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Key Points:

- Models and tree rings show no evidence of greatly enhanced regional cooling from extratropical eruptions versus comparable tropical ones
- Extratropical eruptions cool the extratropics no more than is accounted for by the fact that the aerosols are confined to one hemisphere
- Extratropical eruptions have overall historically caused less cooling of the Northern Hemisphere extratropics than tropical eruptions

Supporting Information:

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

Correspondence to:

Z. McGraw,
zachary.mcgraw@univie.ac.at

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Author Contributions:

Conceptualization: Zachary McGraw, Lorenzo M. Polvani

Data curation: Zachary McGraw, Benjamin O. Goldman

Formal analysis: Zachary McGraw, Benjamin O. Goldman

Funding acquisition: Lorenzo M. Polvani

Investigation: Zachary McGraw, Benjamin O. Goldman

Methodology: Zachary McGraw, Lorenzo M. Polvani

Project administration: Lorenzo M. Polvani

Resources: Lorenzo M. Polvani

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No Evidence for Strongly Enhanced Northern Hemisphere Cooling From Extratropical Versus Tropical Eruptions

Zachary McGraw^{1,2,3} , Benjamin O. Goldman¹ , and Lorenzo M. Polvani^{1,4,5}

¹Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, USA, ²NASA Goddard Institute for Space Studies, New York, NY, USA, ³Now at Department of Meteorology and Geophysics, University of Vienna, Vienna, Austria, ⁴Department of Earth and Environmental Sciences, Columbia University, New York, NY, USA, ⁵Division of Ocean and Climate Physics, Lamont-Doherty Earth Observatory, Palisades, NY, USA

Abstract Volcanic eruptions in the Northern Hemisphere extratropics have been reported to produce several times greater cooling in that region than tropical eruptions of similar magnitude. Using a large ensemble of simulations spanning the eruption size range from 5 to 40 Tg of stratospheric sulfur, we find that the extratropical-to-tropical cooling ratio is consistently within a factor of two, indicating no enhancement beyond the effect of aerosols being confined to a single hemisphere. We further show that paleoclimate evidence suggests similarly unexceptional cooling, and also reconcile why earlier analyses yielded unreliable estimates. Moreover, owing to their rarity, we argue that extratropical eruptions exert a smaller overall influence on Northern Hemisphere extratropical temperatures than tropical eruptions. These findings question the notion that extratropical eruptions are of outsized importance for the climate of the Northern Hemisphere.

Plain Language Summary Volcanic eruptions can cool Earth's surface for years by spreading reflective aerosols through the stratosphere. Recent analyses have suggested that eruptions in the Northern Hemisphere extratropics cool this region several times more than comparable tropical eruptions. Using a large ensemble of climate model simulations, we show this is not the case: an extratropical eruption cools the Northern Hemisphere by no more than twice a similar-size tropical eruption, consistently with aerosols being largely confined to one hemisphere after extratropical eruptions but spread between both hemispheres after tropical eruptions. We also analyze temperature reconstructions, which confirm our finding, and explain methodological issues affecting earlier suggestions of a stronger cooling enhancement. Due to the rarity of large extratropical eruptions, we suggest that such events pose a smaller overall climatic risk than tropical eruptions, even in the extratropics.

1. Introduction

While most climate-relevant volcanic eruptions occur in tropical regions, recent studies have suggested an outsized influence of extratropical eruptions on Northern Hemisphere extratropical (NHET) temperature (Burke et al., 2023; Toohey et al., 2019). A twofold enhancement in NHET cooling is expected because aerosols from extratropical eruptions remain within one hemisphere, whereas tropical eruptions distribute aerosols across both. However, much larger enhancement factors have been reported, implying potentially strong climate anomalies and societal risks from extratropical eruptions. Conversely, tropical eruptions have been evidenced to exert more limited cooling effects than previously held (Anchukaitis et al., 2012; McGraw et al., 2024; Timmreck et al., 2009). Here, we use a large simulation ensemble and paleoclimate proxies to revisit claims of an outsized extratropical eruption impact on NHET temperatures.

The first suggestion of outsized NHET cooling potential from extratropical eruptions is found in Toohey et al. (2019). Comparing tree ring temperature reconstructions with volcanic stratospheric sulfur injection (VSSI) estimates from ice cores, they reported 3.2× greater NHET cooling from extratropical versus tropical eruptions of similar magnitude. However, acknowledging large uncertainties in the paleoclimate records, they also presented simulations indicating a smaller enhancement of 1.3–1.8×. Burke et al. (2023) later revisited this metric and obtained a substantially higher enhancement of 7.5×—far beyond any known physical explanation. In addition to revising several ice-core sulfur estimates, they introduced two methodological changes. First, they added two large extratropical eruptions from 536 to 626 CE that had been excluded from the statistical analysis of Toohey et al. (2019) due to the paucity of pre-750 CE tree ring temperature records outside Siberia and northern Scandinavia (Schneider et al., 2015a; Wilson et al., 2015). Second, whereas Toohey et al. (2019) produced cooling

Supervision: Lorenzo M. Polvani

Visualization: Zachary McGraw,
Benjamin O. Goldman

Writing – original draft:
Zachary McGraw

Writing – review & editing: Benjamin
O. Goldman, Lorenzo M. Polvani

efficiency estimates by averaging eruption-specific cooling-to-VSSI ratios separately for extratropical and tropical eruptions, Burke et al. (2023) instead compared linear regressions across all eruptions of each type in cooling-VSSI space.

The challenge of constraining the cooling efficiency of extratropical eruptions is illustrated by three well-studied cases: the 1783 CE Laki eruption in Iceland, a 536 CE eruption of unknown extratropical origin, and the 43 BCE eruption of Mt. Okmok in Alaska. For Laki, post-eruption cooling is confounded by direct volcanic impacts on tree rings (Edwards et al., 2022), while sparse tree-ring coverage of the 536 CE and 43 BCE events limits constraints on the magnitude and spatial extent of cooling. Further, VSSI estimates for all three eruptions are uncertain because Greenland ice core proximity complicates separation of stratospheric from tropospheric deposition (Peccia et al., 2023; Toohey & Sigl, 2017). Notably, only the 536 CE eruption has been examined in either of the two extratropical cooling enhancement studies. Yet all three eruptions have been linked to major societal disruptions: Laki to the onset of the French Revolution (Witze & Kanipe, 2014), the 536 CE event to crises in Scandinavia (Toohey, Krüger, et al., 2016; van Dijk et al., 2023), and Okmok to the decline of the Roman Republic and Ptolemaic Kingdom (McConnell et al., 2020). This discourse motivates improved constraints on NHET cooling to evaluate proposed links to past crises and assess future risks.

In this study, we assess NHET cooling from extratropical eruptions in a large ensemble of model simulations and critically reevaluate the paleoclimate evidence for outsized cooling from extratropical eruptions. Our ensemble samples a wide range of eruption scenarios, enabling us to comprehensively test prior claims while robustly isolating volcanic signals from internal climate variability. We find that simulated extratropical eruptions do not exceed the expected twofold cooling enhancement from hemispheric aerosol confinement, while previously suggested greater enhancement factors likely reflect methodological limitations.

2. Methods

2.1. GISS ModelE2.2 Simulation Ensembles of NHET and Tropical Eruptions

To evaluate how eruption latitude influences cooling potential, we use the NASA Goddard Institute for Space Studies (GISS) ModelE2.2 Earth system model (Orbe et al., 2020), which has been used in several prior volcano-climate studies (DallaSanta & Polvani, 2022; McGraw et al., 2024; McGraw & Polvani, 2024, 2025; Raiter et al., 2025). Because we focus on near-surface air temperature responses, all simulations include interactive ocean and sea ice components.

As no large extratropical eruptions have occurred in the modern observational era, the properties and evolution of their aerosols are highly uncertain. Volcanic forcing in climate models can be represented either interactively, via simulated aerosol microphysics and chemistry, or through prescribed forcings based on reference eruptions. Here we adopt the latter approach, using volcanic aerosol forcings generated by the Easy Volcanic Aerosol (EVA) framework (Toohey, Stevens, et al., 2016). EVA parameterizes sensitivity to eruption latitude, season, and sulfur mass using scaling relationships relative to the 1991 Pinatubo eruption. A key advantage of prescribed aerosols is methodological consistency across models, in contrast to interactive schemes that can produce divergent aerosol properties (Clyne et al., 2021; McGraw et al., 2024).

One key novelty of this paper is that we systematically examine the difference between tropical and extratropical eruptions—specifically, on the equator and at 64°N (representative of Iceland, as in Zhuo et al., 2024)—across a wide range of magnitudes, having four VSSI values: 5, 10, 20, and 40 Tg of sulfur (hereafter TgS), as well as two eruption dates (15 June and 15 December). And crucially, for each combination of eruption parameters, we perform a 10-member ensemble via perturbed initial conditions. This allows us to extract the *forced response* (i.e., the ensemble mean) from the typically large internal variability, yielding 160 simulations ($10 \times 4 \times 2 \times 2$) in total. We follow the protocol of DallaSanta and Polvani (2022), who produced the equatorial June cases used herein. In what follows, NHET temperature averages are computed specifically across land regions north of 30°N to facilitate comparison with tree ring reconstructions.

We wish to emphasize that the EVA-derived volcanic forcings used for our extratropical eruptions represent a *high* estimate of their potential cooling relative to the better-constrained tropical eruptions, as shown in the top row of Figure 1. Here we compare NHET-mean stratospheric aerosol optical depth at 550 nm (SAOD) from EVA forcings of Pinatubo-sized eruptions (here 9 TgS) to equivalent cases simulated with interactive aerosol models for prior studies: the MAECHAM5-HAM model results from Toohey et al. (2019; dashed lines), and the

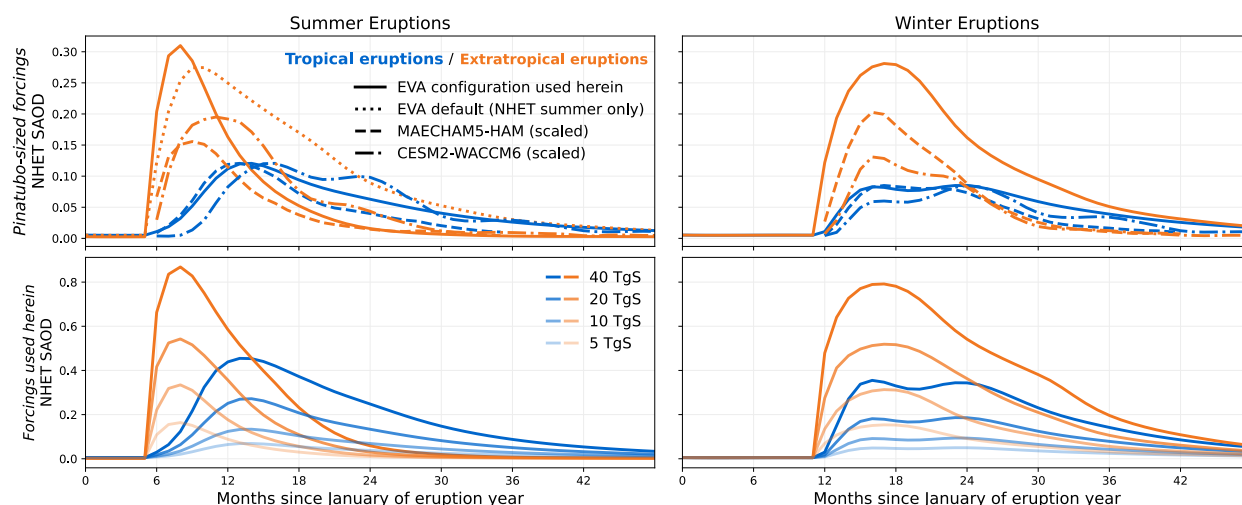


Figure 1. Stratospheric aerosol optical depth averaged over the NHET region. Left: summer eruptions (June 15); right: winter eruptions (December 15). Top row: SAOD for Pinatubo-size NHET eruptions, from our modified easy volcanic aerosol (EVA) (solid lines), and from the MAECHAM5-HAM simulations from Toohey et al. (2019; their Figure 4, rescaled; dashed lines) and the CESM2-WACCM6 simulations from Zhuo et al. (2024; their Figure 6, rescaled; dash-dotted lines). The dotted orange line in the top-left panel shows the default EVA case. Bottom row: SAOD from EVA used in our simulations for 5, 10, 20 and 40 TgS eruptions.

CESM2-WACCM6 results from Zhuo et al. (2024; dash-dot lines). Because these interactive aerosol models overestimate Pinatubo SAOD relative to observations, we here visualize their NHET SAOD values rescaled so that the tropical eruptions (blue lines) match the peak NHET SAOD in EVA. Scaling factors used are as follows: MAECHAM5-HAM, 0.44 (summer) and 0.33 (winter); CESM2-WACCM6, 0.29 (summer) and 0.20 (winter). This rescaling highlights that EVA (solid lines) produces a higher extratropical-to-tropical eruption NHET SAOD ratio than either interactive aerosol model (compare the orange and blue curves of each line style), supporting that our simulated extratropical-to-tropical cooling ratios will not be underestimated.

While EVA has been used previously to simulate extratropical eruption impacts (McConnell et al., 2020; Peccia et al., 2023), we introduce one targeted modification to better match the shorter aerosol lifetime seen in MAECHAM5-HAM simulations of summer extratropical eruptions (Toohey et al., 2019). Specifically, we adjust the aerosol production and loss timescales within EVA (setting $\tau_{loss} = 5.0$, $\tau_{prod} = 3.7$). This adjustment is applied only to summer extratropical eruptions (Figure 1, top-left; solid vs. dotted orange), with default EVA parameters used otherwise. NHET SAOD for the resulting 16 mass-season-latitude scenarios is shown in the bottom row of Figure 1.

3. Results

3.1. Unexceptional Cooling Enhancement in a Large Ensemble of Eruption Simulations

We first compare NHET cooling responses from simulated extratropical and tropical eruptions across our 160-member ensemble. This framework allows us to calculate relative cooling potentials, as in Toohey et al. (2019; their Figure 1) and Burke et al. (2023; their Figure 2), but based on a well-sampled ensemble of synthetic eruptions rather than the few events available in paleoclimate records.

Figure 2a shows the peak cooling following each simulated eruption, with tropical cases in blue, extratropical in orange, and ensemble means as black circles. For completeness, the time-evolving zonal-mean and NHET-mean responses are provided in Figures S1 and S2 in Supporting Information S1, respectively. Peak cooling is calculated as minimum post-eruption June-July-August (JJA) temperature anomaly relative to a pre-eruption baseline. This method follows Burke et al. (2023), except here the minimum is chosen among the eruption year and the subsequent 2 years, relative to the mean of the six pre-eruption JJA seasons, whereas Burke et al. (2023) used only up to 1 subsequent year and three pre-eruption years.

Our first key result is that the simulations do not support the hypothesis that extratropical eruptions produce far stronger NHET cooling than tropical eruptions (compare tropical cases in blue markers to extratropical in orange). Across sulfur masses, the extratropical-to-tropical cooling ratio ranges from $1.4\text{--}1.9\times$ (1.7, 1.9, 1.6, and 1.4 for 5,

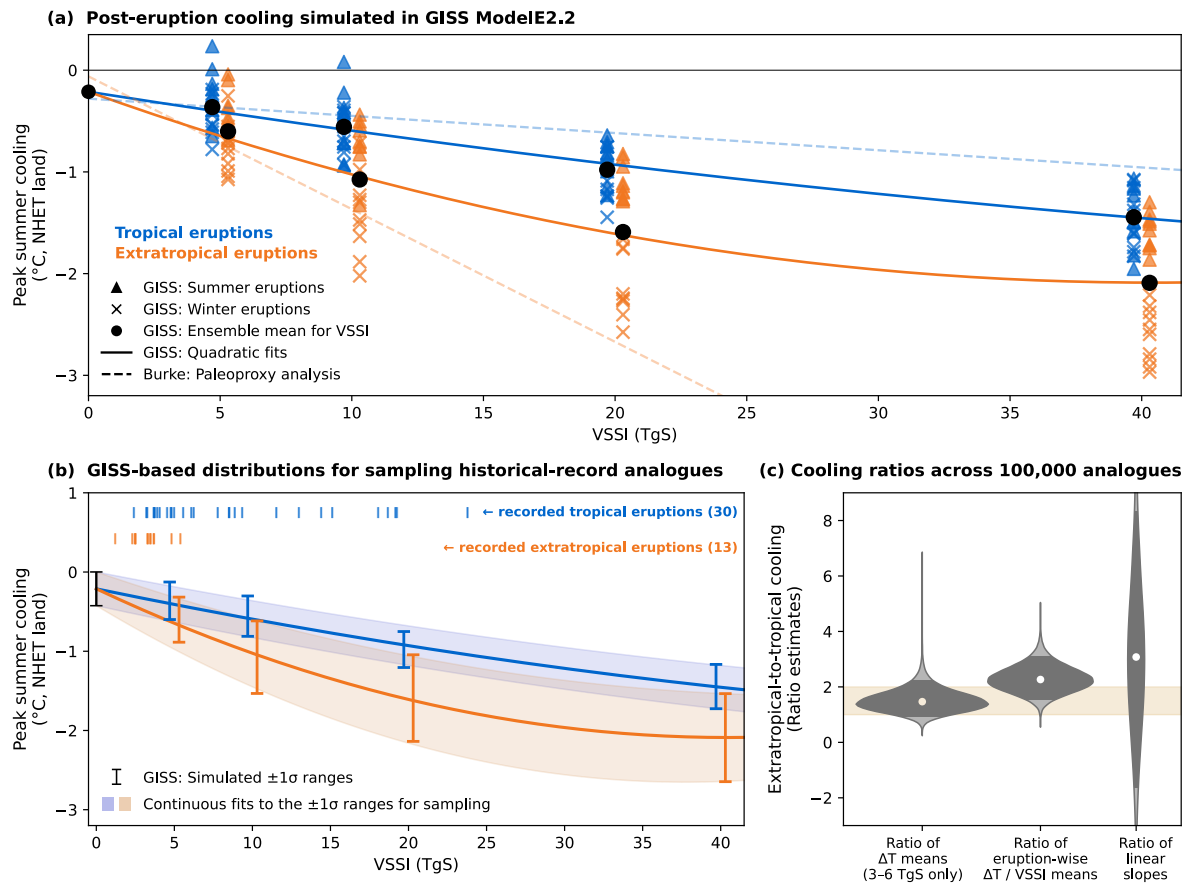


Figure 2. Peak NHET cooling from GISS ModelE2.2 simulations of tropical (blue) and extratropical (orange) eruptions spanning 5–40 TgS. In (a), markers show individual realizations (triangles for summer, x's for winter), and black circles denote ensemble means. Quadratic fits are shown as solid curves, with the linear regressions from Burke et al. (2023) shown for comparison (dashed lines). (b) GISS $\pm 1\sigma$ cooling ranges set by quadratic fits across volcanic stratospheric sulfur injection (VSSI) space (shading), together with the simulated $\pm 1\sigma$ ranges at each VSSI (error bars) and the VSSI values of historical eruptions used to construct synthetic historical record analogs (vertical markers at top). (c) Distributions of cooling ratios across 100,000 historical-record analogs using the three analysis methods, with medians shown by hollow dots, 5%–95% ranges by dark shading, violin widths scaled so that all distributions have equal total area, and the physically expected 1–2 $\times$ region highlighted with tan shading.

10, 20, and 40 TgS, respectively)—far smaller than the 7.5 $\times$ estimate of Burke et al. (2023; comparing slopes of the dashed lines in Figure 2a). Instead, the simulated ratios are weaker than the twofold enhancement expected from hemispheric aerosol confinement, owing in part to the shorter aerosol lifetimes of extratropical summer eruptions relative to tropical injections (Toohey et al., 2019).

A second notable result is that the spread in NHET surface cooling across the 20 members simulated for each VSSI value exceeds the mean difference between the NHET and tropical eruptions. Internal variability and eruption season both exert large influences on post-eruption cooling. For the 5 TgS case—the closest to most observed NHET eruptions (see orange vertical markers at the top of Figure 2b)—the spread in post-eruption cooling across realizations at each eruption latitude is *several times larger* than the difference among the two eruption locations. We argue in the next section that this variability hinders reliable estimates based on the limited eruption sample in paleoclimate records.

A third result is the clear nonlinearity in the simulated relationship between sulfur mass and cooling. Quadratic fits (solid lines in Figure 2a) reveal that the cooling response saturates at high VSSI. Such behavior has been documented for tropical eruptions (McGraw et al., 2024; Raiter et al., 2025) but has not previously been shown for extratropical eruptions. This saturation reflects reduced radiative efficiency as larger sulfur injections produce larger aerosols (Lacis, 2015); the magnitude of this size increase is uncertain and is here prescribed by EVA. We note that the quadratic fits are constrained by a 0.21 $^{\circ}\text{C}$ apparent no-eruption cooling, which arises from applying

the same anomaly definition to our 260-year control simulation and selecting the minimum of each three-summer sequence. As we will consider, the nonlinearity evident here complicates comparisons between eruptions of different magnitudes.

3.2. Reevaluation of Extratropical Cooling Potential From Historical Eruptions

The large spread in simulated cooling responses raises the question of whether the sparse historical eruption record can reliably constrain relative cooling efficiencies. We therefore generated 100,000 synthetic analogs of the volcanic cooling record analyzed by Burke et al. (2023), excluding their two pre-750 CE eruptions because of limited tree-ring coverage. We use the GISS ensemble as the reference distribution for possible peak cooling responses following eruptions at each VSSI. Because the historical VSSI values fall at or between simulated values (e.g., 5 and 10 TgS), we first interpolate across VSSI space using quadratic fits to estimate the $\pm 1\sigma$ range of peak cooling implied by the GISS ensemble at each mass (shown as blue and orange shaded areas in Figure 2b, with error bars indicating the simulated $\pm 1\sigma$ values). For each tropical and extratropical eruption in the record (blue and orange vertical markers at the top of the panel), this $\pm 1\sigma$ range defines a Gaussian distribution from which 100,000 peak cooling values are sampled. Repeating this process at the VSSI values of all sampled eruptions produces 100,000 realizations of peak cooling across the full eruption sequence.

We then evaluate three methods across the analogs: (a) the ratio of mean extratropical-to-tropical cooling for a subset of events from 3 to 6 TgS, which is the most densely sampled VSSI range across both eruption types (8 extratropical and 12 tropical events, with years listed in Table S1, and Figure S4 in Supporting Information S1 comparing these to other eruptions in paleorecords); (b) the ratio of mean cooling-to-VSSI efficiencies computed from individual eruptions, following Toohey et al. (2019); and (c) the ratio of linear regression slopes in cooling-VSSI space for tropical and extratropical eruptions, following Burke et al. (2023). Because our focus is on sampling uncertainty, we use ordinary least squares rather than the maximum-likelihood regression of Burke et al. (2023), which bootstraps over uncertainties in the tree ring and ice core measurements but reduces to ordinary least squares in the absence of measurement uncertainty. For methodological comparability, for all methods we use a 6-year pre-eruption baseline and calculate ratios based on peak cooling, noting that Toohey et al. (2019) instead used 3-year post-eruption mean anomalies. In Figure 2c, we show the distributions of extratropical-to-tropical NHET cooling ratios across the 100,000 historical-record analogs for each method.

These distributions reveal two key issues in tree-ring-based estimates of extratropical cooling. Most crucially, inferred extratropical-to-tropical cooling ratios are highly unreliable, with 5%–95% ranges (dark shaded areas) spanning 0.9 to 2.2 $\times$ with the 3–6 TgS subset mean cooling method (left violin), 1.6 to 3.1 $\times$ with eruption-wise efficiencies (middle violin), and -1.6 to 8.3 $\times$ with linear regression (right violin). This uncertainty is particularly large for the regression approach, where estimated slopes vary strongly across realizations (compare individual synthetic analogs in Figure S3 in Supporting Information S1) due to large internal variability and the scarcity of large extratropical eruptions. This lack of reliability reinforces the low confidence in the extratropical regression slope reported by (Burke et al. (2023); their Figure S9b in Supporting Information S1), whose assessment instead reflects measurement uncertainties within the small sample.

Second, methods that include tropical eruptions >6 TgS are sensitive to the nonlinear cooling-VSSI relationship identified in Section 3.1 because the tropical and extratropical samples span different portions of their response curves (solid lines in Figure 2a). No post-750 CE extratropical eruption exceeds 6 TgS following the VSSI revisions of Burke et al. (2023), whereas 17 tropical eruptions extend into the higher-VSSI regime where cooling gradually flattens. Linear methods—used by both Toohey et al. (2019) and Burke et al. (2023)—therefore bias the inferred extratropical amplification upward. The median cooling ratio among analogs (hollow circles in Figure 2c) for the linear-slope method is 3.1 $\times$, well above the 1.7 $\times$ ratio in the GISS 5 TgS simulations, while the eruption-wise method yields 2.3 $\times$. Restricting the comparison to 3–6 TgS eruptions removes this imbalance, yielding a ratio of 1.5 $\times$, closest to the model ground truth. Thus, the estimation method can substantially bias inferred cooling efficiencies, even before accounting for uncertainties in paleoclimate records not considered here.

We therefore focus subsequent analyses on the 3–6 TgS mean cooling ratio metric. Computing post-eruption temperature anomalies as above, we apply this approach to two tree-ring reconstructions (N-TREND, Schneider et al., 2015a; Wilson et al., 2015) and the LMR Seasonal data assimilation product (Meng et al., 2025), which combines proxy data with a model prior for a more spatially complete view of historical climate variability.

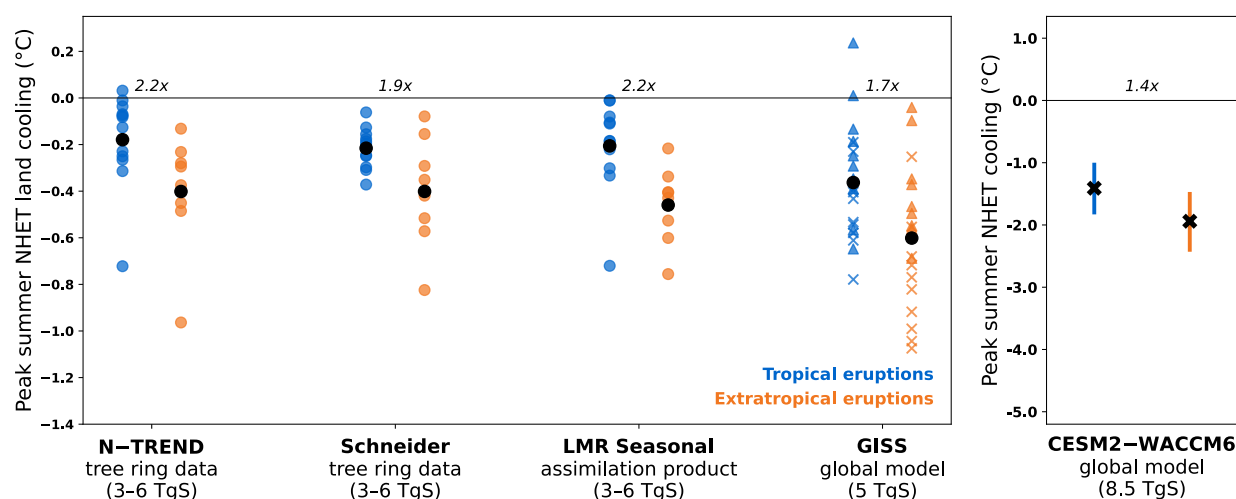


Figure 3. Peak NHET summer (JJA) cooling following tropical (blue) and extratropical (orange) eruptions across paleoclimate reconstructions and model simulations. For the three paleoclimate data sets at left, we examine the recorded post-750 CE eruptions with volcanic stratospheric sulfur injection within 3–6 TgS. For comparison, we also show our 5 TgS model results from GISS ModelE2.2, alongside CESM2-WACCM6 results from Zhuo et al., 2024 that include $\pm 2\sigma$ ranges (extracted from their Figure 6 for the summer with peak mean JJA cooling, with NHET values here including land and ocean). Black markers show mean values; triangles and x's denote simulated summer and winter eruption realizations, respectively, with circles otherwise used. The calculated extratropical-to-tropical eruption cooling ratio for each data set is depicted in italicized text.

Figure 3 presents post-eruption NHET summer cooling following tropical (orange) and extratropical (blue) eruptions across each data set, with black markers indicating mean values.

Across reconstructions, the extratropical-to-tropical cooling ratio is consistently close to 2 (2.2 for N-TREND; 1.9 for Schneider; 2.2 for LMR Seasonal). Comparison of N-TREND to the GISS 5 TgS simulations at tree-ring locations (Figure S5 in Supporting Information S1) likewise gives no indication of exceptional extratropical cooling. Performing an analysis equivalent to Figure 3 across 15 tree ring reconstructions in Büntgen et al. (2021) yields a best estimate of 2.4, but with individual reconstructions ranging from 0.5 to 4.6 (see Figure S6 in Supporting Information S1). While consistent on average with the other assessed reconstructions, this wide spread highlights strong sensitivity of inferred cooling ratios to reconstruction methodology.

Overall, the historical record supports a central estimate near 2, consistent with our GISS simulations. For reference, Figure 3 also shows six-member ensembles of tropical and extratropical 8.5 TgS winter eruptions from CESM2-WACCM6 (Zhuo et al., 2024; from their Figure 6). While the interactive aerosol model captures process effects absent in our prescribed-forcing framework—seasonal photolysis impacts on aerosol formation—the resulting extratropical-to-tropical ratio remains moderate (1.4 $\times$). Together, these results indicate convergence between proxy reconstructions and model simulations: extratropical eruptions produce only moderately stronger NHET cooling than tropical eruptions, consistent with hemispheric aerosol confinement and with no robust evidence for an exceptional amplification.

3.3. Overall Influence of Extratropical versus Tropical Eruptions on NHET Temperature

Finally, to provide a fuller view of the relative importance of tropical versus extratropical eruptions, we address the fact that the latter are relatively rare compared to the former. We here simply ask: *how often has each eruption type coincided with notable NHET cooling anomalies over the historical period?*

To answer that question, we disregard VSSI values and instead count instances of significant post-eruption cooling that align with the post-750 CE volcanic record. Because we no longer construct VSSI-to-cooling relationships, we expand the event set to include 15 eruptions excluded by Toohey et al. (2019) and Burke et al. (2023) due to proximity to earlier eruptions (identified in Table S1 in Supporting Information S1 of Toohey et al., 2019), here adding all events previously excluded on this basis except a 1692 tropical eruption that is followed by a larger included tropical eruption just two years later. We also include the 939 CE Eldgjá and 1783 CE Laki eruptions, previously excluded due to their partly effusive nature. Our Table S1 in Supporting Information S1 lists all events used across this study.

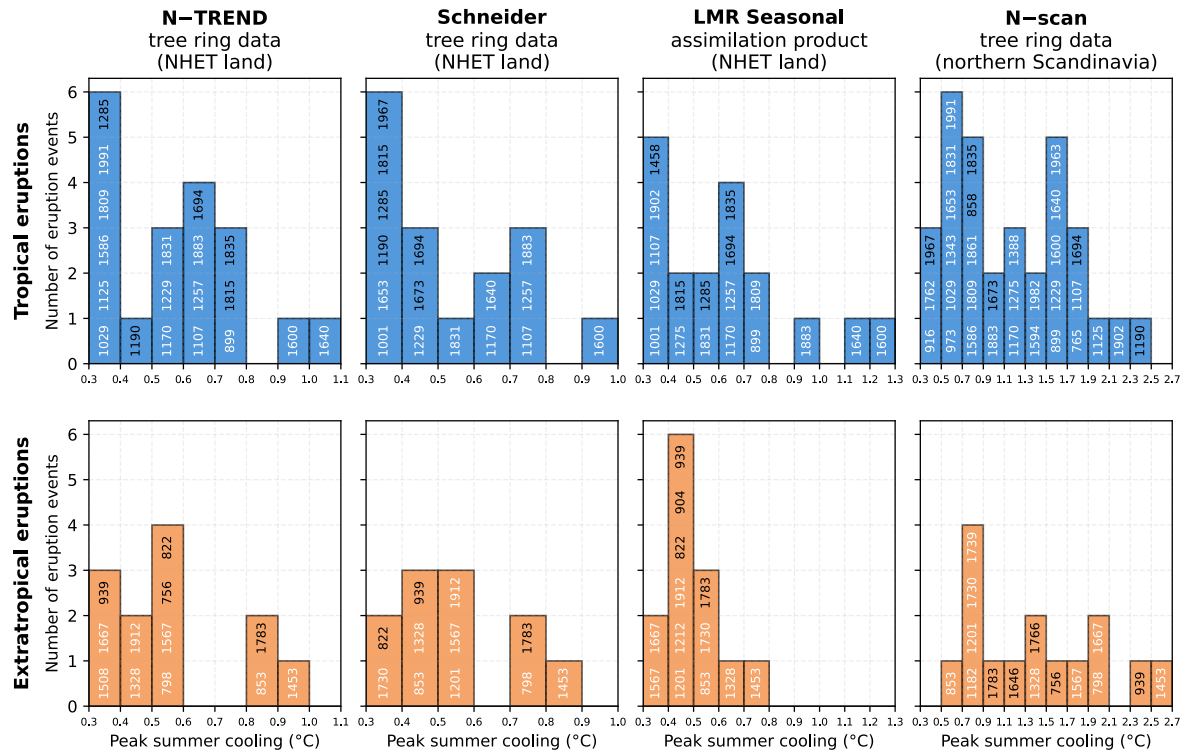


Figure 4. Number of instances with anomalous ($>0.3^{\circ}\text{C}$) summer cooling following tropical (top) and extratropical (bottom) eruptions across historical data sets. Cooling events are binned by 0.1°C (0.2°C for N-scan). Post-750 CE eruptions included in Burke et al. (2023) are labeled in white, while black labels indicate additional eruptions excluded by both that study and Tooley et al. (2019).

Figure 4 shows the number of peak NHET summer (JJA) cooling anomalies exceeding 0.3°C across the three data sets of NHET temperatures shown in the last section, plus the N-scan tree ring record (Esper et al., 2012) from northern Scandinavia. Tropical eruptions are shown in the top panels and extratropical in the bottom, with labels indicating eruption years (white labels: post-750 CE Burke et al. (2023) eruption set; black labels: additional events included here).

Across all reconstructions, anomalous NHET cooling more frequently coincides with tropical than extratropical eruptions (top vs. bottom row in Figure 4), despite the up-to-twofold enhancement commensurate with hemispheric aerosol confinement. This pattern persists even in the high-latitude N-scan tree ring data set (rightmost column), where extratropical eruptions might be expected to produce the strongest signal due to the proximity to eruption latitudes. These results indicate that, although individual large extratropical eruptions may regionally exceed similarly sized tropical eruptions, their rarity limits their overall contribution, leaving tropical eruptions as the dominant driver of NHET volcanic cooling.

4. Discussion and Conclusions

Our modeling and paleoclimate record analyses show that large extratropical eruptions produce only moderately more NHET cooling per unit sulfur than tropical eruptions. Across reconstructions and simulations, we estimate extratropical-to-tropical cooling ratios of 1.4–2.4, far below previous estimates of 3.2 and 7.5. Further, when accounting for the rarity of large extratropical eruptions, we find their overall impact on NHET temperature to be secondary to that of tropical eruptions. These findings challenge the notion that extratropical eruptions exert an outsized influence on extratropical climate.

The relatively limited enhancement from extratropical eruptions aligns with physical expectations: there is no known mechanism to strongly amplify cooling beyond the effect of aerosols being confined to a single hemisphere. Previously cited support for outsized extratropical impacts, such as Burke et al. (2023)'s reference to Yang et al. (2019), lack a clear physical basis. Yang et al. showed that a relatively small eruption with aerosols confined to the Northern Hemisphere could produce Northern Hemisphere temperature anomalies comparable to the

substantially larger Pinatubo eruption. Yet smaller eruptions typically generate smaller aerosol particles, yielding disproportionately strong radiative forcing per unit sulfur (Lacis 2015; McGraw et al., 2024; Timmreck et al., 2009). Therefore, Yang et al.'s result does not generalize to eruptions of comparable magnitude across latitudes—which our large ensemble directly simulates. Moreover, the aerosols from extratropical eruptions have relatively short lifetimes, limiting the potential for outsized cooling.

We emphasize that this area of climate research remains fundamentally data-limited: estimates of extratropical eruption impacts rely on a small number of events, and large uncertainties persist in temperature and sulfur reconstructions. At the same time, climate models necessarily simplify some aspects of volcanic aerosol evolution and its interaction with the climate system, while limited data from rare past events hinders efforts to assess and improve the representation of these processes (e.g., McGraw et al., 2024).

Longer and better-resolved paleoclimate records offer one avenue for reducing these limitations, with emerging Holocene forcing and temperature data sets providing increasingly extensive records for testing volcanic climate responses (e.g., Hantemirov et al., 2022; Sigl et al., 2022; Verkerk et al., 2025). For now, our results build on previous work to provide a more self-consistent and constrained estimate of the cooling efficacy of large extratropical eruptions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

We have placed gridded surface temperature output from the NASA GISS ModelE2.2 simulations online at McGraw et al. (2026), and ModelE source code is available online (<https://www.giss.nasa.gov/tools/modelE/>). The examined paleoclimate data sets are all available online: see references to Esper et al. (2013), Schneider et al. (2015b), and Wilson et al. (2016), and for LMR Seasonal the webpage https://atmos.uw.edu/~zilumeng/LMR_Seasonal/index.html.

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References

- Anchukaitis, K. J., Breitenmoser, P., Briffa, K. R., Buchwal, A., Büntgen, U., Cook, E. R., et al. (2012). Tree rings and volcanic cooling. *Nature Geoscience*, 5(12), 836–837. <https://doi.org/10.1038/ngeo1645>
- Büntgen, U., Allen, K., Anchukaitis, K. J., Arseneault, D., Boucher, É., Bräuning, A., et al. (2021). The influence of decision-making in tree ring-based climate reconstructions. *Nature Communications*, 12(1), 3411. <https://doi.org/10.1038/s41467-021-23627-6>
- Burke, A., Innes, H. M., Crick, L., Anchukaitis, K. J., Byrne, M. P., Hutchison, W., et al. (2023). High sensitivity of summer temperatures to stratospheric sulfur loading from volcanoes in the Northern Hemisphere. *Proceedings of the National Academy of Sciences of the United States of America*, 120(47), e2221810120. <https://doi.org/10.1073/pnas.2221810120>
- Clyne, M., Lamarque, J.-F., Mills, M. J., Khodri, M., Ball, W., Bekki, S., et al. (2021). Model physics and chemistry causing intermodel disagreement within the VolMIP-Tambora interactive stratospheric aerosol ensemble. *Atmospheric Chemistry and Physics*, 21(5), 3317–3343. <https://doi.org/10.5194/acp-21-3317-2021>
- DallaSanta, K., & Polvani, L. M. (2022). Volcanic stratospheric injections up to 160 Tg(S) yield a Eurasian winter warming indistinguishable from internal variability. *Atmospheric Chemistry and Physics*, 22(13), 8843–8862. <https://doi.org/10.5194/acp-22-8843-2022>
- Edwards, J., Anchukaitis, K. J., Gunnarson, B. E., Pearson, C., Seftigen, K., von Arx, G., & Linderholm, H. W. (2022). The origin of tree-ring reconstructed summer cooling in northern Europe during the 18th century eruption of Iaki. *Paleoceanography and Paleoclimatology*, 37(2), e2021PA004386. <https://doi.org/10.1029/2021pa004386>
- Esper, J., Frank, D. C., Timonen, M., Zorita, E., Wilson, R. J. S., Luterbacher, J., et al. (2012). Orbital forcing of tree-ring data. *Nature Climate Change*, 2(12), 862–866. <https://doi.org/10.1038/nclimate1589>
- Esper, J., Frank, D. C., Timonen, M., Zorita, E., Wilson, R. J. S., Luterbacher, J., et al. (2013). NOAA/WDS paleoclimatology—Northern Scandinavia, 138 BC–2006 AD, maximum latewood density, living and subfossil pine, PAGES euro-med 2k version [Dataset]. *NOAA National Centers for Environmental Information*. <https://doi.org/10.25921/RZZC-9S27>
- Hantemirov, R. M., Corona, C., Guillet, S., Shiyatov, S. G., Stoffel, M., Osborn, T. J., et al. (2022). Current Siberian heating is unprecedented during the past seven millennia. *Nature Communications*, 13(1), 4968. <https://doi.org/10.1038/s41467-022-32629-x>
- Lacis, A. A. (2015). Volcanic aerosol radiative properties. *PAGES Magazine*, 23(2), 50–51. <https://doi.org/10.22498/pages.23.2.50>
- McConnell, J. R., Sigl, M., Plunkett, G., Burke, A., Kim, W. M., Raible, C. C., et al. (2020). Extreme climate after massive eruption of Alaska's Iki volcano in 43 BCE and effects on the late Roman Republic and Ptolemaic Kingdom. *Proceedings of the National Academy of Sciences*, 117(27), 15443–15449. <https://doi.org/10.1073/pnas.2002722117>
- McGraw, Z., DallaSanta, K., Polvani, L. M., Tsigaridis, K., Orbe, C., & Bauer, S. E. (2024). Severe global cooling after volcanic super-eruptions? The answer hinges on unknown aerosol size. *Journal of Climate*, 37(4), 1449–1464. <https://doi.org/10.1175/JCLI-D-23-0116.1>
- McGraw, Z., Goldman, B. O., DallaSanta, K., & Polvani, L. M. (2026). GISS ModelE2.2 simulations of tropical and extratropical eruptions [Dataset]. *Zenodo*. <https://doi.org/10.5281/zenodo.18346583>
- McGraw, Z., & Polvani, L. M. (2024). How volcanic aerosols globally inhibit precipitation. *Geophysical Research Letters*, 51(13), e2023GL107930. <https://doi.org/10.1029/2023GL107930>

- McGraw, Z., & Polvani, L. M. (2025). Do climate models support claims of volcanic global catastrophes? *Geophysical Research Letters*, 52(18), e2025GL117611. <https://doi.org/10.1029/2025GL117611>
- Meng, Z., Hakim, G. J., & Steig, E. J. (2025). Coupled seasonal data assimilation of sea ice, ocean, and atmospheric dynamics over the last millennium. *Journal of Climate*, 38(23), 7229–7247. <https://doi.org/10.1175/jcli-d-25-0048.1>
- Orbe, C., Rind, D., Jonas, J., Nazarenko, L., Faluvegi, G., Murray, L. T., et al. (2020). GISS model E2.2: A climate model optimized for the middle atmosphere. Part 2: Validation of large-scale transport and evaluation of climate response. *Journal of Geophysical Research: Atmospheres*, 125(24), e2020JD033151. <https://doi.org/10.1029/2020JD033151>
- Peccia, A., Moussallam, Y., Plank, T., DallaSanta, K., Polvani, L., Burgisser, A., et al. (2023). A new multi-method assessment of stratospheric sulfur load from the okmok II caldera-forming eruption of 43 BCE. *Geophysical Research Letters*, 50(21), e2023GL103334. <https://doi.org/10.1029/2023gl103334>
- Raiter, D., McGraw, Z., & Polvani, L. M. (2025). Non-linear and distinct responses of temperature and precipitation to volcanic eruptions with stratospheric sulfur injection from 5 to 160 Tg. *Geophysical Research Letters*, 52(20), e2025GL116372. <https://doi.org/10.1029/2025GL116372>
- Schneider, L., Smerdon, J. E., Büntgen, U., Wilson, R. J., Myglan, V. S., Kirdyanov, A. V., & Esper, J. (2015a). Revising midlatitude summer temperatures back to AD 600 based on a wood density network. *Geophysical Research Letters*, 42(11), 4556–4562. <https://doi.org/10.1002/2015gl063956>
- Schneider, L., Smerdon, J. E., Büntgen, U., Wilson, R. J. S., Myglan, V. S., Kirdyanov, A., & Esper, J. (2015b). NOAA/WDS paleoclimatology–Northern hemisphere extratropics 1400 year MXD summer temperature reconstruction [Dataset]. *NOAA National Centers for Environmental Information*. <https://doi.org/10.25921/6MDT-5246>
- Sigl, M., Toohey, M., McConnell, J. R., Cole-Dai, J., & Severi, M. (2022). Volcanic stratospheric sulfur injections and aerosol optical depth during the Holocene (past 11 500 years) from a bipolar ice-core array. *Earth System Science Data*, 14(7), 3167–3196. <https://doi.org/10.5194/essd-14-3167-2022>
- Timmreck, C., Lorenz, S. J., Crowley, T. J., Kinne, S., Raddatz, T. J., Thomas, M. A., & Jungclaus, J. H. (2009). Limited temperature response to the very large AD 1258 volcanic eruption. *Geophysical Research Letters*, 36(21), L21708. <https://doi.org/10.1029/2009GL040083>
- Toohey, M., Krüger, K., Schmidt, H., Timmreck, C., Sigl, M., Stoffel, M., & Wilson, R. (2019). Disproportionately strong climate forcing from extratropical explosive volcanic eruptions. *Nature Geoscience*, 12(2), 100–107. <https://doi.org/10.1038/s41561-018-0286-2>
- Toohey, M., Krüger, K., Sigl, M., Stordal, F., & Svensen, H. (2016). Climatic and societal impacts of a volcanic double event at the dawn of the Middle Ages. *Climatic Change*, 136(3), 401–412. <https://doi.org/10.1007/s10584-016-1648-7>
- Toohey, M., & Sigl, M. (2017). Volcanic stratospheric sulfur injections and aerosol optical depth from 500 BCE to 1900 CE. *Earth System Science Data*, 9(2), 809–831. <https://doi.org/10.5194/essd-9-809-2017>
- Toohey, M., Stevens, B., Schmidt, H., & Timmreck, C. (2016). Easy volcanic aerosol (EVA v1.0): An idealized forcing generator for climate simulations. *Geoscientific Model Development*, 9(11), 4049–4070. <https://doi.org/10.5194/gmd-9-4049-2016>
- van Dijk, E., Mørkestøl Gundersen, I., de Bode, A., Høeg, H., Loftsgarden, K., Iversen, F., et al. (2023). Climatic and societal impacts in Scandinavia following the 536 and 540 CE volcanic double event. *Climate of the Past*, 19(2), 357–398. <https://doi.org/10.5194/cp-19-357-2023>
- Verkerk, M., Aubry, T. J., Smith, C., Hopcroft, P. O., Sigl, M., Tierney, J. E., et al. (2025). Using reduced-complexity volcanic aerosol and climate models to produce large ensemble simulations of Holocene temperature. *Climate of the Past*, 21(10), 1755–1778. <https://doi.org/10.5194/cp-21-1755-2025>
- Wilson, R. J. S., Anchukaitis, K. J., Briffa, K. R., Büntgen, U., Cook, E. R., D'Arrigo, R. D., et al. (2016). NOAA/WDS paleoclimatology - Northern hemisphere 1250 year N-TREND summer temperature reconstructions [Dataset]. *NOAA National Centers for Environmental Information*. <https://doi.org/10.25921/KZTR-JD59>
- Wilson, R. J. S., Anchukaitis, K. J., Briffa, K. R., Büntgen, U., Cook, E. R., D'Arrigo, R. D., et al. (2015). Last millennium northern hemisphere summer temperatures from tree rings: Part I – The long-term context. *Quaternary Science Reviews*, 134, 1–18. <https://doi.org/10.1016/j.quascir.2015.12.005>
- Witze, A., & Kanipe, J. (2014). Island on fire: The extraordinary story of Iaki, the forgotten volcano that turned eighteenth-century Europe dark (profile books).
- Yang, W., Vecchi, G. A., Fueglistaler, S., Horowitz, L. W., Luet, D. J., Muñoz, Á. G., et al. (2019). Climate impacts from large volcanic eruptions in a high-resolution climate model: The importance of forcing structure. *Geophysical Research Letters*, 46(13), 7690–7699. <https://doi.org/10.1029/2019GL082367>
- Zhuo, Z., Fuglestedt, H. F., Toohey, M., & Krüger, K. (2024). Initial atmospheric conditions control transport of volcanic volatiles, forcing and impacts. *Atmospheric Chemistry and Physics*, 24(10), 6233–6249. <https://doi.org/10.5194/acp-24-6233-2024>