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Key Points:
- Both reconstructions and simulations show that the NH experienced nearly two decades of strong cooling after the Samalas mega eruption
- A single mega volcanic eruption will cause remarkable asymmetry of temperature variation and duration between the Arctic and Antarctic
- Asymmetric temperature changes are caused by the combined effects of albedo feedback and ocean-atmosphere heat exchange related to sea ice

Supporting Information:
- Supporting Information S1

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Global and Polar Region Temperature Change Induced by Single Mega Volcanic Eruption Based on Community Earth System Model Simulation

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Abstract In order to understand the pure long-term influence of single mega volcanic eruption (SMVE) of universal significance on global and polar region temperature changes, the AD 1258 Samalas mega volcanic eruption in Indonesia which is the largest eruption over the past millennium is selected as an ideal eruption for simulation study based on Community Earth System Model. Both reconstructions and simulations show that the Northern Hemisphere experienced nearly two decades of strong cooling after the Samalas mega eruption. The significant cooling in the Arctic lasts for 16 years, while the cooling in the Antarctic lasts only 2 years. As the volcanic aerosol gradually disappears, stronger cooling occurs in Arctic winter, and warming occurs in Antarctic winter. This asymmetric temperature changes over Arctic and Antarctic after SMVE (such as Samalas) are caused by the combined effects of albedo feedback and ocean-atmosphere heat exchange related to sea ice.

Plain Language Summary Polar climate is the focus of earth system investigation because they are very sensitive to external forcings and its related impacts on global climate. Volcanic eruption is one of the important external factors affecting global and polar climate change. The AD 1258 Samalas mega volcanic eruption in Indonesia was the largest eruption over the past millennium, which makes it an ideal eruption to study pure long-term climatic effects of single mega volcanic eruption (SMVE). Here, we use an Earth System Model and find that the duration of surface cooling caused by SMVE (such as Samalas) is longer than we generally believed before and varies in latitude. The Northern Hemisphere experienced nearly two decades of strong cooling after the Samalas event. The significant cooling in the Arctic lasts for 16 years, while the cooling in the Antarctic lasts only 2 years. The SMVE (such as Samalas) could expand Arctic sea ice for more than two decades, but the expansion of Antarctic sea ice lasts only 2–3 years. The asymmetric temperature changes over polar regions are influenced by the combined effects of albedo feedback and ocean-atmosphere heat exchange related to sea ice. The knowledge gained from this research is critical for improved understanding of the potential long-term impacts of SMVE on the projected future global and polar region temperature change.

1. Introduction

As one of the greatest external forcings for climate change before the Industrial Revolution, volcanic eruption is known to be an important natural forcing on many timescales (Robock, 2000; Stevenson et al., 2016). Furthermore, the mega volcanic eruption should be paid more attention because of their potentially serious effects on global climate change and ecosystems (Timmreck et al., 2010; Whiteside et al., 2010). Most previous climate simulation studies suggested that single volcanic eruption can induce temperature decrease no more than 5 years (Church et al., 2005; Hansen et al., 1992; Robock & Liu, 1994). However, there are also studies pointing out that although volcanic aerosols typically remain in the stratosphere for no more than 2 or 3 years, a series of volcanic eruptions could significantly increase the mean optical depth over a longer period and lead to a decadal-scale cooling (Robock, 2000). Climate simulations also suggested that it is possible to induce centennial long-term cooling by a sequence of volcanic eruptions (Zhong et al., 2010), and the Little Ice Age (LIA) was triggered by the Samalas eruption and the following three large sulfur-rich volcanic eruptions, mainly through the consequent Atlantic meridional overturning circulation and Arctic sea ice feedbacks (Miller et al., 2012). Whether and how a single mega volcanic eruption (SMVE) could also cause decadal to multidecadal temperature reduction remains unanswered.

Polar climate is the focus of earth system investigation because they are very sensitive to external forcings and its related impacts on global climate. Due to the lack of background during the strong volcanic activities before the satellite age or the lack of fully solved Antarctic sea ice reconstruction methods to evaluate anomalies, there are few scientific studies on the response of Antarctic temperature and sea ice to volcanic forcing. In observation, especially in simulation results, the dynamic atmospheric response of the strongest 20th century volcanic eruption in the Southern Hemisphere (SH) is not robust (Karpechko et al., 2010; Robock et al., 2007). But the Antarctic sea ice expands significantly after the super volcanic eruption simulated by the coupled climate model (Jones et al., 2005). These studies show that the effect of SMVE on Antarctic temperature change has yet to be understood, which is crucial for Antarctic ecosystems and even global climate. There is complexity behind volcanic eruptions, temperature changes, and sea ice changes, and our understanding of the mechanism behind specific mega-volcanic events is still limited.

The AD 1258 Samalas mega volcanic eruption on Lombok Island, Indonesia, was the largest volcanic eruption over the past millennium (Guillet et al., 2017), which makes it an ideal eruption to study possible prolonged effects of SMVE. Previous research estimated that Samalas mega volcanic eruption injected 257.91, 145.80, and 112.11 Tg of annual stratospheric volcanic sulfate aerosol in the globe, Northern Hemisphere (NH) and SH, respectively (Gao et al., 2008). Emission on this scale causes global temperature decrease during the second half of the 13th century (Lavigne et al., 2013; Vidal et al., 2015, 2016). Based on proxy records and historic evidence, previous studies suggested that NH experienced some of the coldest summers of the past millennium in the following 2 years after the Samalas eruption (Guillet et al., 2017; Oppenheimer, 2003), and sudden temperature drop, crop yield reduction, dry fog, and pestilence occurred in Europe and the Middle East (D'Arrigo et al., 2001; Stothers, 2000). This cooling phenomenon also occurred in the SH summer during that period according to the tree ring, ice core, and coral calcification reconstructions (Briffa, 2000; Jones et al., 1998). However, the researches about Samalas eruption stated above mainly focused on hemispheric scale and some small regions because of the limited suitable records. Besides, most previous volcanic modeling studies that contain the Samalas eruption focused on the cumulative effects of a sequence of volcanic eruptions, such as Samalas and the following three eruptions in 13th century, which means that it is difficult to obtain the pure long-term climatic effect of single Samalas eruption (Miller et al., 2012; Schneider et al., 2009; Slawinska & Robock, 2018; Zhong et al., 2010). There is still a lack of research on the pure long-term effect of SMVE (such as Samalas) on temperature changes over Arctic and Antarctic.

Could SMVE have a pure lasting impact on global and polar temperature changes? How long can this influence last? What are the differences in temperature changes between the Arctic and Antarctic after SMVE, and what cause the differences? The Samalas mega volcanic eruption which is the largest one over the past millennium is selected as an ideal eruption case for simulation study to address these questions based on Community Earth System Model (CESM).

2. Data and Experiments

We use the fully coupled CESM with the Community Atmosphere Model version 4 (CAM4) (Neale et al., 2013), the Parallel Ocean Program version 2 (POP2) (Danabasoglu et al., 2012), the Community Land Model version 4 (CLM4) (Lawrence et al., 2012), and the Sea Ice Model version 4 (CICE4) (Caldeira & Cvijanovic, 2014), developed by National Center for Atmospheric Research (NCAR). A number of studies have evaluated the reliability of CESM compared with observations, proxy-based reconstructions, and

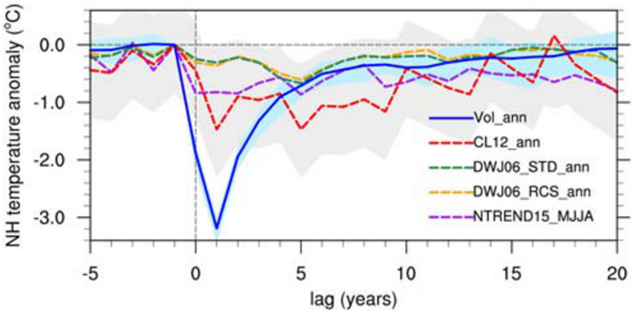

Figure 1. Comparisons of Northern Hemisphere (NH) temperature change of Vol and four reconstructions. The blue solid line indicates the annual mean temperature change over NH in Vol. The other four dashed lines indicate reconstructed NH temperature time series around AD 1258, include CL12 (annual, Christiansen & Ljungqvist, 2012), DWJ06_STD (annual, D'Arrigo et al., 2006), DWJ06_RCS (annual, D'Arrigo et al., 2006), and NTREND15 (MJJA, Wilson et al., 2016). The lag (0) corresponds to the Samalas eruption year. The anomaly is calculated with respect to the last year before the eruption year for each data separately. The gray shadow area is the uncertainty range of 2-sigma error of the reconstructions. The lightblue shadow area is the range of maximum to minimum in eight Vol cases.

multimodel simulations and showed that CESM has good simulation performance in terms of temperature, global monsoon precipitation, and other aspects (Liu et al., 2016; Otto-Bliesner et al., 2016; Wang et al., 2015).

The CESM low-resolution version (T31_g37, about 3.75° in longitude and latitude) was used to carry out the integration in this study, given the limited computing resources available to us and the limitation of server settings. A control experiment (Ctrl), which uses fixed external forcing conditions of AD 1850, consists of 400 years spin-up run and 2,000 years control simulation (Wang et al., 2015). The mega-volcanic sensitivity experiments (Vol) contain 8-member 20-year ensemble simulations. Each volcanic eruption experiment with the same prescribed volcanic forcing was initiated with different initial conditions adopted from the Ctrl. The volcanic forcing is the only changing external forcing in the Vol compared with the Ctrl. The magnitude of SMVE in this study refers to the magnitude of Samalas eruption which is a historical ideal eruption case. Each Vol member is forced by reconstructed AD 1258 Samalas volcanic forcing based on Ice-Core Volcanic Index 2 (Gao et al., 2008). All eruption experiments are assumed to begin in 1 April. Year "0" corresponds to the eruption year, while year "1" corresponds to the first year after the eruption. Additionally, we choose eight members to form a no-volcano ensemble. These eight members chose from the Ctrl are the same years as the volcanic forcing were placed in the Vol. The anomalies in each Vol experiment are calculated as the departures from the corresponding unperturbed counterpart (Vol-Ctrl).

3. Results

3.1. Volcanic Aerosol Change and Global Temperature Response

For the reconstructed volcano forcing (Gao et al., 2008) used in the Vol, the Samalas volcano erupted in April of AD 1258 and the aerosol injection increased to a maximum in August of the eruption year, followed by an exponential decrease (supporting information Figure S1a). After the eruption, the aerosol distributes almost symmetrically over the middle to low latitudes of the NH and SH. For the high latitudes, the aerosol always distributes in local summer, and this distribution is particularly evident from year 0 to year 2 (Figure S1b). The largest reduction in the downward solar radiation directly induced by the volcanic aerosol is distributed between 40°S and 40°N, and solar radiation is significantly reduced in the local summer of year 0 and year 1 over the Arctic (60°N–90°N) and Antarctic (60°S–90°S) (Figure S1c). Figure S1c shows the direct effect of Samalas eruption on the weakening of solar radiation lasts no more than 3 years.

Compared with NH temperature reconstructions, the Vol simulation results are still good (Figure 1). Both reconstructions and simulations show that the NH experienced nearly two decades of strong cooling after the Samalas mega eruption (Figure 1). The cooling in Vol simulations of the first 3 years after the eruption is larger than the reconstructions, and the temperature changes in other years are basically within the uncertainty range of the reconstructions. After the Samalas eruption, the Vol ensemble mean result shows significant drops in surface air temperature (SAT) on the global scale as well as the hemispheric scale (Figure 2a). The global average maximum cooling reaches −2.88°C. Meanwhile, the interhemispheric differences are apparent. The maximum cooling for the NH and SH is −3.95°C and −2.60°C, respectively. The cooling amplitude of the middle to low latitudes is basically the same as the hemispheric averages. The maximum temperature decreases by −3.85°C for NH middle to low latitudes (0–60°N), consistent with the results of Schneider et al. (2009), and by −2.35°C for SH middle to low latitudes (0–60°S). The NH cooling is more pronounced than the SH, and the amplitude of NH temperature anomaly (4.00°C) is much larger than the SH counterpart (2.72°C). The higher heat capacity of ocean leads to the smaller temperature change in the SH compared to its NH counterpart (Iles et al., 2013). In the first 6 years (year 0 to year 5), the global and hemispheric temperature cooling is obvious. After that, the SAT is still lower than the temperature before the perturbation, but the cooling amplitude is smaller than before. It takes almost two decades for the global and

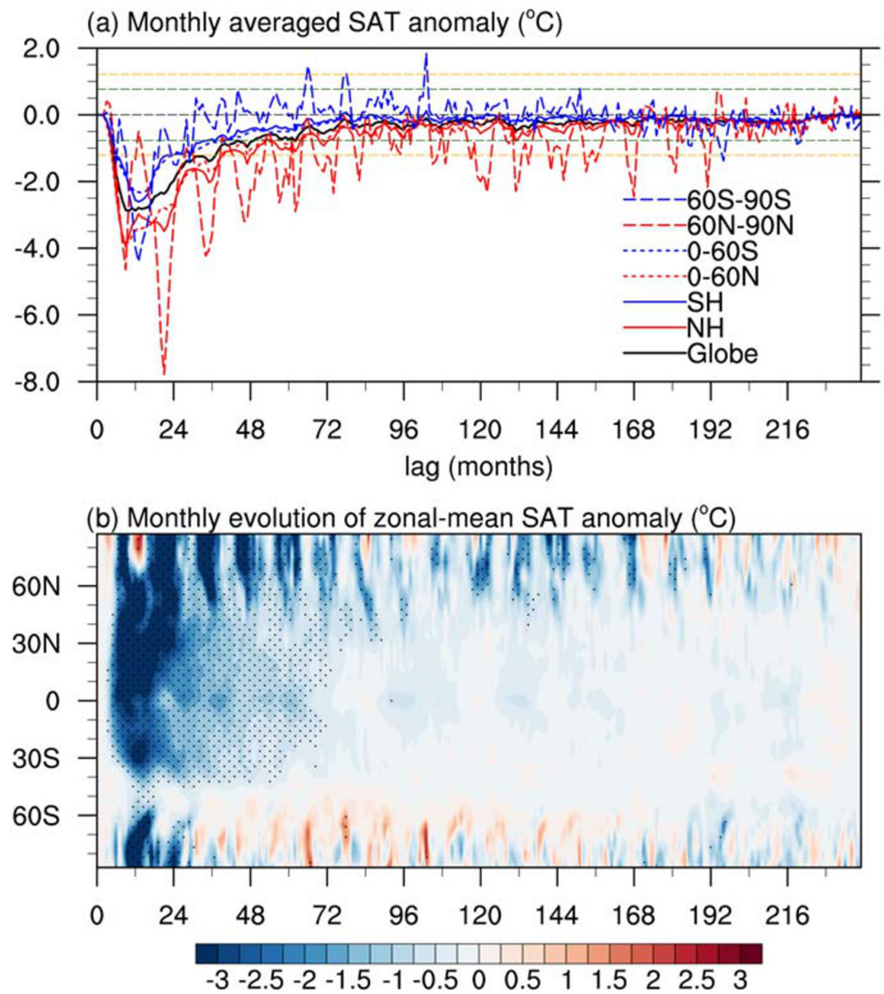

Figure 2. Ensemble-mean post-eruption monthly evolution of (a) averaged surface (2 m) air temperature (SAT) anomalies (°C) and (b) zonal-mean SAT anomalies (°C). The orange horizontal dashed lines in (a) indicate the standard deviation of SAT over the Northern Hemisphere high latitude (60°N–90°N). The green horizontal dashed lines in (a) indicate the standard deviation of SAT over the Southern Hemisphere high latitude (60°S–90°S). The dots in (b) denote areas with confidence exceeding the 90% level. The lag (0) corresponds to January of the eruption year.

hemispheric cooling caused by Samalas eruption to completely disappear. Previous studies have suggested that the surface cooling caused by a single volcanic eruption is typically a temporary (1–3 years) transient due to the short residence time of stratospheric sulfate aerosols (Miller et al., 2012; Robock, 2000). Schneider et al. (2009) found that summer cooling of up to 1°C persists after the 1258 Samalas eruption until 1262 in the tropics and until 1264 in the NH high latitudes. Here, our results show that if other external forcings and new volcanic disturbances are excluded, the duration of surface cooling caused by SMVE (such as Samalas) is longer than we generally believed before and varies in latitude. The cooling in the middle to low latitudes could last for nearly two decades (the first 6 years are remarkable). The significant cooling in the Arctic lasts for 16 years, while the cooling in the Antarctic lasts only 2 years.

Furthermore, it should be noted that the temperature anomaly over high latitudes is much larger than in the middle to low latitudes (Figure 2a). Compared with the Antarctic (maximum cooling is −4.40°C), the Arctic experiences a stronger and more sustained cooling with a maximum cooling of −7.78°C, almost twice of the Antarctic. Unlike the SAT change over the Arctic, it shows a temporary initial recovery of the temperature to normal state during year 2–4 and a persistent warming anomaly from year 5 onward over Antarctic. The significant warming in the Antarctic lasts for 4 years (year 5–8), and the maximum SAT rise is 1.84°C. This Antarctic warming after the large volcanic eruptions was also found by Liu et al. (2018), mainly over the

Southern Pacific. They suggested that the upwelling due to cyclonic wind anomalies that are teleconnected with tropical precipitation anomalies should be one reason.

To better understand the latitude-dependence of temperature changes, the time evolution of monthly zonal-mean SAT anomaly is shown in Figure 2b. The significant cooling in the middle to low latitudes (40°S–60°N) lasts for about 6 years, and the strongest cooling appears in year 0 and year 1. The SAT evolutions of the Arctic and Antarctic show obvious asymmetry after the Samalas eruption. The Arctic shows a significant and continued cooling for 16 years. The cooling mainly occurs in boreal summer in year 0 and year 1. From year 2 onward, the temperature changes from a significant decrease in boreal summer to boreal winter (Figure 2b), as the volcanic aerosol gradually disappears (Figure S1). Schneider et al. (2009) pointed that although the volcanic forcing is strongest in summer, it seems that the cooling response is largest and most lasting in boreal winter over NH high latitudes after the eruption, which is consistent with our results. Zhong et al. (2010) suggested that the four sequenced eruptions of the 13th century caused a significant expansion in NH sea ice, particularly for March after the direct radiative forcing from explosive volcanism is removed. This indicates the operation of feedbacks related to sea ice, which will be discussed further below. Unlike the Arctic, the cooling is not persistent in the Antarctic. The Antarctic experiences a pronounced cooling in the austral summer for just 2 years (year 0 and year 1) and followed by warming anomalies in austral winter.

3.2. The Reason for the Asymmetric Temperature Changes Between Arctic and Antarctic

Arctic amplification (AA) has been found in instrumental observations, paleoclimate reconstructions, and climate model simulations (Bekryaev et al., 2010; Dahl-Jensen et al., 1998; Merlis & Henry, 2018; Pithan & Mauritsen, 2014). The shrinking of sea ice plays a leading role in the amplification of Arctic warming (Liu et al., 2018; Screen & Simmonds, 2010). A question arises: After SMVE (such as Samalas), what roles the sea ice plays in the polar temperature change?

The anomalies of sea ice extent and sea ice volume over Arctic and Antarctic show the remarkable interhemispheric differences after the Samalas eruption (Figure 3). Over the Arctic, the sea ice extent increases by up to 0.69 million square kilometers (5.09% changes compared with normal state), and the sea ice volume increases remarkably by 7,601 cubic kilometers (17.87% changes) (Figure 3). Due to the reinjection of new volcanic disturbances in AD 1268 and 1275, Slawinska and Robock (2018) found that the sea ice response caused by Samalas eruption could last for about 10 years. Using CCSM3 model simulation, Schneider et al. (2009) showed that closely spaced (~10 years) temporal sequences of tropical eruptions incited expansion in NH sea ice that was sustainable for longer than a decade after the direct radiative forcing by volcanic aerosols had been removed. Berdahl and Robock (2013) found that the sea ice extent generally expanded between about AD 1250 and 1500 based on CCSM4 last millennium simulation, indicating that the model had a multidecadal sea ice response after the Samalas eruption. As the above simulation studies added new volcanic eruption shortly after the Samalas eruption, which was mixed with the Samalas mega volcanic impacts, it was difficult for them to obtain the pure long-term climatic effect of SMVE. Here, our results suggest that SMVE (such as Samalas) could expand Arctic sea ice for at least two decades without new volcanic disturbances (Figure 3), thus greatly prolonging the influence time of sea ice on Arctic temperature change after SMVE.

Compared with the Arctic sea ice, a sharp but short-lived increase of Antarctic sea ice extent only occurs within year 0 and year 1, and the anomaly (1.60 million square kilometers, 10.38% changes) is about twice larger than the Arctic counterpart (0.69 million square kilometers) (Figure 3a). But this is not accompanied by a large increase in the sea ice volume (Figure 3b). The amplitude of Antarctic sea ice volume changes is much smaller than Arctic and the maximum is 2,253 cubic kilometers (12.55% changes) (Figure 3b). This means that Antarctic sea ice covers larger area but is thinner during the first 2 years. In sharp contrast to the Arctic, the sea ice extent and volume of Antarctic both turn into negative anomalies from year 2 onward (Figure 3). The geographic configuration is one of the important factors for the different responses of the Arctic and Antarctic sea ice to volcano forcing. The Arctic Ocean is surrounded by continents except its connection with the North Atlantic Ocean. This configuration limits the drifting of Arctic sea ice, which is conducive to the persistence, expansion and thickening of Arctic sea ice (Zanchettin et al., 2014). On the other hand, Antarctic sea ice exists in the coastal regions facing the open Southern Ocean (SO) surrounding the Antarctic continent, and its northern boundary is influenced by the circumpolar system consisting of

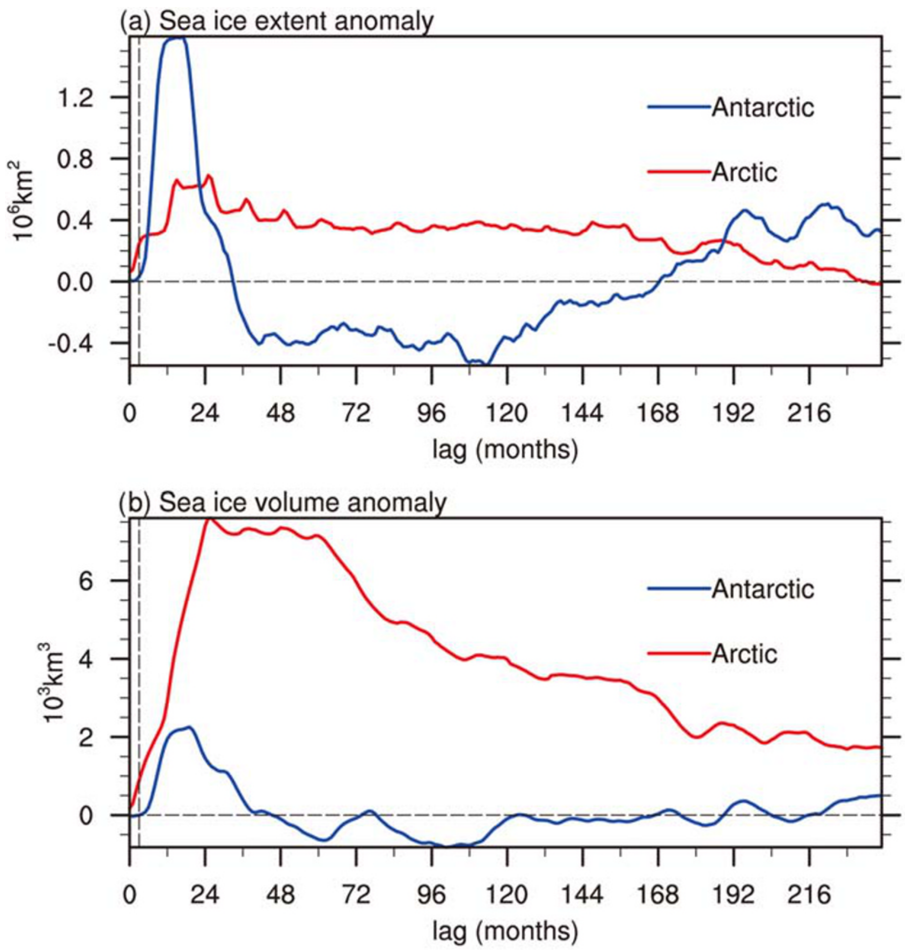

Figure 3. Simulated post-eruption anomalies of Arctic (60°N–90°N, red line) and Antarctic (60°S–90°S, blue line) sea ice extent (a) and sea ice volume (b). Anomalies are smoothed with a 13-month moving average. The dashed vertical black lines indicate the start of the Samalas mega volcanic eruption in Vol. The lag (0) corresponds to January of the eruption year.

strong westerlies and eastward ocean currents. This SO system and the specific Antarctic geographical characteristics favor for melting and equatorward drift of the Antarctic sea ice, resulting in a weak persistence of Antarctic sea ice (Zhang, 2007, 2014).

Polar sea ice changes have direct impacts on albedo change over the Arctic and Antarctic, and albedo can affect polar temperature changes through snow-ice positive feedback (Curry et al., 1995; Eisenman & Wettlaufer, 2009; Pithan & Mauritsen, 2014). After the Samalas eruption, the albedo increases steadily for two decades both in Arctic local summer and winter, which contribute to the reflection of solar radiation and strengthening and persistence of the Arctic cooling (Figure 4a). The albedo anomaly in boreal summer increases rapidly in year 0 and year 1, reaching a maximum of 5.07%, and then slowly declines in consistent with the change of the sea ice extent. The albedo change in boreal winter is smooth, with the maximum of 1.28%, which is obviously smaller than that in boreal summer (Figure 4a). Over the Antarctic, the increase in albedo before year 2 helps to lower the temperature, and then the albedo anomalies switch from positive to negative and last for a decade both in local summer and winter due to the shrinking of sea ice coverage, which is conducive to the absorption of solar radiation and the warming (Figure 4a). The maximum and minimum of austral summer albedo changes over Antarctic are 6.82% and −1.99% respectively, and the change of austral winter albedo is much smaller (Figure 4a). A previous study mentioned that the polar amplification and the positive feedback of Antarctic snow and ice are not as robust as the Arctic (Parkinson, 2004).

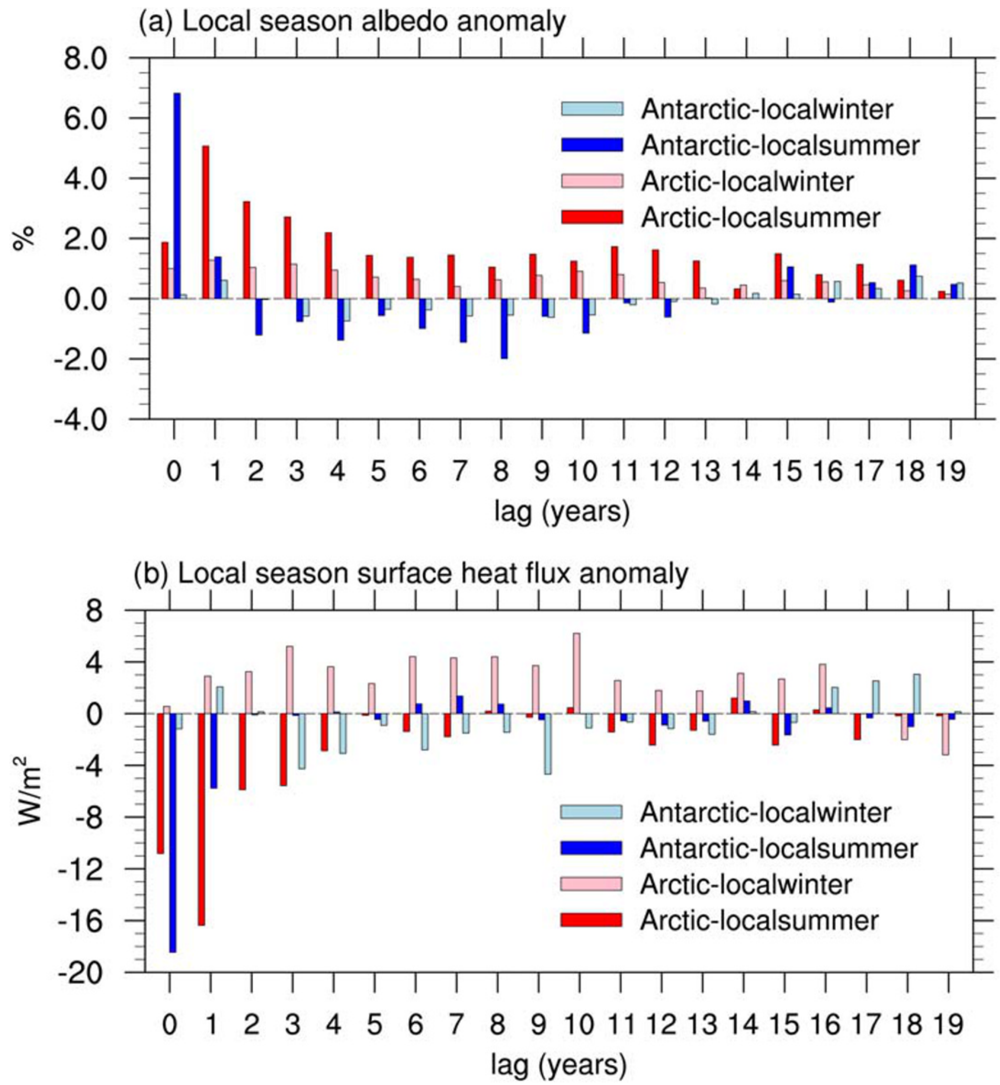

Figure 4. Simulated post-eruption anomalies of Arctic (60°N–90°N) and Antarctic (60°S–90°S) local season albedo (a) and downward surface heat flux (b) over ocean area. Red bar and pink bar indicate Arctic local summer (May–September) and local winter (November–March), respectively. Blue bar and lightblue bar indicate Antarctic local summer (November–March) and local winter (May–September), respectively. The lag (0) corresponds to the eruption year. In (b), positive (negative) anomaly means ocean gains (loses) heat from (to) the atmosphere.

Albedo changes partly contribute to the persistent cooling over Arctic and the warming after year 2 over Antarctic. But the main season for the polar temperature change shifts from local summer to local winter remain unknown. In addition to affecting albedo change, sea ice changes also have an important impact on the heat exchange between atmosphere and ocean over polar regions. In a normal state, the ocean-atmosphere heat flux has a seasonal cycle (Deser et al., 2010), that is, during summer, the heat is transferred downward from atmosphere to ocean, while during winter the heat flux is reversed (Figure S2). Figure 4b shows that over the Arctic ocean the anomalous surface heat flux is basically negative in boreal summer, which indicates that the heat transfer from the atmosphere to the ocean is reduced, which does not favor sea ice melting and continued significant summer SAT cooling. The surface heat flux in Arctic winter basically presents a positive anomaly from year 0 to year 16, indicating that the expansion of the Arctic sea ice (Figure 3) hinders the ocean transfers heat to the atmosphere, resulting in less heat released to the atmosphere (Figure 4b), which makes the more obvious and lasting SAT cooling in Arctic local winter, in agreement with Liu et al. (2018). In the Antarctic ocean, the surface heat flux anomaly in austral summer shows a large negative anomaly in year 0 and year 1, indicating that the heat transfer from the atmosphere to the ocean weakens in austral summer, after which the anomaly becomes very weak (Figure 4b). In austral winter, since year 3, the surface heat flux continues to exhibit negative anomalies until the year 15 (Figure 4b), suggesting that the retreat of Antarctic sea ice (Figure 3) promotes more heat transfer from the upper ocean to the atmosphere (Figure 4b), which gives the atmosphere more heat and leads to winter SAT warming over Antarctic.

4. Discussion and Conclusions

The climate response to Samalas eruption is controversial because climate model simulations generally predict that the NH surface air cooling is stronger and more lasting than inferred from the temperature reconstruction based on tree ring (Guillet et al., 2017). Reconstructions represent the combined effect of various external forcings (including solar radiation, volcanic eruption, greenhouse gases, land use and land cover). Due to the counteracting effect between different external forcing factors, the temperature change amplitude of reconstructions is smaller than that of single factor sensitive experiment of volcanic eruption (Vol). Timmreck et al. (2009) suggested that the cooling effect of a large volcanic eruption, like Samalas event, is more consistent with reconstructions if the aerosol particles are significantly larger than those observed after the 1991 Pinatubo eruption. Since we are based on the Gao et al. (2008) volcanic forcing which contains no information about particle size distribution, the size distribution is not considered in this study, which may be one of the sources of simulation results uncertainty. In fact, there might also be some uncertainties in the paleoclimate reconstructions (Mann et al., 2012). In addition, according to the linear relationship between temperature changes and volcanic magnitudes (Figure S3) and considering that the Samalas volcanic stratospheric sulfur injection in IVI2 forcing (64.5 Tg S, Gao et al., 2008) is slightly greater than in eVolv2k forcing (59.4 Tg S, Toohey & Sigl, 2017), the impact of Samalas eruption on the temperature change in this study may be overestimated by about 6.68%, which will not affect the main results.

Recent research suggested that AA is caused by increased outgoing long-wave radiation and heat fluxes from the newly opened waters resulted from sea ice loss under increasing CO_2 (Dai et al., 2019), whereas all other processes can only indirectly contribute to AA by melting sea ice. From our results, SMVE (such as Samalas) has the opposite effect on polar temperature changes compared with the increase of greenhouse gases, but the influence mechanism is similar to greenhouse gases.

This study focuses on the pure long-term influence of SMVE (such as Samalas) of universal significance on global and polar region temperature changes with the ensemble simulations of the single Samalas mega volcanic eruption based on CESM. Both reconstructions and simulations show that the NH experienced nearly two decades of strong cooling after the Samalas mega eruption. The Arctic shows a significant and continued cooling for 16 years with its maximum cooling (−7.78°C) being almost twice of the Antarctic (−4.40°C), whereas the Antarctic experiences a pronounced cooling for just 2 years, and followed by warming anomalies lasting for 4 years. Single Samalas eruption can expand Arctic sea ice for at least two decades without new volcanic disturbances, while the expansion of Antarctic sea ice lasts only 2–3 years. In first stage (year 0 and year 1), both the Arctic and Antarctic experience pronounced local summer cooling due to the direct weakening of summer solar radiation induced by volcanic aerosol and the enhancement of solar radiation reflection caused by the increased albedo resulted from sea ice expansion. In the second stage (from year 2 onward), the temperature change over the polar region is mainly in local winter, which is characterized by continuous cooling in Arctic winter and slight warming in Antarctic winter. This asymmetric polar temperature changes are due to the fact that the direct weakening effect of the volcanic aerosol on solar radiation is weakened, and the combined effects of albedo feedback and ocean-atmosphere heat exchange which are caused by sea ice changes become the main influencing factors.

Data Availability Statement

The simulation results are available online (http://doi.org/10.5281/zenodo.3914734).

Acknowledgments

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