Disproportionately strong climate forcing from extratropical explosive volcanic eruptions

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Abstract

Extratropical volcanic eruptions are commonly thought to be less effective at driving large-scale surface cooling than tropical eruptions. However, recent minor extratropical eruptions have produced a measurable climate impact, and proxy records suggest that the most extreme Northern Hemisphere cold period of the Common Era was initiated by an extratropical eruption in 536 CE. Using ice core-derived volcanic stratospheric sulfur injections and Northern Hemisphere summer temperature reconstructions from tree rings, we show here that in proportion to their estimated stratospheric sulfur injection, extratropical explosive eruptions since 750 CE have produced stronger hemispheric cooling than tropical eruptions. Stratospheric aerosol simulations demonstrate that for eruptions with sulfur injection magnitude and height equal to that of the 1991 Mt. Pinatubo eruption, extratropical eruptions produce time-integrated radiative forcing anomalies over the Northern Hemisphere extratropics up to 80% greater than tropical eruptions, as decreases in aerosol lifetime are overwhelmed by the enhanced radiative impact associated with the relative confinement of aerosol to a single hemisphere. The model results are consistent with the temperature reconstructions, and elucidate how the radiative forcing produced by extratropical eruptions is strongly dependent on eruption season and sulfur injection height within the stratosphere.

Main

Major volcanic eruptions impact climate through the injection of sulfur into the stratosphere, leading to the production of stratospheric sulfate aerosol, which scatters incoming solar radiation and cools the Earth's surface[1]. The climatic impact of any eruption depends on the properties of the stratospheric aerosol enhancement, and is tied principally to the amount of sulfur injected, but also to the aerosol's atmospheric lifetime, spatial spread, and size distribution.

It is commonly thought that extratropical eruptions have a weaker climatic impact than tropical eruptions[2,3]. This hypothesis rests on the idea that aerosol resulting from tropical eruptions spreads globally, and has a longer stratospheric lifetime due to a longer transport path from the tropics to removal across the mid- or high-latitude tropopause[4]. Shorter lifetimes for stratospheric aerosol from extratropical eruptions have been assumed in prior volcanic forcing reconstructions[5,6] and are thus implicit in model studies which support the idea of weaker climate forcing from extratropical eruptions[4].

Comparing the aerosol clouds and climate impacts resulting from tropical vs. extratropical eruptions based on observations and proxy records is complicated by a number of confounding factors. During the satellite era, stratospheric sulfur injections from the strongest extratropical eruptions have been an order of magnitude weaker than the largest tropical eruptions[7]. On longer timescales, ice cores record sulfate from major eruptions from both the tropics and extratropics[8], however, limited knowledge of the height of the volcanic sulfur injection from those eruptions adds uncertainty to estimates of radiative forcing from ice cores[9].

Interest in extratropical eruptions has recently increased, due in part to a series of minor extratropical volcanic eruptions which produced significant radiative forcing on climate, counteracting a portion of greenhouse gas warming[10,11]. Furthermore, model results suggest the hemispherically asymmetric radiative forcing from extratropical eruptions has distinct impacts on tropical precipitation[12,13], and atmospheric and ocean circulation[14,15]. Reconstructions of volcanic activity spanning the past 2500 years from ice cores have identified large extratropical volcanic events with associated large-scale cooling[8], including extreme NH cold conditions initiated by an extratropical eruption around the year 536 CE[8,16,17]. These findings motivate a re-examination of the radiative forcing and climate impacts of extratropical eruptions.

Hemispheric cooling by extratropical vs. tropical eruptions

Reconstructions of Northern Hemisphere (NH) extratropical summer temperatures over land from tree rings show a clear cooling response to volcanic eruptions[18]. Here, we examine the magnitude of the cooling recorded in three tree ring NH temperature reconstructions[19–21] over the 750-2000 CE period, supplemented with estimates of eruption region and volcanic stratospheric sulfate injection (VSSI) deduced from ice core sulfate records[22]. We select eruptions with VSSI> 2 Tg S, excluding cases potentially affected by prior eruptions (see Methods, Supplementary Table 1) and five events linked to Iceland (Supplementary Table 2).

Post-volcanic 3-year mean NH temperature anomalies, averaged over the three reconstructions ($\Delta T_{\mathrm{3yr}}^{\mathrm{ALL}}$, see Methods) show a clear relationship with VSSI (Fig. 1). Tropical eruptions show a particularly coherent correlation (*r*=-0.68) between temperature and VSSI. There is also clearly scatter in the relationship between ΔT_{3yr} and VSSI, which can be due to uncertainties in both quantities, but also the influences of internal climate variability on ΔT_{3yr} and the impact of secondary eruption characteristics such as eruption season and plume height. Ratios of temperature response to VSSI (Supplementary Tables 4 and 5, Fig. 1 inset) show a broad range of values, with outliers including events with apparent post-eruption warming to very strong apparent cooling. On average, tropical and extratropical eruptions lead to ΔT-to-VSSI ratios of -0.025 ± 0.005 °C $(\mathrm{Tg\ S})^{-1}$ and -0.080 ± 0.018 °C $(\mathrm{Tg\ S})^{-1}$ respectively (Table 1). The difference between the ΔT-to-VSSI ratios for extratropical and tropical eruptions is significant at the 99% level (p=0.006): a factor of roughly 2-4 difference is consistent across the three NH temperature reconstructions (Table 1, Supplementary Fig. 1).

The stronger temperature response per unit VSSI to extratropical eruptions is based on a sample of extratropical eruptions with VSSI mostly limited to values less than 7 Tg S (Supplementary Table 4). While this limits the comparability of the temperature responses to extratropical and tropical eruptions, we note that the mean ΔT-to-VSSI ratios for tropical eruptions are consistent between eruptions less than and greater than 7 Tg S (Fig. 1 inset), suggesting that the stronger ΔT-to-VSSI ratios seen for extratropical eruptions are likely representative. The ΔT-to-VSSI ratio for extratropical eruptions after 750 CE is consistent with the strong cooling estimated for the 536 CE eruption, albeit from a single reconstruction (Fig. 1, Supplementary Table 5). On the other hand, the extratropical eruptions of 626 and 1180 CE produce ΔT-to-VSSI ratios on par with tropical eruptions.

One pertinent issue in the calculation of ΔT-to-VSSI ratios is uncertainty in the methods used to calculate VSSI, which apply a smaller transfer function for extratropical eruptions than tropical eruptions in the estimation of volcanic aerosol from ice core sulfate[22,23]. Nonetheless, if VSSI values for extratropical eruptions were calculated as for tropical eruptions, extratropical eruptions would still produce an 81% stronger average ΔT-to-VSSI ratio than tropical eruptions (Table 1).

Since aerosol from extratropical eruptions is largely contained within the hemisphere of the eruption[24], while that from tropical eruptions spreads globally, a factor of two difference between ΔT-to-VSSI ratios for extratropical and tropical eruptions could be explained by a relatively equal temperature response to hemispheric aerosol loading, irrespective of latitude of injection. This explanation however seemingly contradicts the expectation of a significantly reduced stratospheric aerosol lifetime for extratropical eruptions.

The lifetime of volcanic stratospheric sulfur

To investigate the impact of eruption latitude on the volcanic stratospheric sulfate aerosol evolution we performed ensemble simulations with the coupled aerosol-atmospheric general circulation model MAECHAM5-HAM (see Methods). All simulations include a stratospheric injection of 8.5 Tg S, consistent with satellite-based estimates of the 1991 Pinatubo eruption[25], with eruptions in both January and July to include the effect of season[20,26,27]. A set of four eruption latitudes were chosen based on maxima in the latitudinal distribution of identified eruptions within the Volcanoes of the World database[28] (Supplementary Fig. 2), and simulations (Supplementary Table 6) were performed with SO_2 injected at each latitude and 30 hPa (~24 km), consistent with the 1991 Pinatubo eruption. Eruptions at 56°N were also performed with injections into the lower stratosphere at 100 hPa (~16 km) and 150 hPa (~13 km), roughly consistent with the range of estimates[7] of the injection heights of recent minor (VSSI < 1 Tg S) extratropical eruptions including Kasatochi (2008, 52°N) and Sarychev (2009, 48°N).

The simulated spatiotemporal evolution of volcanic aerosol burden (Fig. 2a-d, Supplementary Fig. 3) shows global spread of aerosol following tropical eruptions and hemispheric containment of aerosol for extratropical eruptions. These patterns of aerosol spread are consistent with prior simulations[24], comparisons of tropical vs. extratropical temperature reconstructions[29] and understanding of the general features of large-scale circulation within the stratosphere[30].

For sulfur injections at a fixed height of 30 hPa, global mean sulfate mass burdens show sensitivity to both the injection latitude and season (Fig. 2e, f). For January (i.e., NH winter) eruptions, extratropical eruptions produce sulfate burdens which are similar to tropical eruptions, with stratospheric e-folding lifetimes only ~10% smaller (Fig. 2g). For July (i.e., NH summer) eruptions, global sulfate burdens from extratropical eruptions reach maxima similar to those from tropical eruptions, but decay faster, with lifetimes 24-44% shorter.

Simulations of sulfur injections at 56°N with varying injection heights show that injection height within the stratosphere plays an important role in controlling the lifetime of stratospheric sulfate. The lifetimes of stratospheric sulfur for extratropical injections at 100 hPa and 150 hPa are notably shorter than from both tropical and extratropical 30 hPa injections (Fig. 2g). These results can be understood as arising from differences in transport processes between the lowermost stratosphere (LMS) and "overworld"[31]. In the LMS, defined as the region between the tropopause and the 380 K potential temperature surface, large-scale two-way transport along potential temperature isentropes exchanges air between the tropopause and stratosphere, while in the overworld, isentropes do not cross the tropopause and therefore transport simply redistributes mass within the stratosphere. Sulfate aerosol resulting from simulated sulfur injection into the LMS are transported into the troposphere and deposited to the surface rapidly after the injection (Supplementary Fig. 4), whereas cross-tropopause transport of sulfur injected into the extratropical stratospheric overworld only proceeds after aerosol has descended into the LMS, which prolongs the aerosol lifetime.

Global mean aerosol properties and radiative forcing

The radiative impact of stratospheric aerosol depends not only on its mass, but also on its size distribution[32], since stratospheric sulfate aerosol has maximum scattering efficiency at effective radius of ~0.2 µm, with decreasing efficiency for the larger effective radii observed after major eruptions[33,34]. Sulfate-mass-weighted mean effective radius ($\langle r_{\text{eff}} \rangle$, see Methods) and global mean stratospheric aerosol optical depth (SAOD) are shown in Fig. 3 as a function of injection location. Simulated effective radius shows sensitivity to eruption latitude, season and injection height (Fig. 3a, b). For January 30 hPa injections, the evolution of $\langle r_{\text{eff}} \rangle$ is similar for extratropical and tropical eruptions, with a peak $\langle r_{\text{eff}} \rangle$ of around 0.4 µm. For July 30 hPa injections, simulated $\langle r_{\text{eff}} \rangle$ for extratropical eruptions reaches much larger values (>0.6 µm) than comparable tropical eruptions (~0.4 µm). Sulfur injections into the extratropical lower stratosphere (100 and 150 hPa) result in lower $\langle r_{\text{eff}} \rangle$ compared to 30 hPa injections, with again, July eruptions leading to larger $\langle r_{\text{eff}} \rangle$ than January eruptions. The sensitivity of $\langle r_{\text{eff}} \rangle$ to eruption latitude, season and injection height can be understood to be primarily controlled by the availability of hydroxyl radical (OH), which controls the rate of SO_2-to-H_2SO_4 conversion. Higher OH values, which occur in the high-latitude stratosphere during summer (Supplementary Fig. 5), lead to faster H_2SO_4 production. When H_2SO_4 production is fast compared to stratospheric mixing and transport processes, H_2SO_4 concentrations are relatively enhanced at a local to regional scale, promoting aerosol growth through condensation and coagulation.

SAOD at 550 nm quantifies the attenuation of solar radiation by aerosol, and is a function of the sulfate burden as well as effective radius. January extratropical 30 hPa injections lead to a global mean SAOD (Fig. 3c) very similar to tropical 30 hPa eruptions, reflecting similar global sulfate burdens and $\langle r_{\mathrm{eff}} \rangle$. July extratropical 30 hPa injections lead to a much weaker global mean SAOD than tropical 30 hPa eruptions (Fig. 3d), due to both the faster decay of the sulfate burden and larger $\langle r_{\mathrm{eff}} \rangle$. In terms of three-year cumulative SAOD (Fig 3e), extratropical 30 hPa injections in January produce only ~10% less global mean SAOD than comparable tropical eruptions, while extratropical 30 hPa eruptions in July produce 30% (36°N) to 53% (56°N) less SAOD compared to tropical counterparts. Injections into the extratropical lower stratosphere in general lead to smaller SAOD than injections to 30 hPa, although due to the smaller $\langle r_{\mathrm{eff}} \rangle$ for lower injection heights, the impact of injection height is weaker on SAOD than on sulfate burden lifetime. The importance of r_{eff} is especially apparent for July eruptions at 56°N, where the simulated peak and cumulative SAOD resulting from an 100 hPa injection is similar to that from a 30 hPa injection, despite a smaller sulfate burden.

Post-volcanic surface temperature anomalies result from the impact of aerosol on atmospheric radiative transfer, which is often quantified as radiative forcing (W m^{-2}). The radiative impact of the simulated eruptions is quantified through the top-of-atmosphere net radiative anomalies: since the simulations are performed with fixed sea surface temperatures (SST) and sea ice, this is equivalent to the "fixed SST" version of effective radiative forcing (ERF)[35,36]. Simulated global mean ERF anomalies for extratropical eruptions (Supplementary Fig. 6) at 30 hPa are smaller than that of corresponding tropical eruptions in the ensemble mean, although this difference is as small as 15%, and in many cases the ensemble range for extratropical eruptions overlaps with that of tropical eruptions. Global mean ERF anomalies for extratropical LMS injections range from 57-91% smaller than for tropical eruptions.

Impact of volcanic radiative forcing in the NH extratropics

Modelling studies suggest that regional surface temperature responses to external radiative forcing depend on the structure of the forcing, and that NH extratropical temperatures respond predominantly to extratropical forcing[37]. Since the NH tree ring-based temperature reconstructions explored above are based on samples collected in the mid-to high latitudes, we examine the simulated radiative forcing in the NH extratropics (NHext = 30-90°N).

Aerosol from extratropical eruptions is heavily concentrated within the NH (Fig. 2), and particularly within the NHext where SAOD resulting from extratropical 30 hPa eruptions peak at values up to 2-3 times larger than those of tropical 30 hPa injections (Fig. 4a,b). As a result, NHext-averaged ERF (Fig 4c,d) from extratropical 30 hPa injections is stronger than that from tropical 30 hPa injections. Three-year cumulative NHext-averaged ERF (Fig 4e) from extratropical 30 hPa January injections are 70-80% stronger than the average of tropical 30 hPa injections. Extratropical 30 hPa July injections, in contrast, produce cumulative NHext-averaged ERF of -3 to +34% compared to tropical eruptions, indicating a strong sensitivity to eruption season. Differences between tropical and extratropical injections are also apparent in the time evolution of ERF: for January eruptions (Fig. 4c), peak ERF values for tropical 30 hPa and extratropical lower stratosphere injections occur within the first four months, while ERF for extratropical 30 hPa injections peaks 6 months after the eruption during NH summer. For July eruptions (Fig. 4b), the peak forcing from extratropical injections occurs within the summer of eruption, while that of tropical 30 hPa injections occurs 6-9 months later, during NH winter and spring.

Results described above challenge the perception that extratropical eruptions are less climatically important than tropical eruptions. While simulated SAOD and ERF are weaker for NH extratropical eruptions than for tropical eruptions in the global mean, the hemispheric confinement of aerosol results in stronger radiative anomalies over the NH, with NHext ERF for extratropical eruptions up to 80% stronger than tropical eruptions. This result is consistent with the stronger ΔT-to-VSSI ratio for extratropical eruptions in tree ring based NH temperature reconstructions. While the tree rings imply a stronger difference between ΔT-to-VSSI ratios for extratropical and tropical eruptions than model-based differences in radiative forcing, an 80% stronger response to extratropical eruptions lies within the 2σ uncertainty range of the percent differences in ΔT-to-VSSI ratio between extratropical and tropical eruptions. Furthermore, quantitative differences between tree ring-based ΔT-to-VSSI ratios and model-based radiative forcing may reflect non-linearity in temperature sensitivity to spatially inhomogeneous radiative forcing[38], and uncertainties in proxy-based estimates. We note particularly that quantitative agreement between ΔT-to-VSSI ratios and modeled radiative forcing is much closer if VSSI values for extratropical eruptions were calculated using the same transfer function as for tropical eruptions (Table 1).

Implications for past and future extratropical eruptions

Past reconstructions of volcanic forcing have assumed short stratospheric lifetimes and weak radiative forcing of aerosol from extratropical eruptions. Our modeling experiments confirm a shorter aerosol lifetime for extratropical injections, however, for a constant injection height in the stratospheric overworld, the effect is as little as 10%. Our simulations demonstrate that the lifetime of stratospheric aerosol from extratropical injections is strongly connected to the injection height within the stratosphere. The assumption of a short lifetime for extratropical eruptions in previous work[4] is likely tied to an implicit assumption of lower injection heights. However, volcanic plume models suggest that plume heights have weak dependence on eruption latitude[39,40], and estimated maximum plume heights for the 1912 Katmai (58°N) eruption based on estimated mass eruption rates and tephra dispersal reach 28 km[41], comparable to that of Pinatubo. Prior reconstructions of volcanic forcing, for example those[5,42] used in simulations of the Last Millennium as part of the fifth phase of the Coupled Model Intercomparison Project[43], appear to underestimate the climate impact of extratropical eruptions relative to tropical eruptions (Supplementary Fig. 7). More accurate reconstruction of the magnitude and timing of past extratropical eruptions, and the optical properties of the associated stratospheric aerosol, may increase the proportion of temperature variability attributable to external forcing.

Strong sensitivity of simulated radiative forcing to the season and injection height of extratropical eruptions—resulting from impacts on stratospheric lifetime, aerosol effective radius and phasing between SAOD and incoming solar radiation[27]—is consistent with the scatter in the relationship between tree ring-derived cooling and VSSI for extratropical eruptions. Reconstructions of volcanic forcing could therefore benefit from information of season and injection height. Information on eruption season has been obtained in some cases from high resolution analysis of ice cores[44], historical records[20,45], and geochemical analysis of volcanic tephra in ice cores[46–48]. Analysis of the isotopic composition of ice core sulfate has been suggested as indicative of the height reached by the sulfate aerosol[49–51], although this approach has been criticized on the basis that isotopic sulfur fractionation is related to the height of aerosol with respect to the peak in the vertical profile of extratropical ozone concentration rather than with respect to the tropopause[9]. Our model results suggest that aerosol lifetime varies throughout the extratropical lower stratosphere, with an important threshold being the interface between the LMS and overworld, which is comparable to the level of peak ozone concentration. Thus, our results support the utility of sulfur isotope analysis for providing valuable information on volcanic radiative forcing.

Volcanic eruptions with large VSSI have been less frequent in the extratropics than in the tropics over recent centuries (Fig. 1). Many of the largest ice core sulfate signals from extratropical eruptions originate from eruptions like Laki (1783/84 CE) that were at least partly effusive[52]. In other cases, extratropical eruptions with large erupted mass like Changbaishan (946 CE)[53] appear to have had a small VSSI. A clear example of an extratropical explosive eruption with strong VSSI is that of the ca. 536 CE eruption, which produced solar dimming lasting over a year[54], leading to some of the coldest NH temperatures of the Common Era. The Common Era is however a short sample in geological terms, and the (admittedly incomplete[55])

Holocene volcanic record[28] suggests major (VEI ≥ 5) eruptions are just as common in the NH extratropics as in the tropics. Extratropical volcanic eruptions with large sulfur injections into the stratospheric overworld have occurred in the past, and they will in the future. Our results suggest that rather than reducing the radiative forcing and climate impact of such major eruptions, the extratropical eruption latitude acts primarily to focus the radiative impacts within the NH, strengthening its hemispheric climate impact.

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Author Contributions

M.T., K.K., C.T. and H.S. designed the model experiments. M.T. performed the model simulations and analysis with input from K.K., C.T., and H.S. M.T. performed the analysis of tree-ring temperature reconstructions and volcanic stratospheric sulfur injections with input from M. Sigl, M. Stoffel and R.W. M.T. led the manuscript writing with input from all coauthors.

Competing Financial Interests statement

The authors declare no competing financial interests.

Tables

Table 1: Ratios of hemispheric temperature anomalies to stratospheric sulfur injection (VSSI) ratios for tropical and NH extratropical explosive eruptions. Mean $\Delta T/VSSI$ values over the tropical ("trop") and extratropical ("extrop") events listed in Supplementary Tables 4 and 5, with 1σ standard error of the mean are listed for the N-TREND[19], STO15[20], SCH15[21] and NH temperature reconstructions, along with that from the composite mean of the three reconstructions (ALL). Percent differences between mean extratropical and tropical $\Delta T/VSSI$ values are listed with 1σ uncertainties. Percent differences between mean extratropical and tropical $\Delta T/VSSI$ values are repeated in the final row with VSSI for extratropical eruptions adjusted ($VSSI^{*} = VSSI/0.57$) such that the scaling from ice core sulfate flux to VSSI is the same for both tropical and extratropical eruptions.

	N-TREND	STO15	SCH15	ALL
$\left.\frac{\Delta T}{VSSI}\right\vert_{\text{trop}}$ (°C [Tg S]$^{-1}$)	-0.019 ± 0.006	-0.036 ± 0.009	-0.021 ± 0.003	-0.025 ± 0.005
$\left.\frac{\Delta T}{VSSI}\right\vert_{\text{extrop}}$ (°C [Tg S]$^{-1}$)	-0.081 ± 0.020	-0.102 ± 0.024	-0.059 ± 0.018	-0.080 ± 0.018
$\left.\frac{\Delta T}{VSSI}\right\vert_{\text{extrop}} - \left.\frac{\Delta T}{VSSI}\right\vert_{\text{trop}}$ (%)	330 ± 150	180 ± 82	180 ± 94	220 ± 85
$\left.\frac{\Delta T}{VSSI^{*}}\right\vert_{\text{extrop}} - \left.\frac{\Delta T}{VSSI}\right\vert_{\text{trop}}$ (%)	150 ± 87	58 ± 47	61 ± 54	81 ± 48

Figures

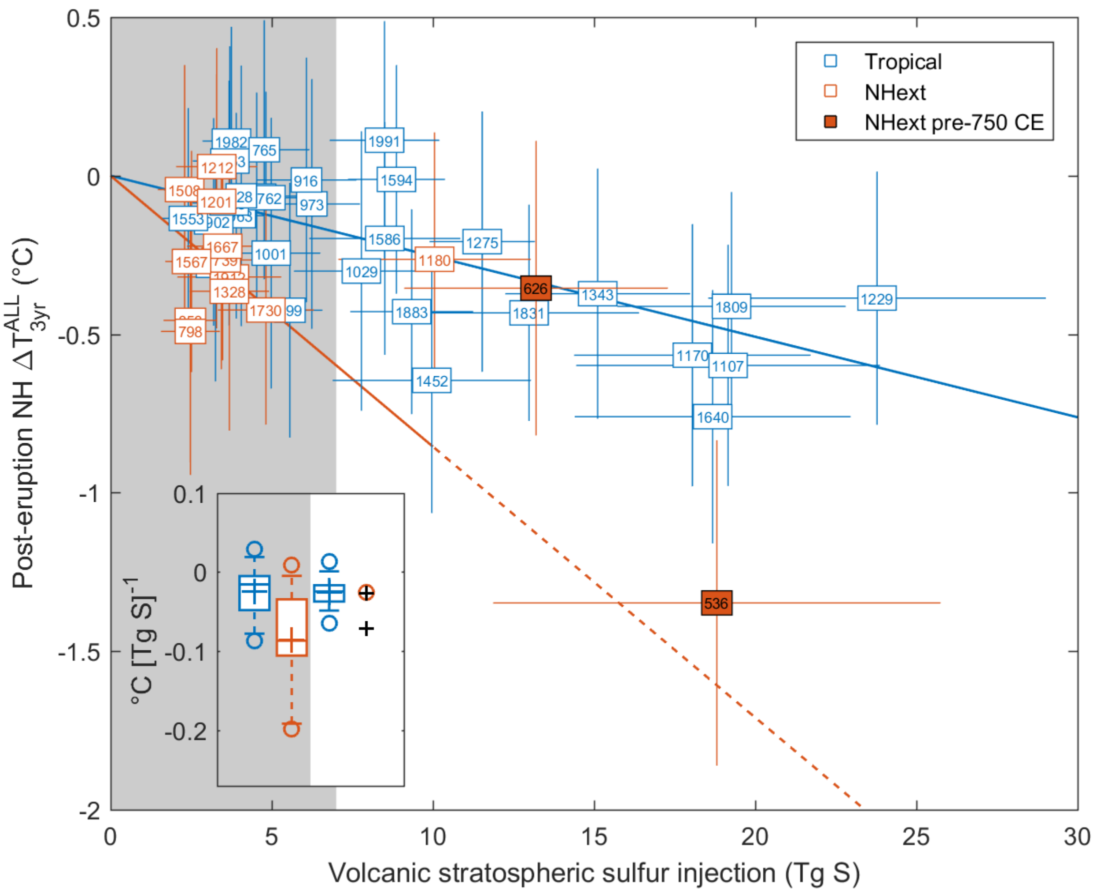

Figure 1: Reconstructed post-volcanic NH temperature response to NH extratropical and tropical eruptions in relation to volcanic stratospheric sulfur injection. Three-year mean temperature anomalies (ΔT^{ALL}_{3yr}) are plotted versus estimated volcanic stratospheric sulfur injection (VSSI, Tg [S]) for (blue) tropical and (orange) extratropical explosive eruptions. Number labels indicate eruption years. Vertical and horizontal error bars represent ±1σ uncertainties. The 1257 Samalas eruption (see Supplementary Table 4), lies outside the chosen limits of the plot. Colored lines indicate the mean ΔT-to-VSSI ratio for both tropical and extratropical eruptions after 750 CE. Temperature anomalies for NH extratropical events before 750 CE are shown with orange-filled markers. **Inset panel** shows boxplots of the distribution of three-year

mean NH temperature anomalies per unit VSSI. Boxplots are shown separately for eruptions with VSSI less than (gray shading on both plots) and greater than 7 Tg S. Crosses denote the distribution mean, horizontal line the median, box the 25-75% interquantile range, whiskers the 1-99% interquantile range, and outliers are marked with circles. For extratropical eruptions with VSSI>7 Tg S, markers show cooling-to-VSSI ratios for individual eruptions in orange (post-750 CE) and black (pre-750 CE).

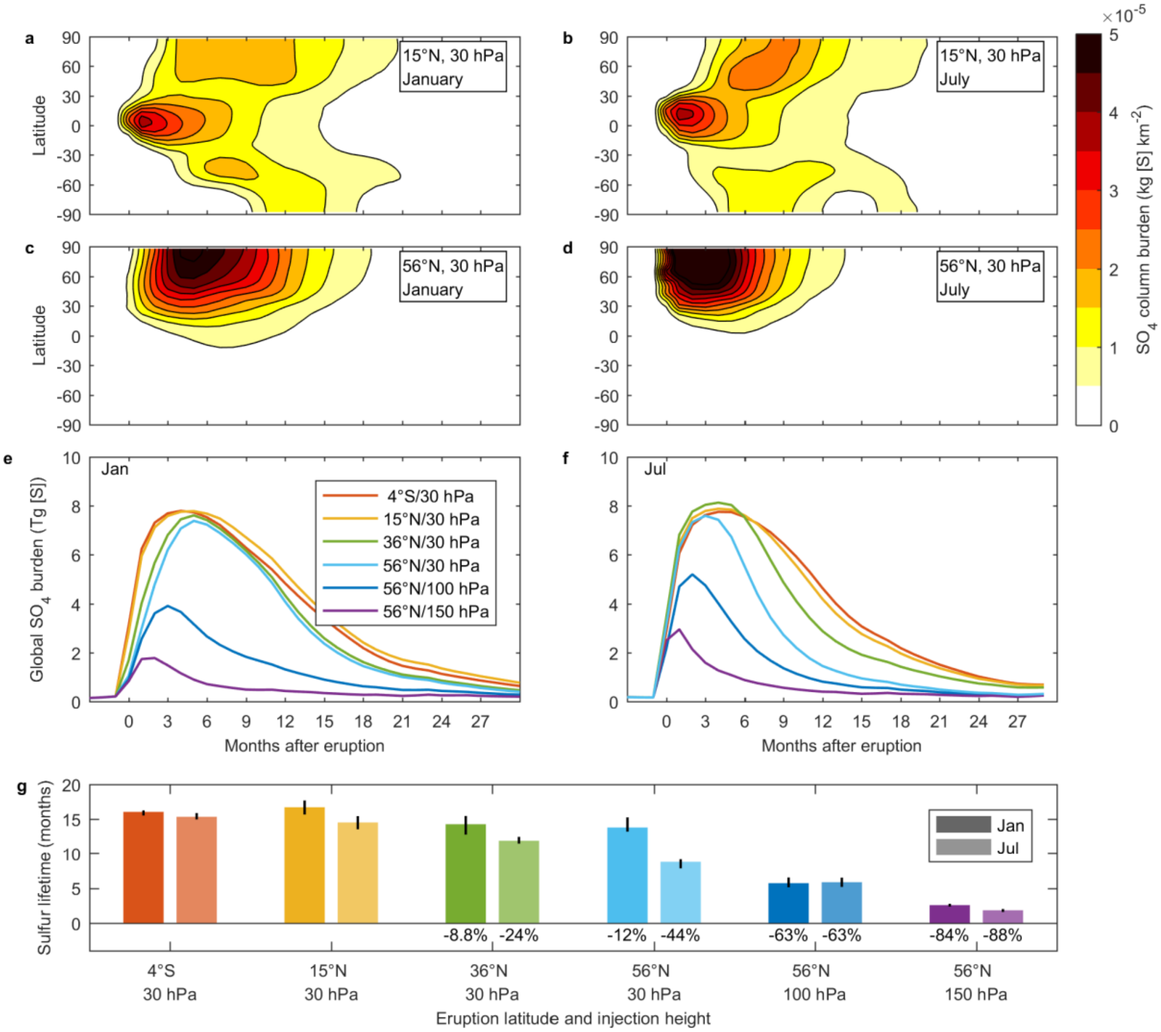

Figure 2: Simulated volcanic stratospheric aerosol burdens and lifetimes for varying eruption latitude, season and injection height. Ensemble mean zonal mean aerosol burdens (in kg [S] km^{-2}) are shown for (a, b) tropical (15°N) and (c, d) extratropical (56°N) eruptions of 8.5 Tg S in (a, c) January and (b, d) July. Ensemble mean global sulfur burden (Tg [S]) time series are shown (e, f) for the six simulated injection locations. Line colors denote injection latitude and heights as listed in legend of panel (e). In panel (g) stratospheric sulfur e-folding lifetimes are shown for each eruption latitude and injection height, with black whiskers indicating the full ensemble spread. For the extratropical injection cases, text labels show the percent difference of sulfur e-

folding lifetime with respect to the mean of the tropical (4°S and 15°N, 30 hPa) injection eruption simulations.

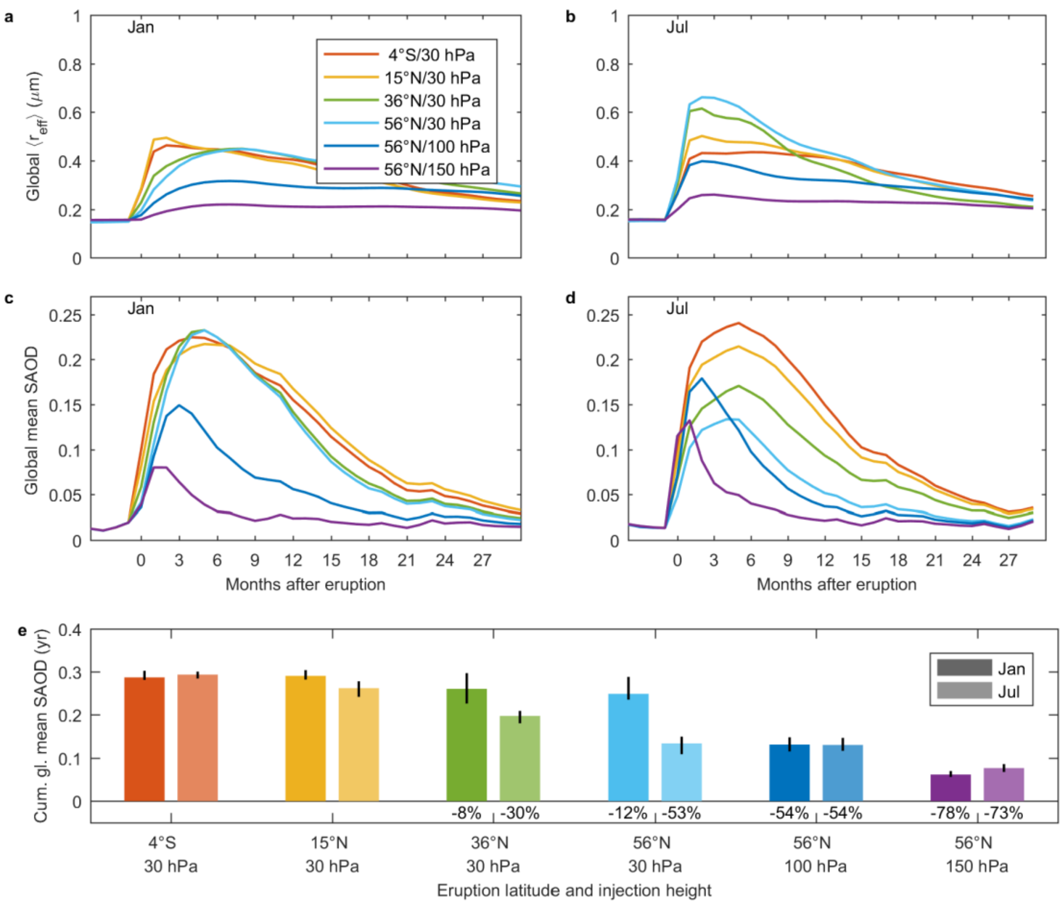

Figure 3: Simulated global mean volcanic aerosol properties for varying eruption latitude, season and injection height. Panels show (a, b) ensemble mean sulfate-weighted effective radius ($\langle r_{\mathrm{eff}} \rangle$), and (c,d) ensemble mean stratospheric aerosol optical depth (SAOD), from simulated eruptions of 8.5 Tg S in (left) January and (right) July. Line colors denote injection latitude and heights as listed in legend of panel (c). Three-year cumulative SAOD is shown in panel (e) as a function of injection latitude and height, with black whiskers indicating the full ensemble spread. For the extratropical injection cases, text labels show the percent difference of cumulative SAOD with respect to the mean of the tropical (4°S and 15°N, 30 hPa) injection eruption simulations.

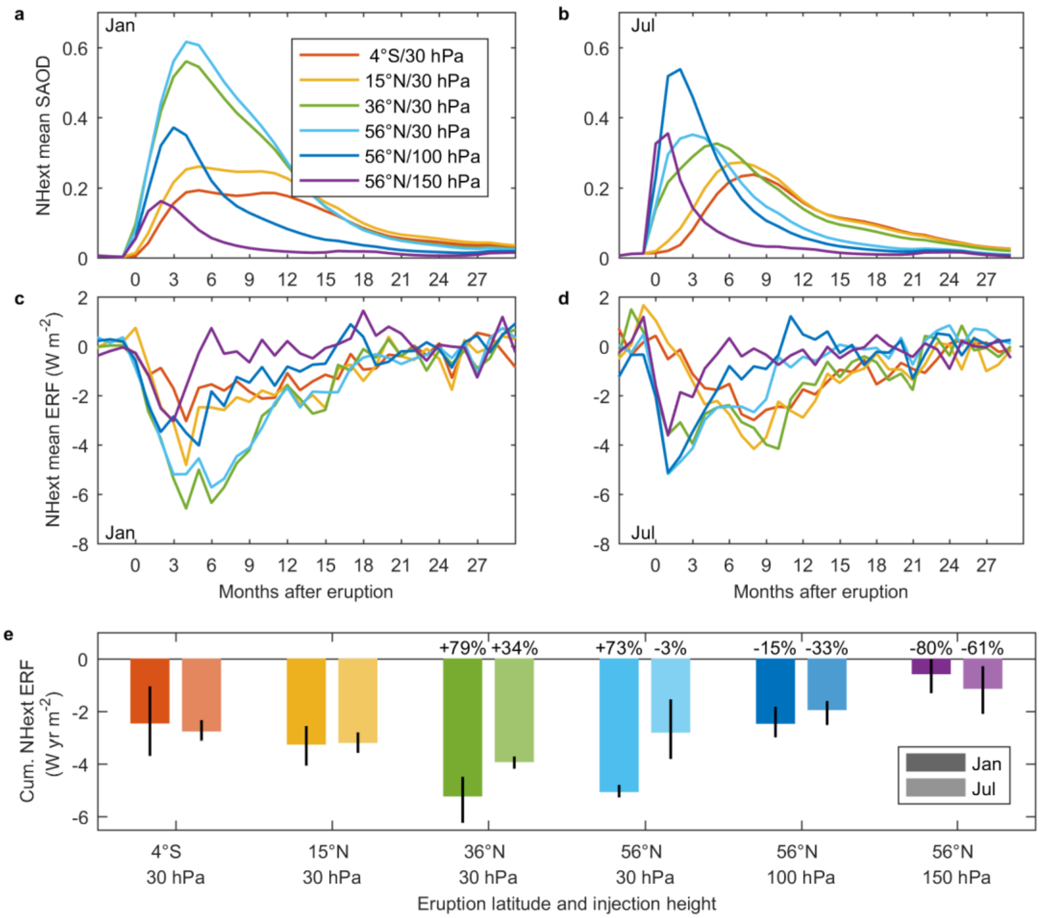

Figure 4: Simulated volcanic SAOD and effective radiative forcing over the NH extratropics (30-90°N) for varying eruption latitude, season and injection height. Shown are (a,b) SAOD and (d,e) effective radiative forcing (ERF) for simulated eruptions of 8.5 Tg S in (left) January and (right) July. Line colors denote injection latitude and heights as listed in legend of panel (a). Three-year cumulative NHext ERF is shown in panel (e) as a function of injection latitude and height, with black lines indicating the full ensemble spread. For the extratropical injection cases, text labels show the percent difference of cumulative ERF with respect to the mean of the tropical (4°S and 15°N, 30 hPa) injection eruption simulations.

Methods

Volcanic stratospheric sulfur injections

Volcanic stratospheric sulfur injection (VSSI) estimates before 1900 CE are taken from the eVolv2k database[22], based on analysis of bipolar ice core arrays. For the 20th Century, satellite observations[7] are used for estimates of VSSI for Pinatubo (1991) and El Chichón (1982). For eruptions between 1900 and the start of the satellite era, we used Antarctic and Greenland ice core sulfate fluxes from the ICI reconstruction of Ref 42, and applied the scaling methodology used in the construction of eVolv2k. Categorization of eruptions as tropical or extratropical is provided by the eVolv2k reconstruction based on the presence or lack of bipolar ice core sulfate signals, or from observations for 20th Century eruptions. Eruption years for unidentified tropical eruptions are adjusted one year earlier than listed in the eVolv2k database, to account for the typical 1-year lag between eruption and ice sheet deposition. All unidentified eruptions are thereafter assumed to have a dating uncertainty of ±1 year for 1750-1900 CE and ±2 years from 500-1750 CE.

Post eruption Northern Hemisphere temperature anomalies

Based on the compiled VSSI record, we first select tropical and NH extratropical volcanic events between 500-2000 CE with estimated VSSI greater than 2 Tg S. From this list, in order to exclude events in which cooling from the eruption in question may be superimposed on the return to normal conditions after a preceding eruption, we exclude events for which an eruption of magnitude greater than 2 Tg S occurred within the preceding 6 years, and also those for which an event greater than 10 Tg S occurred within the preceding 10 years. This process excluded 17 eruptions (Supplementary Table 1), including well known examples such as

Tambora (1815) and an unidentified eruption of ca. 1457 CE. Extratropical eruptions which are known or suspected to have been characterized by some degree of effusive eruption style, including the strong Icelandic “fire” eruptions of Laki (1783-84) and Eldgjá (939) have also been excluded (Supplementary Table 2): the remaining extratropical events are assumed to represent extratropical explosive events although it should be clear that this list likely includes signals from additional Icelandic effusive events.

For each volcanic event, NH summer temperature anomalies are constructed using three recent reconstructions [19–21]. First, based on a simple mean of the three reconstructions, eruption dates for unidentified eruptions are adjusted within the dating uncertainty to maximize the post-eruption 3 year mean cooling anomaly. This adjustment aims to take into account uncertainty in the dating of the ice core signals, but also the possible shift related to eruptions occurring before or after summer of any calendar year. Temperature anomalies for each event and each temperature reconstruction are then calculated with respect to the preceding 5 years. Given an estimated eruption at year y_0, NH 3 year mean temperature anomalies ($\Delta T_{3\mathrm{yr}}$) are calculated as follows for tropical and NH extratropical eruptions:

	Tropical eruption	NH extratropical eruption
$\Delta T_{3\mathrm{yr}}$: Three year mean anomaly	$\frac{1}{3}\sum_{i=1}^{3} T_{y_0+i} - \frac{1}{5}\sum_{i=-5}^{-1} T_{y_0+i}$	$\frac{1}{3}\sum_{i=0}^{2} T_{y_0+i} - \frac{1}{5}\sum_{i=-5}^{-1} T_{y_0+i}$

Uncertainties (σ) in the tree ring-based temperature reconstructions are taken from the original data sets. Uncertainties in post volcanic three year temperature anomalies and multireconstruction means are calculated using reported uncertainties and standard rules of error propagation.

MAECHAM5-HAM

Simulations of volcanic stratospheric sulfur injections are performed with the aerosol-climate model MAECHAM5-HAM [26,56,57]. The spatial resolution is ~2.8° by 2.8°, with T42 spectral truncation and 39 vertical levels up to 0.01 hPa (~80 km). The atmospheric component of the model is free running, while sea surface temperatures are prescribed as an annually repeating climatology.

Volcanic simulations are initiated by the injection of SO_2 into a specified model grid box and height. A sulfur chemistry module converts SO_2 to H_2SO_4 via the reactions:

$$SO_2 + OH + M \rightarrow HSO_3 + M \tag{1}$$

$$HSO_3 + O_2 \rightarrow HO_2 + SO_3 \tag{2}$$

$$SO_3 + H_2O \rightarrow H_2SO_4 \tag{3}$$

The rate of SO_2 to H_2SO_4 conversion depends on concentrations of hydroxyl radical (OH) taken from prior chemistry–climate model simulations[58]. The use of prescribed OH concentrations neglects potential changes in H_2SO_4 production rates due to local consumption of OH, which is thought to play an important role for extremely large eruptions[59]. The prescribed monthly mean OH fields contain significant spatial structure (Supplementary Fig. 5), with very low concentrations in polar winter due to the dependence of OH production on solar insolation. There is also a strong vertical gradient in OH concentrations through the lower and middle stratosphere, due to changes in solar ultraviolet radiative flux and the availability of H_2O, which has a minimum around the level of the tropopause.

After oxidation of the volcanic SO_2 source gas, H_2SO_4 condenses with water to form sulfate (SO_4) aerosol. Aerosol processes in MAECHAM5-HAM are calculated by the aerosol microphysical module HAM[60], and include aerosol formation and growth via nucleation, condensation, accumulation, and coagulation; vertical redistribution via sedimentation; and finally the removal processes wet and dry deposition.

Pinatubo-magnitude simulations with MAECHAM5-HAM have resulted in good agreement with observations in terms of the aerosol optical depth (AOD), top of atmosphere short-wave radiation anomalies, and aerosol effective radius[26,56]. The MAECHAM5-HAM configuration used here has no quasi-biennial oscillation (QBO): winds in the equatorial stratosphere are easterly throughout the year, and therefore variability of stratospheric dynamics[61] and aerosol transport related to the QBO are not included in the simulations. The decay of simulated AOD was found to be slightly faster than that observed, which is perhaps related to a slight high-bias in the simulated aerosol effective radius[56]. On the other hand, consistency in the timing of extratropical AOD peak values suggests the model reproduces well the seasonal variation in aerosol transport[26]. For tropical eruptions of Pinatubo magnitude and below, the model produces a linear relationship between radiative forcing and VSSI[62].

Model experiments

To isolate the impact of eruption latitude on the aerosol evolution and resulting radiative forcing, we performed ensemble MAECHAM5-HAM simulations with a fixed magnitude of volcanic stratospheric sulfur injection at various latitudes, months and injection heights. We choose the estimated VSSI of the 1991 eruption of Pinatubo (17 Tg SO_2 or equivalently 8.5 Tg [S] injection), since observations of the Pinatubo aerosol provide the best estimates of sulfur injection, aerosol evolution and radiative forcing of any major volcanic eruption, making it a standard modeling validation experiment. Simulation eruption locations are chosen based on the global distribution of identified volcanic eruptions with Volcanic Explosivity Index equal to or greater than 5 (Supplementary Fig. 2) according to the Volcanoes of the World (VOTW) database[28]. Four 10-degree latitude ranges contain 57% of all VEI ≥ 5 eruptions in the VOTW database: in order of eruption frequency, these latitude bands are 50-60°N, 30-40°N, 0-10°S, and 10-20°N. For each of these four latitude ranges, we chose a "typical" eruption location, roughly consistent with the highest density of identified eruptions, sampling global eruptions hot spots including Indonesia, Central America, Japan and Alaska (Supplementary Table 6). The chosen eruption locations are spread evenly between the western and eastern coasts of the Pacific Ocean, although model simulations suggest no significant impact of the eruption longitude on the aerosol evolution following explosive tropical eruptions[26]. To include the potential impacts of eruption season, simulations are performed with eruptions in both January and July. This choice of months is somewhat arbitrary, but is motivated by: (1) the common use of January 1 as a standard eruption date for eruptions on unknown eruption timing in volcanic forcing reconstructions[22,42]; (2) the rough agreement of July 1 with the actual seasonal timing of the Pinatubo eruption (on June 15, 1991); and (3) the fact that NH radiative anomalies from January and July tropical eruptions nearly span the full range of SAOD and radiative forcing seen in model simulations using a fuller sample of eruption season distribution[26]. Since the spatial spread of aerosol is sensitive to the meteorological conditions at the time of the eruption[63], ensembles of simulation were performed. For each of the four eruption locations, we performed ten MAECHAM-HAM eruption simulations with SO_2 injection at 30 hPa (~23 km), five simulations each for injections in January and July. To investigate the impact of injection height for extratropical eruptions, simulations at 56°N were repeated with injection heights of 100 hPa (~16 km) and 150 hPa (~13 km), with again, five simulations for January eruptions, and five simulations for July eruptions.

A 30 year control run was performed with no stratospheric sulfur injections, with all other boundary conditions and forcings identical to the eruptions simulations.

Model output

Sulfate aerosol column burdens and stratospheric aerosol optical depth (SAOD) are output directly by the model, and zonal means over the full globe and the NH extratropics were calculated using area-weighted means. Stratospheric sulfur lifetimes are calculated as the time taken for the total sulfur (SO_2 + H_2SO_4) to cross $1/e$ of the injected amount—this metric is typically longer than lifetimes calculated based on the decay of sulfate after its peak value, but is a better measure of the efficiency of loss processes since the timing of the sulfate peak also depends on the rate of SO_2-to-H_2SO_4 conversion. Sulfate aerosol effective radius (r_{eff}), a function of height, latitude and longitude, was averaged in space using sulfate aerosol mass as a weighting function. The resulting sulfate-mass-weighted, $\langle r_{\mathrm{eff}} \rangle$, represents the typical r_{eff} in the region of the most sulfate aerosol, which will dominate the radiative transfer calculations. Net (shortwave + longwave) top of atmosphere (TAO) radiative anomalies were calculated as the difference radiative fluxes between each eruption simulation and the control run climatology, corresponding to the "fixed SST" effective radiative forcing (ERF) quantity[35,36].

Data availability

Volcanic stratospheric sulfur injection estimates used in this study are available in the World Data Center for Climate hosted by the German Climate Computing Center (DKRZ) with the identifier doi:10.1594/WDCC/eVolv2k_v1. NH temperature reconstructions used are available from the NOAA/World Data Service for Paleoclimatology archives via links https://www.ncdc.noaa.gov/paleo-search/study/19743, https://www.ncdc.noaa.gov/paleo-search/study/19039, and https://www.ncdc.noaa.gov/paleo-search/study/18875.

Code availability

The Matlab scripts used for the analyses described in this study can be obtained from the corresponding author upon reasonable request.

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