are the two most important anthropogenic forcing agents, having a decisive impact on future changes in precipitation intensity (Lin et al., 2016) and the phases of precipitation in the 21st century. However, there are obvious differences in the contributions of these two forcing agents to changes in precipitation (Sillmann et al., 2019). Unlike the longer lifetime and globally homogeneous mixing of GHGs, aerosols are short-lived climate forcers that have a net cooling effect on climate change (Andreae et al., 2005; Boucher, 2013; Storelvmo et al., 2016; Wang et al., 2016). In addition, the aerosol concentration is not just a function of emission but also meteorological condition (such as humidity and wind) and chemistry (such as atmospheric oxidizing capacity and nonlinear production chemistry) (Le et al., 2020); thus, its radiative forcing (RF) exhibits significant regional differences on a global scale (Samset et al., 2018; Sillmann et al., 2019). The regional changes in air temperature and precipitation strongly depend on the balance between aerosol and GHG forcings (Samset et al., 2018).

In the Arctic, the opposite aerosol forcings from different midlatitude regions are nearly canceled out in the past decades, and GHG forcing can basically explain all observed Arctic sea ice loss up to present (Notz & Stroeve, 2016). However, the projected reduction in aerosol emissions in the northern hemisphere will make its climate effects in the Arctic stand out (Wang et al., 2017). The relative contributions of different forcing agents in the trends of Arctic precipitation and its phase changes in the next decades have been poorly understood. Here we quantitatively evaluates the contribution of GHG and aerosol forcings to future changes in Arctic precipitation and its phase transition under various emission scenarios. The sensitivities of the precipitation phase changes, total precipitation, rainfall, and snowfall in the Arctic to the warming caused by global aerosol and GHG forcings are also evaluated.

2. Data and Methods

The Community Earth System Model Version 1 (CESM1), a fully coupled global climate model (Hurrell et al., 2013), is used to investigate the contributions of GHG and aerosol forcing to the changes in precipitation phase in the Arctic. The model outputs include total precipitation and snowfall; thus, we first use their difference to obtain the rainfall amount and then calculate the rainfall to precipitation ratio (RPR) by dividing rainfall by total precipitation at each grid. The anthropogenic forcing in CESM1 includes GHGs and tropospheric ozone, stratospheric ozone, aerosols, and tropospheric oxidants that evolve over time and space (Lamarque et al., 2011). The resolution of the atmosphere, ocean, and land models is approximately 1° (latitude) × 1° (longitude). In this model, the three-mode modal aerosol scheme (Liu, 2012) includes Aitken, accumulation, and coarse modes of various aerosol species (sulfate, black carbon, organic carbon, dust, and sea salt). The direct, semidirect and indirect forcings due to aerosols are included (Morrison & Gettelman, 2008) for both liquid and ice phase clouds (Gettelman et al., 2010).

CESM1 overall simulates the global atmosphere relatively well (Knutti et al., 2013), but there are still some known issues in the Arctic atmosphere. For example, Arctic clouds are underestimated in this model (e.g., Kay et al., 2012), and supercooled liquid containing clouds in the Arctic are underrepresented in CESM1 (Cesana et al., 2015; McIlhattan et al., 2017; Tan & Storelvmo, 2016), an issue shared by most

climate models (Cesana et al., 2012; Forbes & Ahlgrimm, 2014). The liquid clouds in this model only include stratiform clouds, and the effects of aerosols on the shallow convective clouds are still absent. This issue may introduce biases in the Arctic surface energy balance estimation since downwelling longwave radiation at the surface is strongly connected with cloud presence and phase (McIlhattan et al., 2017).

We utilized three sets of CESM1 ensemble simulations: RCP8.5 Large Ensemble (RCP8.5_LE), RCP4.5 Medium Ensemble (RCP4.5_ME), and RCP8.5 with fixed aerosols Medium Ensemble (RCP8.5_FixA). The RCP8.5_LE includes 30 members (1920–2080), which are forced by the same GHG and aerosols. The discrepancies among various ensembles are only leaded to by the different atmospheric initial conditions (i.e. internal climate variability) (Kay et al., 2014). The RCP4.5_ME, including 15 members (2005–2080), is similar to RCP8.5_LE but follows the RCP4.5 scenario, and the reductions in aerosol emissions in the RCP8.5 and RCP4.5 scenarios are similar (Lin et al., 2016; van Vuuren et al., 2011). RCP8.5 is a high scenario corresponding to larger GHG forcing than RCP4.5 (Sanderson et al., 2018; van Vuuren et al., 2011). Thus, the purpose of comparing RCP4.5 and RCP8.5 is to evaluate the effect of various GHG emissions. The RCP8.5_FixA is a 15-member ensemble simulation (2005–2,100), which is forced by the RCP8.5, but aerosol emissions and tropospheric oxidants are fixed at the levels from 2005 (Xu et al., 2015). Therefore, the effect of aerosol emissions in RCP8.5 can be separately estimated by subtracting the simulations in RCP8.5_FixA from those in RCP8.5 (Lin et al., 2015). Then, the GHG-induced temperature change in the RCP4.5 scenario was derived by subtracting the simulations under the aerosol forcing alone from those in RCP4.5.

We collected the precipitation data from 8 stations in Alaska (http://climate.gi.alaska.edu/acis_data) and 11 stations in Canadian Arctic Archipelago (http://climate.weather.gc.ca/index_e.html) to verify the model results. The station observations involve daily precipitation, rainfall, and snowfall as water equivalent during 1961–2010. All observation data were subjected to unified quality control (Han et al., 2018) based on observations made at manned and automated sites (see http://climate.weather.gc.ca/about_the_data_index_e.html). The map of stations used in this study can be seen in Figure 1a.

3. Results

The rainfall to total precipitation ratio (RPR) was used to characterize the changes in the precipitation phase in this study. An increased RPR means that there is a transition from solid to liquid precipitation, and vice versa. The sensitivity of the Arctic precipitation variables (total precipitation, RPR, rainfall, and snowfall) to the forcing from GHGs and aerosols was scaled by their changes for every degree Celsius of global mean surface air temperature increase due to these two forcing agents. The mean values of the surface temperature and the precipitation variables in 2006–2015 were selected as a reference to calculate their decadal variations during 2016–2080. The change rates of precipitation variables with surface warming were adopted by regressing the changes in total precipitation, RPR, rainfall, and snowfall to the mean near-surface temperature increments (Pendergrass et al., 2015). To achieve consistency between various ensemble simulations, the period from 2006 to 2080 was chosen for the analysis.

Before analyzing the projection results, we evaluated the reliability of CESM1 in simulating the Arctic RPR over the past decades. A total of 19 stations in Alaska and Canadian Arctic Archipelago north of 60°N were selected for the model validation. The station observations contain both rainfall and precipitation data from 1961 to 2010, which can be used to calculate RPR during this period. The period of historical simulation of the model is only up to 2005. Thus, the model-observation comparison was conducted during the period from 1961 to 2005. The results demonstrated that CESM1 can basically reproduce the observed RPR both for its climatology (Figure 1a) and long-term trend in the Arctic (Figure 1b).

From 2006 to 2080, the RF by global GHG forcing increases from 2.3 to 6.9 W m^{-2} in the high emission scenario (RCP8.5), yielding a net RF of +4.6 W m^{-2}. Compared with the 2006–2015 average, the RF increases by +4.4 W m^{-2} by 2080. In contrast, the increase in RF is approximately +1.7 W m^{-2} under the RCP4.5 scenario during the same period. The negative RF by aerosol forcing declined from −0.8 to −0.2 W m^{-2} during 2006–2080. Compared with the 2006–2015 average, the aerosol reduction will induce +0.6 W m^{-2} RF by 2080, which is approximately one third of that from increased GHG emission under RCP4.5 scenario.

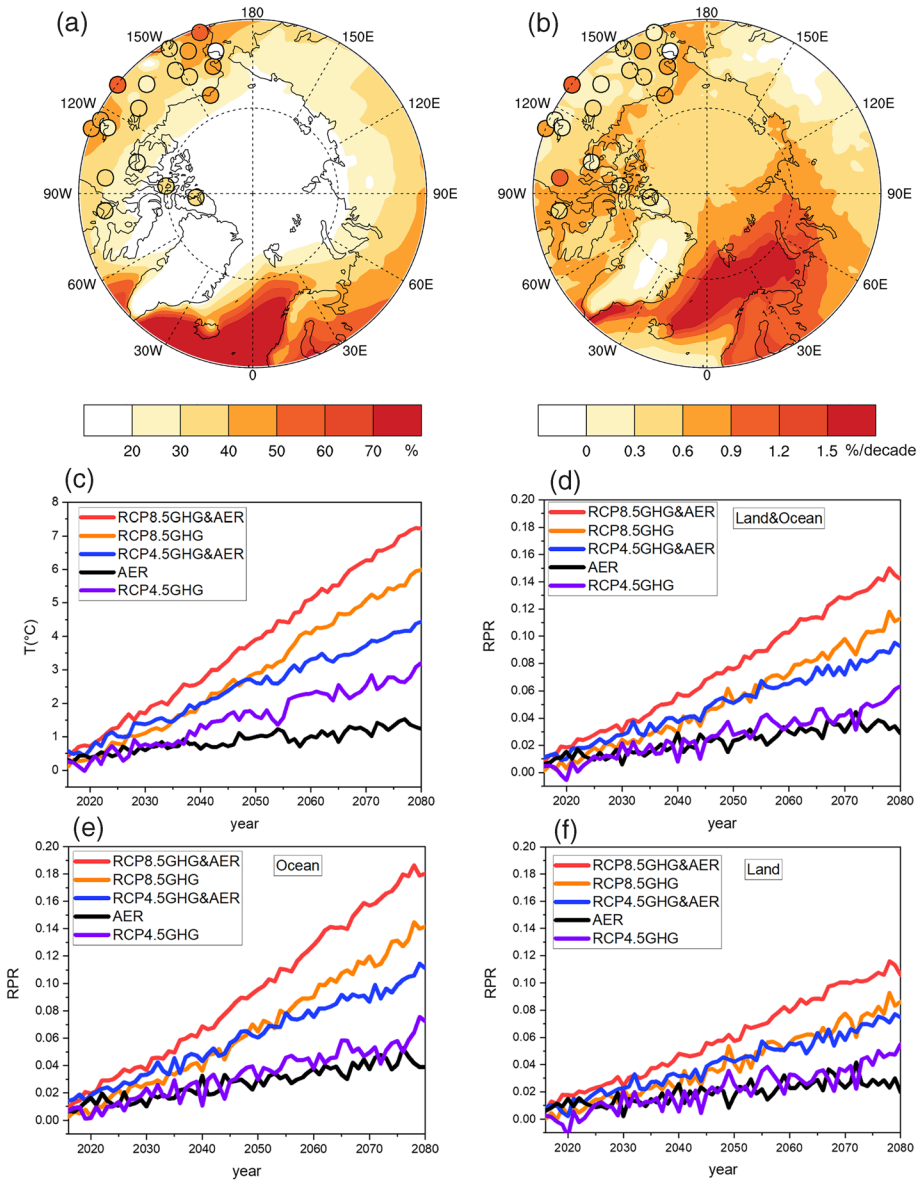

Figure 1. Model-observation comparison of spatial distribution and trend of RPR in the Arctic (60–90°N) over the period of 1961–2005. (a) Multi-year mean RPR; (b) trend of annual mean RPR. The color shading represents the simulation of CSEM. The colored circle marks the observed values from 19 stations in Alaska and Canadian Arctic Archipelago. Projected variations in the near-surface air temperature (T) and RPR (%) resulting from anthropogenic GHG and aerosol (AER) forcings in the Arctic (60–90°N) during 2016–2080 relative to the 2006–2015 period. (c) T averaged over the entire Arctic (d). RPR averaged over the entire Arctic (e). RPR averaged over the Arctic Ocean (f). RPR averaged over the land region of the Arctic.

Figure 1c shows the changes in near-surface temperature in the Arctic (60–90°N) during 2016–2080 caused by different anthropogenic forcings under the RCP8.5 and RCP4.5 scenarios relative to that during 2006–2015. The strongest warming will emerge in the case of combined forcing from GHGs and aerosols under the high emission scenario (RCP8.5), followed by GHG-induced warming alone, and aerosol-induced warming is the smallest. Even in the RCP4.5 scenario, the GHG-induced temperature rise (+3.2°C) is much higher than that (+1.2°C) caused by the aerosol forcing by 2080 (Figure 1c). In contrast, although the increase in RPR caused by GHG forcing are much higher than those caused by aerosol forcing in the RCP8.5 scenario, the increase in RPR caused by warming due to global aerosol reduction is comparable to

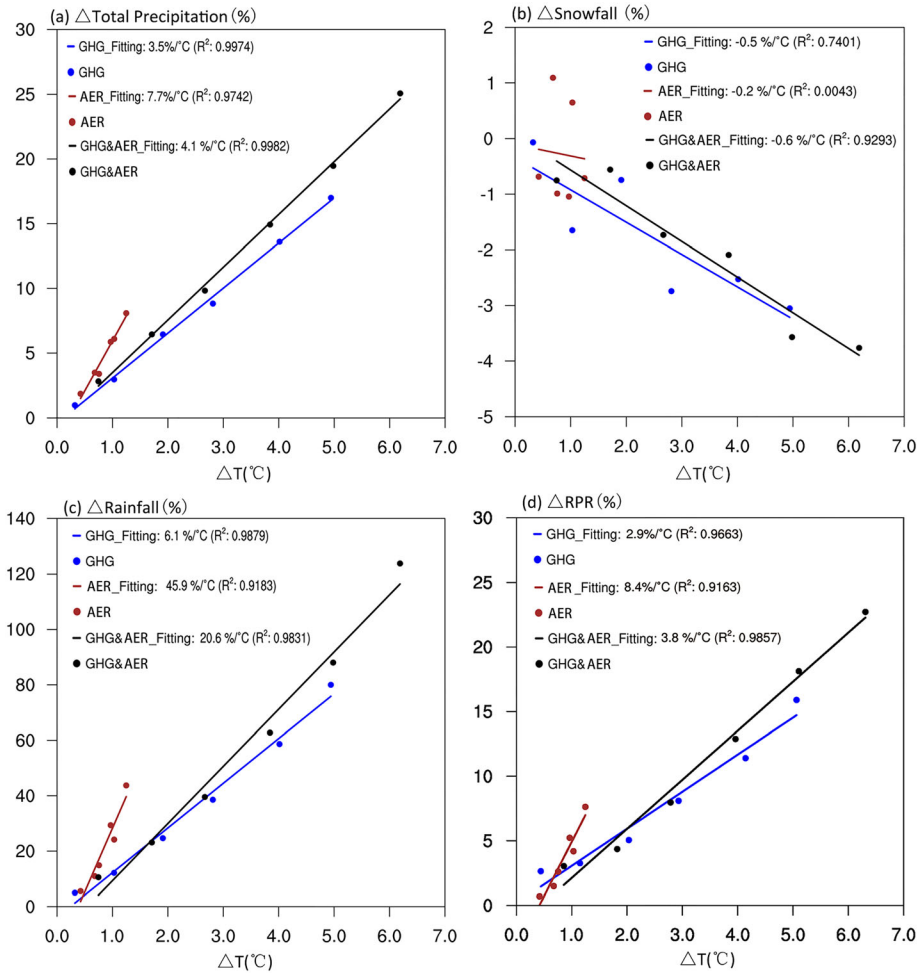

Figure 2. Scatterplots of changes in Arctic precipitation variables (y axis) with surface temperature changes (x axis) under different anthropogenic forcings during the period from 2016 to 2080. (a) Total precipitation, (b) snowfall, (c) rain, and (d) RPR. All of the results caused by GHG, aerosol (AER), and GHG and AER forcing under the RCP8.5 scenario are shown.

the contribution of GHG emissions in the RCP4.5 scenario (Figures 1d–1f). This result indicates that aerosol forcing will play an important role in the precipitation phase changes in the Arctic if a lower GHG emission pathway (RCP4.5) is adopted. The rate of the increase in the RPR in the Arctic Ocean is larger than that over land (Figures 1e and 1f) in both the RCP4.5 and RCP8.5 scenarios. Under the RCP8.5 scenario, the combined forcing from GHGs and aerosols can lead to increases in the RPR of approximately 18% and 10% in 2080, respectively, in the Arctic Ocean and the surrounding land area (confidence level is 0.05 from t test) relative to the average of 2006–2015 period. In contrast, the increases in RPR are smaller under the same forcings in the RCP4.5 scenario, which are approximately 11% and 7%, respectively, in the Arctic Ocean and the surrounding land area, since the change of precipitation phase in the Arctic is mainly determined by the local temperature rise.

The responses of the changes in the total precipitation, RPR, rainfall, and snowfall to various forcing agents are investigated below. Under the combined forcing from GHGs and aerosol emissions, all precipitation variables have a high goodness-of-fit ($R^2 > 0.9$) with temperature changes (Figure 2), supporting that the increased precipitation amount and changes in precipitation phases in the Arctic can be largely attributed to the climate warming caused by the reduced anthropogenic aerosols and enhanced GHGs globally. With the climate warming caused by GHG and aerosol forcings, except for snowfall, all other precipitation variables present an increasing trend in the Arctic during the period from 2016 to 2080. Because the

temperature rise caused by GHG forcing is greater than that by aerosol forcing in the Arctic region (Figure 1c), most attention has been drawn by the GHG-induced climate change in the Arctic. However, our analysis showed that the increased rate in RPR caused by the temperature rise per degree due to aerosol forcing (8.4%/°C) is larger than that caused by GHG forcing (2.9%/°C), indicating that the changes in the RPR in the Arctic are more sensitive to aerosol-induced warming than GHG-induced warming (Figure 2d). The sensitivities are for individual forcing agents around present levels. The increased rate in the RPR caused by the aerosol-driven temperature rise is approximately 2.9 times that caused by GHG forcing.

Above we evaluated the sensitivity of Arctic RPR to global GHG and aerosol forcings. We further analyze to what extent the larger sensitivity due to aerosol forcing is coming from Arctic temperature response (i.e., the sensitivity of Arctic amplification). Results showed that aerosol-induced Arctic amplification (2.39 ± 0.40) is generally comparable with GHG-induced Arctic amplification (2.23 ± 0.20) during 2016–2080, although the interannual variability of the former is more significant, indicating that the higher sensitivity of Arctic RPR to aerosol forcing is not caused by more sensitive Arctic amplification to this forcing but may be determined mainly by local forcing of aerosols. This is supported by a recent study based on the same model (Wang et al., 2017), which pointed out that the local RF by aerosols within the Arctic, due to either local emissions or long-range transports, is more efficient in promoting the Arctic warming than the aerosol-induced energy imbalance in lower latitudes outside the Arctic.

The changes in rainfall are more sensitive to various forcings than the RPR (Figure 2c). The sensitivity of Arctic rainfall to aerosol forcing is higher than that to GHG forcing (GHG: 16.1%/°C; aerosol: 45.9%/°C). The sensitivity of Arctic total precipitation to various forcings is lower than those of RPR and rainfall (Figure 2a), and its rate of increase due to aerosol-induced warming is 2.2 times that due to GHG-driven warming (GHG: 3.5%/°C; aerosol: 7.7%/°C). It is interesting to note that the warming rate due to combined effect is not an additivity of that from aerosol and GHG forcing. Instead, the warming rate even lies between that from aerosol and GHG forcing. The reasons are worthy future investigation. A likely reason is that the large scale circulation could be altered when both forcings exist, making the effects from both forcings partially canceled out.

Further analysis indicated that the combined forcing from GHG and aerosols can result in a decrease in snowfall in the Arctic in the future (Figure 2b). Linear regression analysis showed that the decrease in Arctic snowfall in the future is mainly caused by the warming effect of GHGs ($R^2 = 0.74$), corresponding to a sensitivity of −0.5%/°C (Figure 2b). There is no obvious relationship between the snowfall decrease and the aerosol-induced warming ($R^2 = 0.0043$); thus, the sensitivity of Arctic snowfall to the aerosol forcing has no statistical significance. In general, the sensitivity of snowfall to various forcings from anthropogenic emissions is much lower than those of rainfall, the RPR, and total precipitation in the Arctic.

The above analysis indicated that both GHG and aerosol forcing have significant impacts on the changes in the total precipitation, RPR, and rainfall in the Arctic. We further quantified the regional dependence of these forcings in the Arctic. As shown in Figure 3, there are increasing trends in total precipitation, RPR, and rainfall in the Arctic with warming under combined forcing from GHG and aerosols, especially over the Greenland ice sheet and central Arctic Ocean. There are no significant spatial differences in the sensitivity of changes in the total precipitation to the forcing from GHG emissions (Figure 3a), while the sensitivity to aerosol forcing presents a certain spatial difference, with high sensitivity over Greenland ice sheet, central and eastern Arctic Ocean (Figure 3b).

The sensitivity of rainfall to aerosol forcing in the eastern Arctic Ocean is significantly higher than that to GHG forcing (Figures 3c and 3d). The area with higher sensitivity of rainfall to aerosol forcing is basically the same as area with higher sensitivity of total precipitation (Figures 3b and 3d), leading to a high sensitivity of RPR to aerosol forcing in the eastern Arctic Ocean and Greenland ice sheet (Figure 3f). As a result, the precipitation phase change averaged across the Arctic is more sensitive to aerosol forcing than to GHG forcing (Figure 2d).

The response of snowfall to various forcings shows significant spatial variabilities. For both forcing agents, snowfall presents a decreasing trend in the Atlantic sector, North America, and the Pacific sector and an increasing trend in the Greenland ice sheet and most parts of Eurasia and the Arctic Ocean (Figures 3g

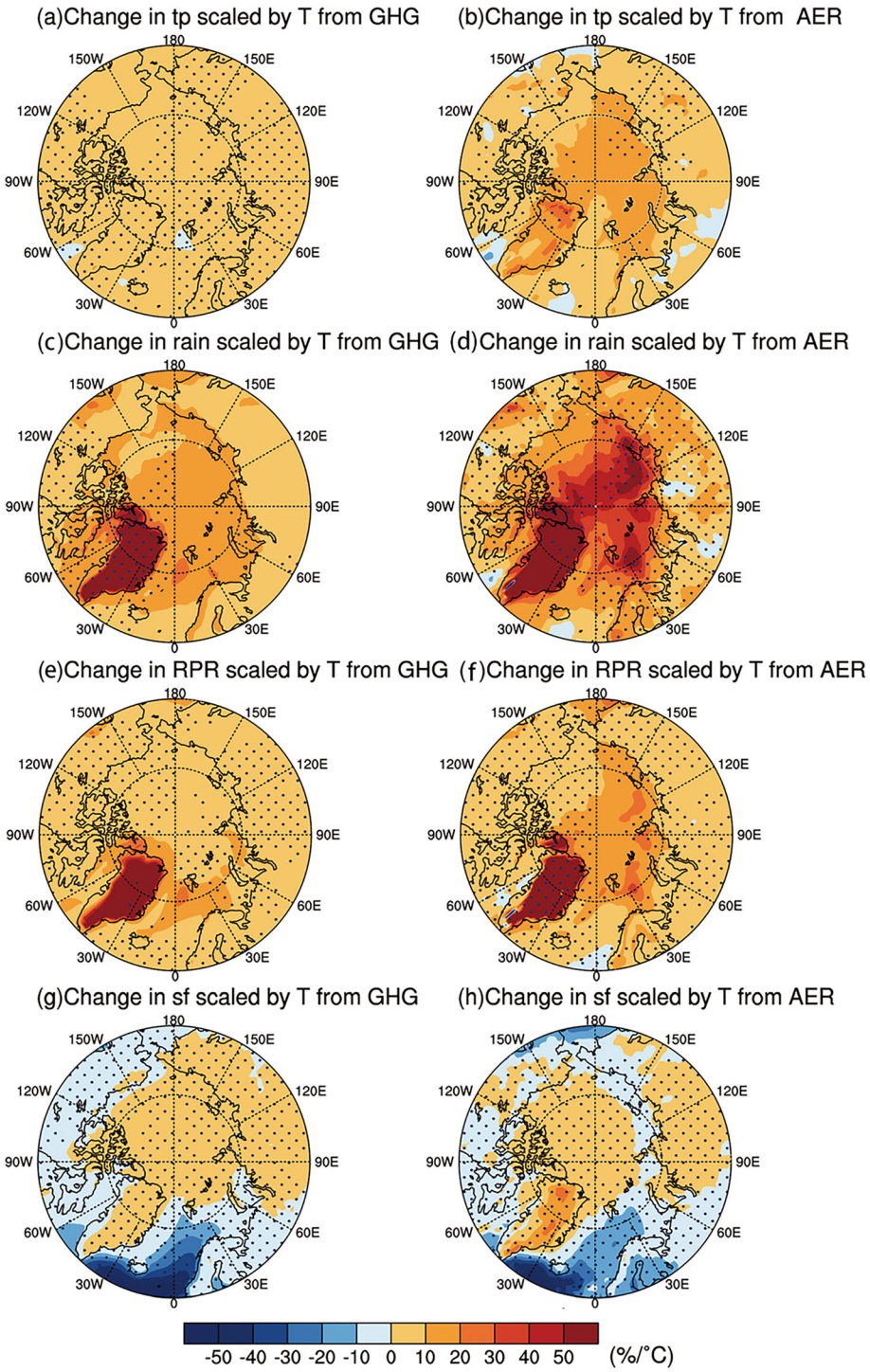

Figure 3. Spatial distributions of the rate of change in Arctic precipitation variables with mean surface temperature under different anthropogenic forcings during the period from 2016 to 2080. The left panels show the rates of change caused by GHG forcing under the RCP8.5 scenario, and the right panels show the rates of change caused by aerosol forcing under the same scenario. Total precipitation (a, b), rainfall (c, d), RPR (e, f), and snowfall (g, h).

and 3h). However, the response of snowfall to aerosol forcing exhibits a decreasing trend in the marginal seas of the Eurasian sector (Figure 3h), while the response to GHG forcing exhibits the reverse trend in this area (Figure 3g). In addition, the sensitivity of snowfall to aerosol forcing is higher than that to GHG forcing in the Greenland region.

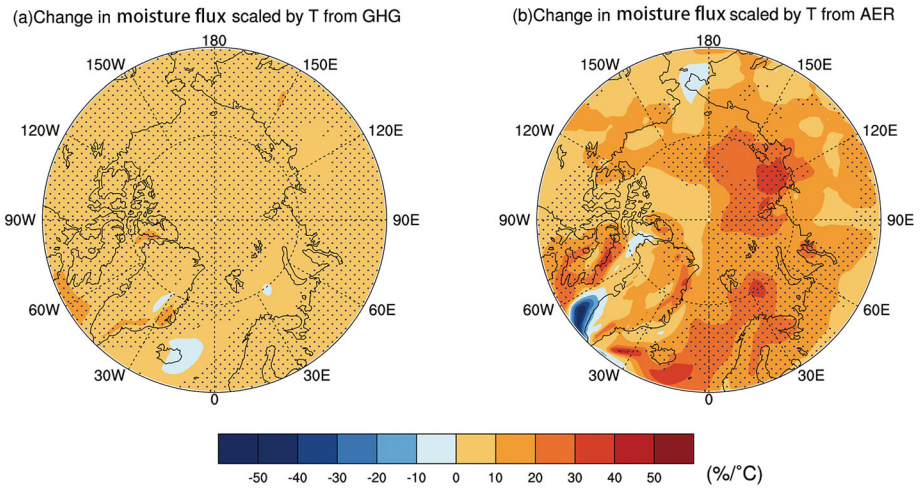

Figure 4. Same as Figure 3, but for the changes in the moisture flux with surface warming in the Arctic under the RCP8.5 scenario. The changes caused by global GHG forcing (a) and aerosol forcing (b).

To determine the reasons for the regional differences in precipitation sensitivity to various forcing agents, we analyzed the response of water vapor flux in the Arctic to climate warming due to aerosol and GHG forcing. Water vapor convergence is considered to be a prerequisite for precipitation to occur in the Arctic (Banacos & Schultz, 2005; Huang et al., 2019); thus, we mainly analyze the response of water vapor convergence to various forcing agents. The results show that there is no significant spatial difference in the water vapor flux in the Arctic due to GHG forcing (Figure 4a). However, affected by the reduced aerosol emissions globally, obvious moisture convergence occurs over the Greenland and most of the eastern Arctic Ocean (Figure 4b), leading to more precipitation in these areas (Figure 3b). Further analysis shows that the projected increase in total Arctic precipitation is entirely contributed by the increase in rainfall whether under the forcing from GHG, aerosol (AER), or both, while changes in snowfall are generally small. This is consistent with the result of Bintanja and Andry (2017) based on CMIP5. Precipitation increased in liquid form will lead to an increase in RPR. Therefore, the moisture convergence in the eastern Arctic Ocean and Greenland caused by aerosol-induced warming will result in more rainfall and an increased RPR, corresponding to higher sensitivity of RPR in these areas. The different sensitivities to various forcings emphasize the importance of the balance between the forcings from GHGs and aerosols in the study of future Arctic climate change.

4. Discussion and Conclusions

The impacts of climate warming caused by global GHG forcing and aerosol forcing on the changes in total precipitation, the RPR, rainfall, and snowfall in the Arctic during 2016–2080 are investigated based on CESM1 ensemble simulations. Under the RCP 4.5 and RCP8.5 scenarios, precipitation will show a transition from the solid to liquid phase (increased RPR) over the Arctic in the coming decades. The strongest warming and largest increase in the RPR will emerge in the case of combined forcing from GHGs and aerosols under RCP8.5 scenario. The rate of the increase in the RPR over the Arctic Ocean is higher than that over the Arctic land area no matter in RCP8.5 or RCP4.5 scenarios. Although the near-surface temperature rise caused by aerosol forcing is smaller than that caused by GHG forcing in various scenarios, in the RCP4.5 scenario, the increase in the RPR due to aerosol forcing is equivalent to that due to GHG forcing.

The increased precipitation amount and changes in precipitation phases in the Arctic can be largely attributable to the warming caused by reduced anthropogenic aerosols and enhanced GHGs globally. The increased rate in the RPR (%/°C) caused by aerosol-driven warming is approximately 3 times that caused by GHG forcing, although the temperature rise contributed by aerosol forcing in the coming decades is much weaker than that contributed by GHG forcing. This result indicates that the sensitivity of the change in the precipitation phase to aerosol forcing is much higher than that to GHG forcing in the Arctic.

Further analysis indicates that the increased rate of RPR is generally higher in the Arctic Ocean and Greenland region than in other regions of the Arctic under the two different forcing agents. The increased rate of RPR caused by warming due to aerosol forcing is higher than that due to GHG forcing in the above two regions, especially in the eastern Arctic Ocean. This indicates that the higher sensitivity of the Arctic precipitation phase to the warming effect due to global aerosol forcing is mainly reflected in the eastern Arctic Ocean. Compared to GHG forcing, aerosol forcing would promote the convergence of moisture in the eastern Arctic Ocean and Greenland region more effectively, leading to more rainfall and a significant increase in RPR in these regions.

Current restrictions on aerosol emissions (Samset et al., 2014, 2018) add a great deal of uncertainty to the relative contribution of reduced GHG and aerosol emissions to the changes in the precipitation phase in the Arctic. If a lower emission scenario is adopted, aerosol forcing may play a critical role in the Arctic precipitation phase changes in the coming decades. This study has implications for policies related to Arctic climate adaptation to increased rainfall events in this region. Sufficient attention should be drawn to the influences of aerosol emission reduction on the phase changes of Arctic precipitation in the future, especially for the influence mechanism of local aerosol forcing. The impacts of local aerosols include not only the RF but also the indirect cloud albedo and lifetime effect (or microphysical effect; see Albrecht, 1989; Twomey, 1977); that said, a decrease in aerosols will result in an increase in both the size of cloud droplets and precipitation/rainfall. Local aerosols mainly have a warming effect when solar radiation is weak in the Arctic (Garrett & Zhao, 2006; Zhao & Garrett, 2015), meaning that local aerosol reduction in the Arctic during the cold season could cause cooling effects, which is contrary to the climate effect of aerosols during the warm season. In-depth research is needed on the contribution of local aerosol forcing to Arctic precipitation phase changes during different seasons.

Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

The model data used in this study are available at https://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.CESM_CAM5_BGC_LE.html (CESM RCP8.5 LE), https://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.CESM_CAM5_BGC_ME.html (CESM RCP4.5 ME), and https://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.CESM_CAM5_BGC_YY.html (CESM RCP8.5 FixA). The station precipitation and snowfall data in Northern America are available at http://climate.gi.alaska.edu/acis_data (Alaska) and http://climate.weather.gc.ca/index_e.html (Canadian Arctic Archipelago).

Acknowledgments

We wish to acknowledge National Center for Atmospheric Research (NCAR) UCAR for CESM1 data. This study is funded by the National Key Research and Development Program of China (2018YFC1406103) and the National Nature Science Foundation of China (NSFC 41971084 and 41925022). The National Center for Atmospheric Research is supported by the U.S. National Science Foundation. We are also grateful to the High Performance Computing Center of Nanjing University of information science and technology for conducting the numerical calculations.

References

Albrecht, B. A. (1989). Aerosols, cloud microphysics and fractional cloudiness. *Science*, *245*, 1227–1230. https://doi.org/10.1126/science.245.4923.1227

Andreae, M. O., Jones, C. D., & Cox, P. M. (2005). Strong present-day aerosol cooling implies a hot future. *Nature*, *435*, 1187–1190. https://doi.org/10.1038/nature03671

Banacos, P. C., & Schultz, D. M. (2005). The use of moisture flux convergence in forecasting convective initiation: Historical and operational perspectives. *Weather Forecasting*, *20*, 351–366. https://doi.org/10.1175/WAF858.1

Bintanja, R. (2018). The impact of Arctic warming on increased rainfall. *Scientific Reports*, *8*, 16001. https://doi.org/10.1038/s41598-018-34450-3

Bintanja, R., & Andry, O. (2017). Towards a rain-dominated Arctic. *Nature Climate Change*, *7*(4), 263–267. https://doi.org/10.1038/nclimate3240

Bintanja, R., & Selten, F. M. (2014). Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat. *Nature*, *509*, 479–482. https://doi.org/10.1038/nature13259

Boucher, O. (2013). In T. F. Stocker (Ed.), *Clouds and aerosols. Climate change 2013: The physical science basis* (pp. 571–657). Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/CBO9781107415324.016

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., & Saba, V. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*, *556*(7700), 191–196. https://doi.org/10.1038/s41586-018-0006-5

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*, 1–6. https://doi.org/10.1029/2012GL053385

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

Davies, F. J., Renssen, H., & Goosse, H. (2014). The Arctic freshwater cycle during a naturally and an anthropogenically induced warm climate. *Climate Dynamics*, *42*(7), 2099–2112. https://doi.org/10.1007/s00382-013-1849-y

Dou, T., Xiao, C., Liu, J., Han, W., & Eicken, H. (2019). A key factor initiating surface ablation of Arctic sea ice: Earlier and increasing liquid precipitation. *The Cryosphere*, *13*, 1233–1246. https://doi.org/10.5194/tc-2018-239

Forbes, B. C., Kumpula, T., Meschtyb, N., Laptander, R., Macias-Fauria, M., Zetterberg, P., et al. (2016). Sea ice, rain-on-snow and tundra reindeer nomadism in Arctic Russia. *Biology Letters*, *12*(11), 20160466. https://doi.org/10.1098/rsbl.2016.0466

Forbes, R. M., & Ahlgrimm, M. (2014). On the representation of high-latitude boundary layer mixed-phase cloud in the ECMWF global model. *Monthly Weather Review*, 3425–3446. https://doi.org/10.1175/MWR-D-13-00325.1

Garrett, T. J., & Zhao, C. (2006). Increased Arctic cloud longwave emissivity associated with pollution from mid-latitudes. *Nature*, *440*(7085), 787–789. https://doi.org/10.1038/nature04636

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

Han, W., Xiao, C., Dou, T., & Ding, M. (2018). Changes in the proportion of precipitation occurring as rain in northern Canada during spring–summer from 1979–2015. *Advances in Atmospheric Sciences*, *35*(009), 1129–1136. https://doi.org/10.1007/s00376-018-7226-3

Huang, Y., Dong, X., Xi, B., & Deng, Y. (2019). A survey of the atmospheric physical processes key to the onset of Arctic sea ice melt in spring. *Climate Dynamics*, *52*(7–8), 4907–4922. https://doi.org/10.1007/s00382-018-4422-x

Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., et al. (2013). The Community Earth System Model: A framework for collaborative research. *American Meteorological Society*, *94*, 1339–1360. https://doi.org/10.1175/BAMS-D-12-00121.1

Kattsov, V. M., & Walsh, J. E. (2000). Twentieth-century trends of Arctic precipitation from observational data and a climate model simulation. *Journal of Climate*, *13*, 1362–1370. https://doi.org/10.1175/1520-0442(2000)013%3C1362:TCTOAP%3E2.0.CO;2

Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., et al. (2014). The Community Earth System Model (CESM) large ensemble project: A community resource for studying climate change in the presence of internal climate variability. *Bulletin of the American Meteorological Society*, *96*, 1333–1349. https://doi.org/10.1175/BAMS-D-13-00255.1

Kay, J. E., Hillman, B. R., Klein, S. A., Zhang, Y., Medeiros, B., Pincus, R., & Ackerman, T. P. (2012). Exposing global cloud biases in the Community Atmosphere Model (CAM) using satellite observations and their corresponding instrument simulators. *Journal of Climate*, *25*(15), 5190–5207. https://doi.org/10.1175/JCLI-D-11-00469.1

Knutti, R., Masson, D., & Gettelman, A. (2013). Climate model genealogy: Generation CMIP5 and how we got there. *Geophysical Research Letters*, *40*, 1194–1199. https://doi.org/10.1002/grl.50256

Lamarque, J. F., Kyle, G. P., Meinshausen, M., Riahi, K., Smith, S. J., van Vuuren, D. P., et al. (2011). Global and regional evolution of short-lived radiatively active gases and aerosols in the representative concentration pathways. *Climate Change*, *109*, 191–212. https://doi.org/10.1007/s10584-011-0155-0

Le, T., Wang, Y., Liu, L., Yang, J., Yung, Y. L., Li, G., & Seinfeld, J. H. (2020). Unexpected air pollution with marked emission reductions during the COVID-19 outbreak in China. *Science*, *369*(6504), 702–706. https://doi.org/10.1126/science.abb7431

Lin, L., Gettelman, A., Fu, Q., & Xu, Y. (2015). Simulated differences in 21st century aridity due to different scenarios of greenhouse gases and aerosols. *Climatic Change*, *146*(3–4), 407–422. https://doi.org/10.1007/s10584-016-1615-3

Lin, L., Wang, Z., Xu, Y., & Fu, Q. (2016). Sensitivity of precipitation extremes to radiative forcing of greenhouse gases and aerosols. *Geophysical Research Letters*, *43*, 9860–9868. https://doi.org/10.1002/2016GL070869

Liu, X. (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. https://doi.org/10.5194/gmd-5-709-2012

McIlhattan, E. A., L'Ecuyer, T. S., & Miller, N. B. (2017). Observational evidence linking arctic supercooled liquid cloud biases in cesm to snowfall processes. *Journal of Climate*, *30*(12), 4477–4495. https://doi.org/10.1175/JCLI-D-16-0666.1

Morrison, H., & Gettelman, A. (2008). A new two-moment bulk stratiform cloud microphysics scheme in the Community Atmosphere Model, Version 3 (CAM3). Part I: Description and numerical tests. *Journal of Climate*, *21*(15), 3642–3659. https://doi.org/10.1175/2008JCLI2105.1

Neumann, R. B., Moorberg, C. J., Lundquist, J. D., Turner, J. C., Waldrop, M. P., McFarland, J. W., et al. (2019). Warming effects of spring rainfall increase methane emissions from thawing permafrost. *Geophysical Research Letters*, *46*, 1393–1401. https://doi.org/10.1029/2018GL081274

Notz, D., & Stroeve, J. (2016). Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission. *Science*, *354*, 747–750. https://doi.org/10.1126/science.aag2345

Oltmanns, M., Straneo, F., & Tedesco, M. (2019). Increased Greenland melt triggered by large-scale, year-round cyclonic moisture intrusions. *The Cryosphere*, *13*(3), 815–825. https://doi.org/10.5194/tc-13-815-2019

Pendergrass, A. G., Lehner, F., Sanderson, B. M., & Xu, Y. (2015). Does extreme precipitation intensity depend on the emissions scenario? *Geophysical Research Letters*, *42*, 8767–8774. https://doi.org/10.1002/2015GL065854

Perovich, D., Polashenski, C., Arntsen, A., & Stwertka, C. (2017). Anatomy of a late spring snowfall on sea ice. *Geophysical Research Letters*, *44*, 2802–2809. https://doi.org/10.1002/2016GL071470

Samset, B. H., Myhre, G., & Schulz, M. (2014). Upward adjustment needed for aerosol radiative forcing uncertainty. *Nature Climate Change*, *4*(4), 230–232. https://doi.org/10.1038/nclimate2170

Samset, B. H., Sand, M., Smith, C. J., Bauer, S. E., Forster, P. M., Fuglestvedt, J. S., et al. (2018). Climate impacts from a removal of anthropogenic aerosol emissions. *Geophysical Research Letters*, *45*, 1020–1029. https://doi.org/10.1002/2017GL076079

Sanderson, B. M., Oleson, K. W., Strand, W. G., Lehner, F., & O'Neill, Brian, C. (2018). A new ensemble of GCM simulations to assess avoided impacts in a climate mitigation scenario. *Climate Change*, *146*(3), 303–318. https://doi.org/10.1007/s10584-015-1567-z

Screen, J. A., & Simmonds, I. (2012). Declining summer snowfall in the Arctic: Causes, impacts and feedbacks. *Climate Dynamics*, *38*(11–12), 2243–2256. https://doi.org/10.1007/s00382-011-1105-2

Shepherd, A., Ivins, E., Rignot, E., Smith, B., & Wuite, J. (2020). Mass balance of the Greenland ice sheet from 1992 to 2018. *Nature*, *579*(7798), 233–239. https://doi.org/10.1038/s41586-019-1855-2

Sillmann, J., Stjern, C. W., & Myhre, G. (2019). Extreme wet and dry conditions affected differently by greenhouse gases and aerosols. *NPJ Climate and Atmospheric Science*, *2*(1), 1–7. https://doi.org/10.1038/s41612-019-0079-3

Stjern, C. W., Lund, M. T., Samset, B. H., Myhre, G., Forster, P. M., Andrews, T., et al. (2019). Arctic amplification response to individual climate drivers. *Journal of Geophysical Research: Atmospheres*, *124*, 6698–6717. https://doi.org/10.1029/2018JD029726

Storelvmo, T., Leirvik, T., Lohmann, U., Phillips, P. C. B., & Wild, M. (2016). Disentangling greenhouse warming and aerosol cooling to reveal Earth's climate sensitivity. *Nature Geoscience*, *9*(4), 286–289. https://doi.org/10.1038/ngeo2670

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*(2), 709–728. https://doi.org/10.1175/JAS-D-15-0152.1

Trenberth, K. E. (2011). Changes in precipitation with climate change. *Climate Research*, *47*(1), 123–138. https://doi.org/10.3354/cr00953

Twomey, S. (1977). The influence of pollution on the shortwave albedo of clouds. *Journal of the Atmospheric Sciences*, *34*(7), 1149–1152. https://doi.org/10.1175/1520-0469(1977)034%3C1149:TIOPOT%3E2.0.CO;2

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., et al. (2011). The representative concentration pathways: An overview. *Climate Change*, *109*, 5–31. https://doi.org/10.1007/s10584-011-0148-z

Wang, H., Xie, S. P., & Liu, Q. (2016). Comparison of climate response to anthropogenic aerosol versus greenhouse gas forcing: Distinct patterns. *Journal of Climate*, *29*(14), 5175–5188. https://doi.org/10.1175/JCLI-D-16-0106.1

Wang, Y., Jiang, J. H., Su, H., Choi, Y. S., Huang, L., Guo, J., & Yung, Y. L. (2017). Elucidating the role of anthropogenic aerosols in arctic sea ice variations. *Journal of Climate*, *31*. https://doi.org/10.1175/JCLI-D-17-0287.1

Xu, Y., Lamarque, J. F., & Sanderson, B. M. (2015). The importance of aerosol scenarios in projections of future heat extremes. *Climatic Change*, *146*(3–4), 393–406. https://doi.org/10.1007/s10584-015-1565-1

Yang, Q., Dixon, T. H., Myers, P. G., Bonin, J., Chambers, D., van den Broeke, M. R., et al. (2016). Recent increases in Arctic freshwater flux affects Labrador Sea convection and Atlantic overturning circulation. *Nature Communications*, *7*, 10525. https://doi.org/10.1038/ncomms10525

Zhang, X., He, J., Zhang, J., Polyakov, I., Gerdes, R., Inoue, J., & Wu, P. (2013). Enhanced poleward moisture transport and amplified northern high-latitude wetting trend. *Nature Climate Change*, *3*(1), 47–51. https://doi.org/10.1038/NCLIMATE1631

Zhao, C., & Garrett, T. J. (2015). Effects of Arctic haze on surface cloud radiative forcing. *Geophysical Research Letters*, *42*, 557–564. https://doi.org/10.1002/2014GL062015