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Major Differences in Regional Climate Impact Between High- and Low-Latitude Volcanic Eruptions

Jesper Sjolte[1], Florian Adolphi[2], Hera Guðlaugsdòttir[3], and Raimund Muscheler[1]

[1]Department of Geology – Quaternary Science, Lund University, Lund, Sweden, [2]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Sciences, Bremerhaven, Germany, [3]Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

Key Points:

- Contrary to low-latitude eruptions, high-latitude eruptions are associated with a negative North Atlantic Oscillation (NAO)
- The NAO response to low-latitude and high-latitude eruptions is seen during both summer and winter
- Consistent results are shown for independent NAO reconstructions and results from a chemistry climate model simulating a Laki-type eruption

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

J. Sjolte,
jesper.sjolte@geol.lu.se

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Abstract Major low-latitude volcanic eruptions cool Earth's climate, and can lead to a positive phase of the North Atlantic Oscillation (NAO) during winter. However, the question of the climate and circulation impact of Northern Hemisphere high-latitude eruptions has received less attention. Here we show that, contrary to low-latitude eruptions, the response to high-latitude eruptions can be associated with negative NAO both winter and summer. We furthermore demonstrate that also the response to low-latitude eruptions prevails during summer months, and corroborates previous findings of an extended impact on winter circulation lasting up to 5 years. Our analysis of novel climate field reconstructions supports this extended response, with the addition of showing a positive NAO during summer after low-latitude eruptions. The differences in the effect of high- and low-latitude eruptions on atmospheric circulation and regional temperature provide important insights for the understanding of past and future climate changes in response to volcanic forcing.

Plain Language Summary Large volcanic eruptions cool the climate as volcanic particles scatter and absorb part of the solar radiation before reaching the surface. In addition, tropical volcanic eruptions have been shown to strengthen the westerly winds across the North Atlantic for several years after the eruptions. Volcanic eruptions in the high northern latitudes have been generally less strong and less frequent over the last centuries than eruptions in the tropics. In our study we use reconstructions of seasonal temperature and atmospheric circulation to show that high-latitude eruptions have an opposite effect on the circulation than tropical volcanic eruptions as they weaken the westerly winds. This gives large regional differences in the climate impact between high- and low-latitude volcanic eruptions both for summer and winter.

1. Introduction

Volcanic eruptions impact the radiative balance of Earth's atmosphere due to scattering, absorption and reflection of radiation by volcanic aerosols. Explosive eruptions, where the volcanic plume reaches the stratosphere, have the strongest climate effect due to the volcanic aerosols preventing part of the radiation entering the troposphere, as well as the prolonged life time of stratospheric aerosols. The climate effects of large volcanic eruptions have been documented by observations. Most notably the 1991 Pinatubo eruption, which resulted in a peak cooling of the global temperature by 0.5°C 1 year after the eruption (Soden et al., 2002). However, local climate effects from the eruption due to changes in winter atmospheric circulation are thought to have been up to +4°C to −4°C depending on the region (Robock, 2000). Explosive equatorial (EQ) eruptions, such as Pinatubo, eject material into the lower stratosphere, which is then distributed to both hemispheres by the Brewer-Dobson circulation of the stratosphere (Bönisch et al., 2009). In comparison, for Northern Hemisphere high-latitude (NH) eruptions where the plume also reaches the stratosphere, the volcanic aerosols mainly stay in one hemisphere. Hence, differences in the climate effect of NH and EQ volcanic eruptions can be expected.

Over the past millennium there has been a more frequent occurrence of explosive EQ eruptions injecting aerosols into the stratosphere, compared to that of NH eruptions (Sigl et al., 2015), which is probably the reason for the EQ eruptions to have been studied more intensely. The prevailing theory for the impact of EQ eruptions on atmospheric circulation is as follows (Robock, 2000). Due to the geometry of Earth, as well as the polar night, more solar radiation will be absorbed in the stratosphere at low-latitudes by volcanic aerosols compared to the high-latitudes. This causes a differential heating of the lower stratosphere, which results in an anomalous meridional temperature and pressure gradient, that gives rise to a strengthening of the polar jet. The intensification of the high altitude westerlies propagates to lower altitudes, which results in a positive phase of the North Atlantic Oscillation (NAO) (Hurrell et al., 2003). This mechanism is strongest during winter due to the polar night amplifying the differential latitudinal heating. The positive phase of the NAO during winter is associated with stronger westerlies and mild maritime air masses arriving in Northern Europe. This causes a regional winter warming during winter following volcanic eruptions (Kirchner et al., 1999; Zambri & Robock, 2016), despite the radiative cooling effect on the global average.

During the past 100 years only few major volcanic eruptions have occurred. Reconstructions of the aerosol loading of past eruptions show that eruptions several times larger than the Pinatubo eruption have happened during the past millennium (Sigl et al., 2015). For EQ eruptions this includes the strong 1257 Samalas eruption as well as the Tambora eruption in 1815, which is thought to have caused the so-called *year without summer* (Schurer et al., 2019; Stommel & Stommel, 1979), while the largest NH eruption was Laki, Iceland, in 1783, which had widespread impacts on crop yields in Iceland and Europe (Thordarson & Self, 2003). Reconstructions of winter NAO also indicate that major EQ eruptions result in a tendency toward positive NAO following the eruptions, which could last up to 5 years (Michel et al., 2020; Ortega et al., 2015; Sjolte, Sturm, et al., 2018). Such a persistent effect must involve ocean-atmosphere feedbacks as the volcanic forcing lasts a maximum of 1–3 years (Aubry et al., 2020). A persistent effect on summer temperature of at least 5 years has been found using tree ring data (Sigl et al., 2015; Wilson et al., 2016), which has been attributed to a sustained perturbation of the atmosphere-ocean heat exchange (Bronnimann et al., 2019). Although the study of NH eruptions has received less attention than for EQ eruptions, a recent study indicated a strong impact from NH eruptions on Northern Hemisphere temperature over the past 1,500 years (Toohey et al., 2019).

Modeling studies have also mainly focused on the impact of EQ eruptions. Some of these studies also show a positive NAO during the winter following the eruption (Zambri & Robock, 2016; Zanchettin, Timmreck, et al., 2012). However, it is far from all models which show this response, and there is little consistency between Coupled Model Intercomparison Phase 5 (CMIP5) results (Driscoll et al., 2012; Swingedouw et al., 2017). A study by Barnes et al. (2016) showed that selecting CMIP5 models which have a reasonably realistic warming in the lower stratosphere in response to the Pinatubo eruption lead to a more consistent positive zonal wind anomaly and corresponding positive NAO. This points to biases or missing processes in the remaining CMIP5 models involving the atmospheric dynamics, micro-physics, chemistry and/or forcing related to volcanic eruptions. The effect of NH eruptions has to a lesser extent been studied with models. However, a few model studies do point to a different effect of NH eruptions on atmospheric circulation, compared to EQ eruptions, namely a negative NAO following the eruption (Gudlaugsdottir et al., 2018; Oman et al., 2005), although the dynamical effect was determined to be minor compared to the effect of the radiative forcing. A recent set of simulations of the response to a Laki-like eruption using a chemistry climate model also indicates a negative NAO in response to NH eruptions (Zambri et al., 2019b).

Here we use novel seasonal climate field reconstructions (Sjolte, Adolphi, et al., 2020; Sjolte, Sturm, et al., 2018) of sea level pressure (SLP) and surface air temperature (T2m) to investigate the impact of NH and EQ eruptions on atmospheric circulation and temperature during the past 800 years. Furthermore, we use the results from a chemistry climate model to support our conclusions for the impact of NH eruptions. We discuss the results with focus on the duration, pattern and mechanism of the reconstructed changes, and compare to independent reconstructions of atmospheric circulation.

2. Climate Reconstructions and Model Experiments

In this study we use climate reconstructions covering 1241–1970 that link modeled $^{18}O/^{16}O$ isotope ratios of precipitation to isotope records from Greenland ice cores of seasonal resolution, producing ensemble climate reconstructions for summer and winter without the need for calibration (Sjolte, Adolphi, et al., 2020; Sjolte, Sturm, et al., 2018). For the summer season we use an additional climate reconstruction, where the ice core-based reconstruction is further constrained by using tree ring data to improve the performance for temperature (Sjolte, Adolphi, et al., 2020).

Table 1
Reconstructed Volcanic Forcing (Sigl et al., 2015)

Low-latitude eruptions (EQ)			High-latitude eruptions (NH)		
Name	Year	Estimated cumulative forcing [Wm^{-2} yr]	Name	Year	Estimated cumulative forcing [Wm^{-2} yr]
Tambora/Indonesia	1815	−17.20	Novarupta/Alaska	1912	−3.26
UE 1809	1809	−12.01	Laki/Iceland	1783	−15.49
UE 1695 (Serua/Banda Sea?)	1695	−10.24	Tarumae/Japan	1739	−2.36
Parker/Philippines	1641	−11.84	Bàrðarbunga/Iceland	1729	−3.17
Huaynaputina/Peru	1601	−11.58	Tarumae/Japan	1667	−2.33
Kuwae/Vanuatu	1458	−20.55	UE 1646	1646	−1.91
Samalas/Indonesia	1258	−32.79	Veiðivötn/Iceland	1477	−3.08
			UE 1329	1329	−2.92

Note. We have selected low-latitude (EQ) eruptions of larger magnitude than −10 Wm^{-2} yr, and high-latitude (NH) eruptions of larger magnitude than −1.8 Wm^{-2} yr during 1241–1970 CE. UE indicates unknown source of eruption.

To analyze the volcanic response we select the largest EQ and NH volcanic eruptions during 1241–1970 according to the ice core-based estimates of cumulative radiative forcing (unit, Wm^{-2} yr) by Sigl et al. (2015). In the selection there is a trade off in choosing many eruptions, and thereby including weaker eruptions, which gives better statistics, but also results in a weaker climate impact. To achieve a comparable number of NH and EQ eruptions, the threshold for NH eruptions must be set lower to include much weaker eruptions as there are fewer strong NH eruptions. We find that we get a clear climate response using a threshold of −10 Wm^{-2} yr for EQ eruptions and −1.8 Wm^{-2} yr for NH eruptions (Table 1). We analyze the mean climate response to volcanic eruptions by stacking the response using superposed epoch analysis (SEA), and calculating the anomaly with respect to the mean of the 10 years preceding the eruptions.

For the reconstructed response to NH eruptions we compare the output from the WACCM chemistry climate model, which has been run to simulate a Laki-type volcanic eruption (Zambri et al., 2019a). This high-top model includes detailed atmospheric chemistry and micro physics to more accurately represent the atmospheric impact of volcanic eruptions.

3. Reconstructed Response to Volcanic Eruptions

Our analysis of the climate impact of the largest eruptions during 1241–1970 (see Section 2 and Table 1) show a different response to NH eruptions compared to EQ eruptions. The spatial patterns of the mean response in SLP and T2m for volcanic eruptions are consistent with positive NAO for EQ eruptions, and negative NAO for NH eruptions for both summer and winter (Figure 1). For winter the results for EQ eruptions are similar to Sjolte, Sturm, et al. (2018) using the same reconstruction, although with a different selection of volcanic eruptions (see Methods), while the other results are unique to this study. During summer the response to the volcanic forcing is seen immediately during the year of the eruption, while for winter the response is seen the first winter following the eruption. The response during winter is stronger in amplitude for SLP and temperature and appears more consistent compared to summer, which could be due to the actual strength of the response in circulation, as well as due to the better skill of the SLP reconstruction for winter (Sjolte, Adolphi, et al., 2020).

The NAO response during summer is consistent whether or not tree-ring data is included in the reconstruction (Figure S1), although the cooling patterns for Europe only stand out clearly when including tree-ring data (Figure S2). For NH eruptions there is a cooling in central Europe during summer, with indications of warming over the Arctic, Greenland, and central North Atlantic, while for EQ eruptions there is a widespread cooling pattern across Greenland, Scandinavia, and the south-eastern Europe. The differences in response for NH and EQ eruptions are also seen when analyzing the proxy data by itself, indicating that neither the patterns nor the responses are artifacts of the model assimilation of proxy data (Figures S3–S5). It is important to note that the response in the ice core data mainly is seen as a change in the gradient of

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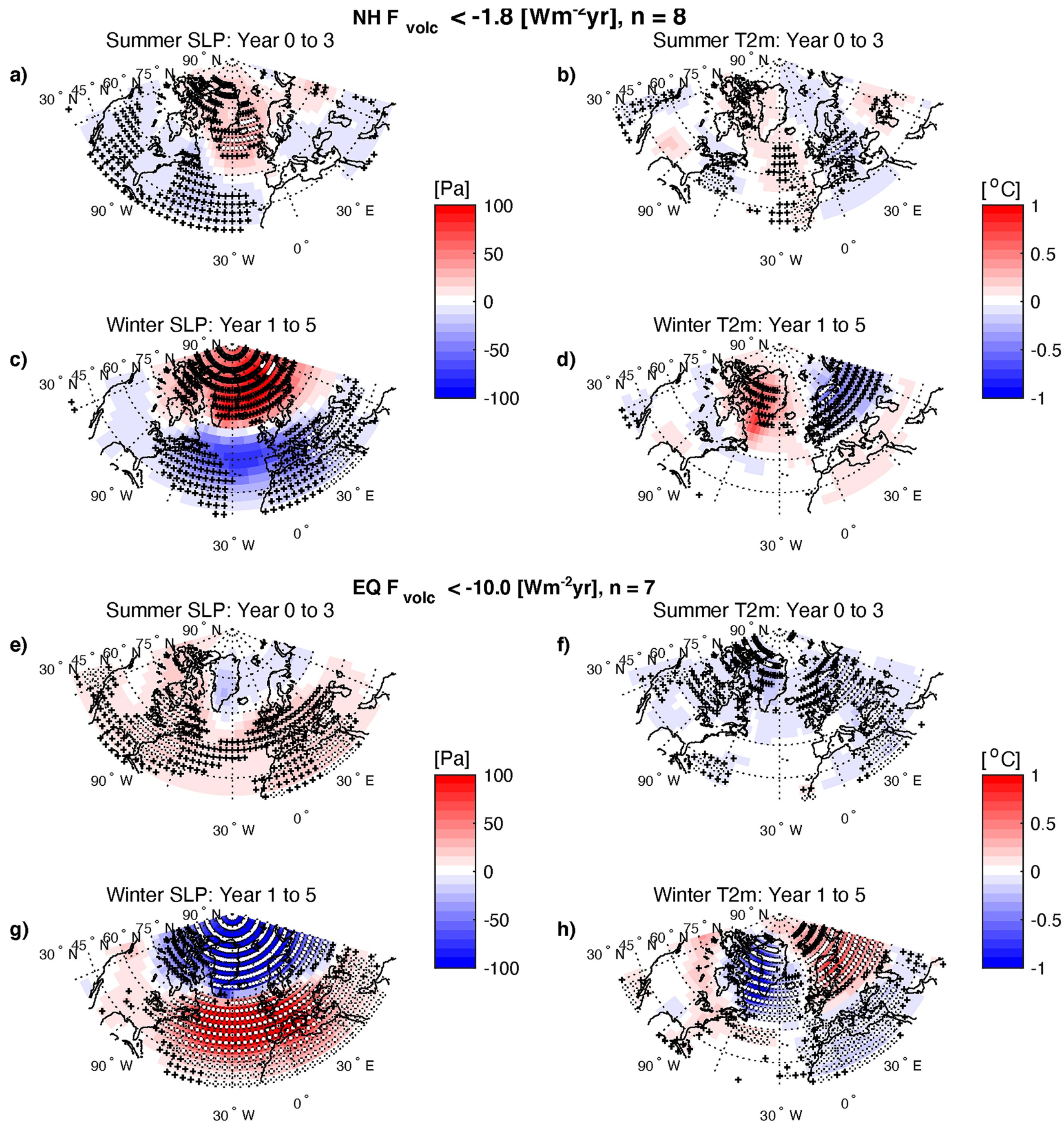

Figure 1. Reconstructed post eruption anomalies in sea level pressure (SLP) and T2m. (a) SLP and (b) T2m anomalies for summer after the 8 largest NH eruptions. (c and d), same as (a and b), but for the winter season. (e) SLP and (f) T2m anomalies for summer after the 7 largest NH eruptions. (g and h), same as (e and f), but for the winter season. Summer reconstructions shown here include 8 tree ring chronologies in Europe. The white stippling indicates significant anomalies $p < 0.01$, and black stippling indicates significant anomalies $p < 0.05$ (two-tailed Student's t test).

the isotope ratios between southern Greenland, in particularly the DYE3 site (Figure S6), and the more northern sites. For the tree ring data the two southern tree-ring sites (TYR and TAT, see Figure S6) stand out in having a stronger response to NH eruptions than to EQ eruptions, as opposed to the other tree-ring sites. This is consistent with the temperature responses shown in Figures 1b and 1f.

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To a large extent the patterns of the temperature anomalies for the response to NH and EQ eruptions mirror each other, as would be expected from the positive and negative NAO phase. However, particularly during summer, the temperature response is likely a mixture of radiative cooling and a dynamic response causing regional warming or cooling. The more widespread cooling reconstructed for EQ eruptions is probably also due to the stronger radiative forcing (<-10 Wm^{-2} yr EQ vs. <-1.8 Wm^{-2} yr NH, Table 1). During winter there is most likely a strong dynamical component in the response, as we for example see a warming over Greenland after NH eruptions, and since there is no direct effect of volcanic aerosols on solar radiation at high-latitudes during the polar night.

The SEA of the temporal response of the reconstructed NAO is shown in Figure 2. Except for the summer response to NH eruptions the analysis indicates that the mean response of the NAO to volcanic eruptions is longer than the 1–3 year duration of the forcing, which is consistent with studies of the winter NAO (Michel et al., 2020; Sjolte, Sturm, et al., 2018). The apparent shorter duration of the summer response to NH eruptions could depend on the choice of the volcanic eruptions used in the SEA, although sensitivity tests show that our results for the NAO response generally is robust with respect to selection of volcanic eruptions (Figure S7). The extension of the response by 1–2 additional seasons after the direct effect of the volcanic forcing points to an ocean feedback on the atmosphere (Schneider et al., 2009; Sigl et al., 2015; Sjolte, Sturm, et al., 2018; Zanchettin, Bothe, et al., 2014).

4. Discussion and Conclusions

Independent NAO reconstructions by Ortega et al. (2015) and Michel et al. (2020) (Figure S8) support the findings of a positive winter NAO after EQ eruptions as well as the negative winter NAO following NH eruptions (Figure S9). In the latter case, the response in the reconstructions by Ortega et al. (2015) and Michel et al. (2020) is somewhat weaker than in our results. For the data by Ortega et al. (2015) this could possibly be due to suppression of high-frequency variability in the reconstruction (Sjolte, Sturm, et al., 2018). However, the Michel et al. (2020) data set shows a similar response to our results when only the 4 strongest NH eruptions are studied. In contrast, a recent NAO reconstruction by Cook et al. (2019) does not indicate a NAO response to volcanic forcing at all (not shown), which is in conflict with observations and model results.

In Figure 3 we show the ensemble mean simulated WACCM summer and winter response to a Laki-type eruption. The patterns of the response matches the reconstructed patterns in Figures 1a–1d very well, and are consistent with a negative NAO response for summer (July and August) and late winter (February to April) (Zambri et al., 2019b). While the dynamical response to NH eruptions to some extent is the mirror opposite to EQ eruptions, the mechanism driving the modeled response is different. Unlike the response to EQ eruptions, the stratospheric temperature gradient remains largely unchanged in the Laki simulation (Zambri et al., 2019a). Instead, the simulated weakened polar vortex is linked to an increase in poleward residual circulation and wave energy flux from the troposphere to the stratosphere (Zambri et al., 2019a). This change in circulation is translated to a southward shift in the mid-latitude tropospheric jet and a negative NAO. The simulation used here is 12 months long and does therefore not enable us to address the response and mechanisms of a modeled long-term response.

While the mean NAO response to volcanic eruptions shown in Figure 2 might give the impression of a deterministic process, there are many factors in both deciding the response and the detection of the response in the data. The approach of subtracting the pre-eruption mean and performing the SEA to some extent takes into account the influence of the state of the atmosphere and ocean at the time of the eruption, as well as the confounding noise of weather variability and in the reconstructions. It can be difficult determining the impact of individual volcanic events in the presence of these other factors. This can be illustrated by looking at the NAO response to individual events compared to the mean response (Figure S10 and S11). While the NAO response to individual events in many cases follows the mean response in amplitude and duration relatively closely, especially for the stronger eruptions, it is clear that the large year-to-year variability both before and after the eruptions makes it challenging to attribute variations to individual eruptions. The nature of the NAO response to volcanic eruptions should thus be thought of as a probable post-eruption

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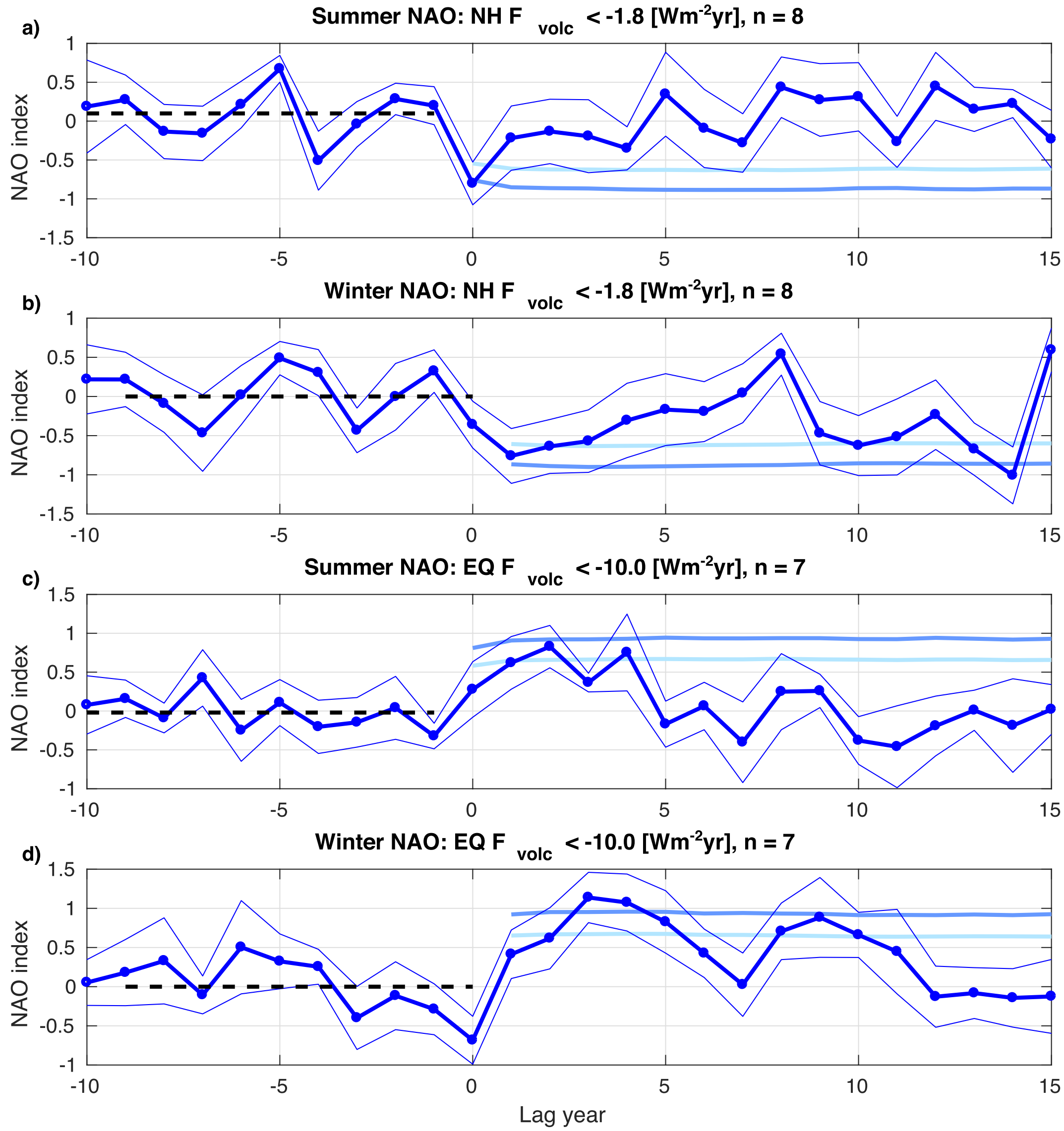

Figure 2. Time series of the mean response in reconstructed North Atlantic Oscillation (NAO). The analysis uses the same eruptions as in Figure 1, but no tree-ring data is included for summer as the addition of the tree-ring data does not improve the performance for the reconstructed summer NAO (Sjolte, Sturm, et al., 2018), with (a) being for summer NAO and NH eruptions, (b) winter NAO and NH eruptions, (c) summer NAO and EQ eruptions, and (d) winter NAO and EQ eruptions, the full blue line indicates the mean, while the thin lines indicate ±1 standard deviation. The time series normalized to the mean NAO of the 10 years preceding the eruption. The significance levels (light blue, 95%; darker blue 99%) are estimated from 100,000 random samples of "eruptions" (NH: $n = 8$, EQ: $n = 7$) drawn from the reconstructed NAO.

tendency rather than a deterministic process. This also underlines the need for ensemble simulations in model studies of volcanic eruptions.

Although the 95% significance level is passed in all four cases in Figure 2, and 99% significance level is passed for the winter response to EQ eruptions, there is still a risk for attributing unforced variability to volcanic forcing when judging the significance of sparsely sampled data. This, and the factors discussed in the previous paragraph, can lead to questioning of the existence of a dynamical response to volcanic eruptions (e.g., Polvani & Camargo, 2020). Future studies of proxy data could attempt to extend reconstructions further back in time to cover more eruptions although the availability of seasonally resolved climate data makes this challenging (Sjolte, Adolphi, et al., 2020).

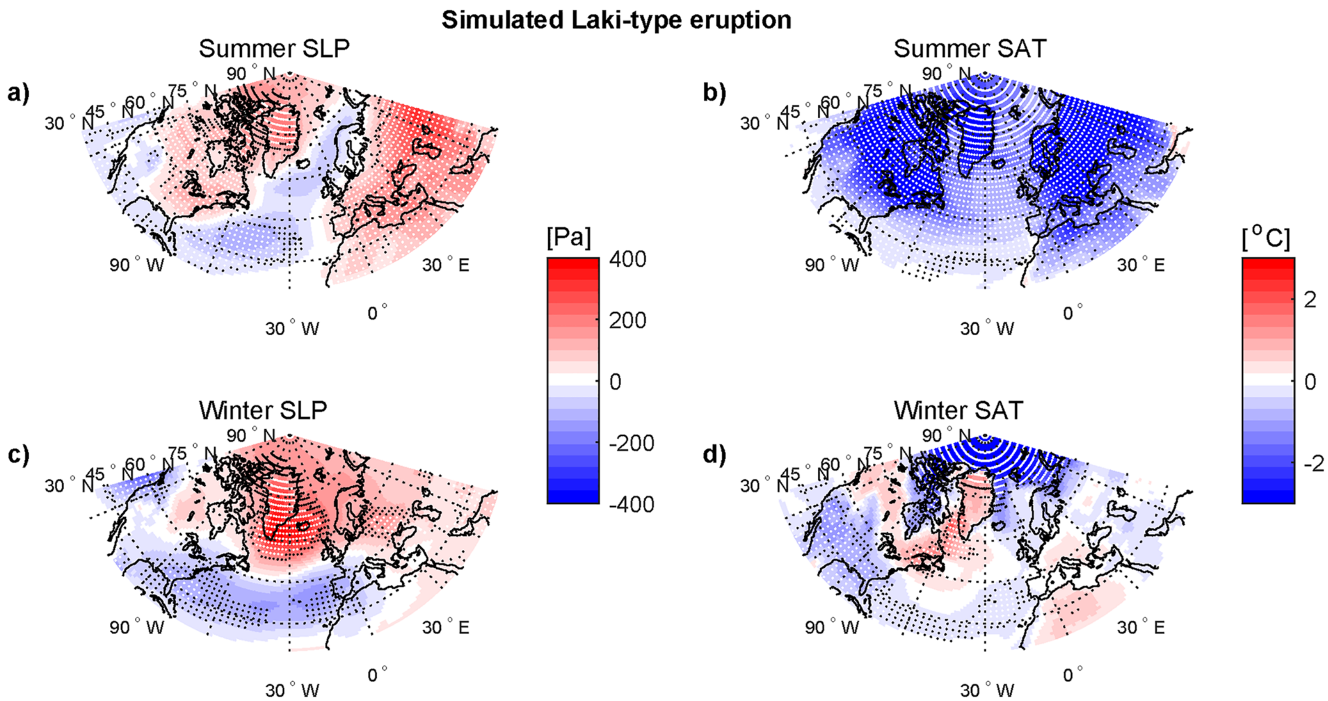

Figure 3. Simulated climate response to Laki-type eruption (Zambri et al., 2019a). Ensemble mean Laki simulation (n = 40) minus ensemble mean control simulation (n = 40) for (a) summer SLP and (b) summer surface air temperature (SAT). (c and d), same as (a and b), but for winter. The white stippling indicates significant anomalies $p < 0.01$, and black stippling indicates significant anomalies $p < 0.05$ (two-tailed Student's t test). Summer is defined here as July and August and winter as February to April to show the months having a significant response in circulation (Zambri et al., 2019b).

Together, our findings provide novel insights on the differences in climate impact of high- versus low-latitude volcanic eruptions. The results show that high-latitude eruptions have distinctly different impact on atmospheric circulation and regional climate than low-latitude volcanic eruptions, underlining their importance for past and current societies, which have so far been overlooked. We demonstrate a long-term (sub-decadal) effect of volcanic eruptions for both summer and winter. Further investigations are needed to uncover the role of ocean-atmosphere interactions in the mechanisms of the extended effect on atmospheric circulation and climate. This will improve regional long-term weather forecasts and mitigation of societal impacts.

Data Availability Statement

The authors thank two anonymous reviewers for helpful comments and constructive suggestions. The seasonally reconstructed SLP and T2m used in this study has been submitted to the PANGAEA data repository (PDI-27146). Tree-ring and ice core data are available through Wilson et al. (2016) and Vinther et al. (2010), respectively, and the chemistry climate model output is available through Zambri et al. (2019a).

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