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Key Points:

- The cooling response to large historical eruptions varies widely across current models, yet is persistently stronger than tree rings imply
- Inconsistent cooling hinders modeling of post-eruption precipitation, since surface temperature strongly controls precipitation amount
- Post-eruption precipitation is unexceptional nearly everywhere in proxy-consistent simulations, disputing claims of global catastrophe

Supporting Information:

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

Correspondence to:

Z. McGraw,
zachary.mcgraw@columbia.edu

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Author Contributions:

Conceptualization: Zachary McGraw, Lorenzo M. Polvani
Formal analysis: Zachary McGraw
Funding acquisition: Lorenzo M. Polvani
Investigation: Zachary McGraw
Methodology: Zachary McGraw, Lorenzo M. Polvani
Project administration: Lorenzo M. Polvani
Supervision: Lorenzo M. Polvani
Validation: Zachary McGraw
Visualization: Zachary McGraw
Writing – original draft: Zachary McGraw
Writing – review & editing: Zachary McGraw, Lorenzo M. Polvani

Do Climate Models Support Claims of Volcanic Global Catastrophes?

Zachary McGraw[1,2] **and Lorenzo M. Polvani**[1,3,4]

[1]Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, USA, [2]NASA Goddard Institute for Space Studies, New York, NY, USA, [3]Department of Earth and Environmental Sciences, Columbia University, New York, NY, USA, [4]Division of Ocean and Climate Physics, Lamont-Doherty Earth Observatory, Palisades, NY, USA

Abstract Climate models have been claimed to support the popular belief that large volcanic eruptions greatly imperil human populations worldwide. These models provide estimates of historical post-eruption climates where observations and paleorecords are lacking. However, as we show, simulations of the last millennium's largest eruptions broadly disagree on resulting climates and typically produce more extreme outcomes than the moderate cooling and ordinary precipitation conditions recorded in tree rings. We demonstrate that strong cooling greatly strengthens the post-eruption precipitation anomalies in simulations. Conversely, simulations with paleoproxy-consistent volcanic surface cooling show post-eruption precipitation to be unexceptional at most locations. Climate models hence do not substantiate the claims that intense eruption-induced wet and dry anomalies have caused widespread historical catastrophes. We suggest that future assessments of global volcanic risk focus on impacts of moderate cooling and on equatorial Africa and South America, which evidence the only regional precipitation responses that are robust across simulations.

Plain Language Summary Historical volcanic eruptions are widely believed to have initiated severe global climate shocks that caused widespread catastrophes. While simulations conveying altered post-eruption climates are often cited in support of this hypothesis, here we show that simulated post-eruption temperature and precipitation broadly disagree across models and are potentially highly exaggerated. We demonstrate with custom simulations that volcanic impacts on precipitation are likely modest nearly everywhere, contradicting global catastrophe claims. Our findings are consistent with precipitation-sensitive tree rings showing a lack of anomalous behavior across the largest eruption event of the last 6,000 years.

1. Introduction

Large volcanic eruptions can alter climate through impacts that have often been deemed capable of disrupting human prosperity on a global scale (Papale & Marzocchi, 2019; Stoffel et al., 2024). However, this belief is based on centuries-old events that left limited evidence of severe climate impacts. Following the three largest eruptions of the last millennium, tree ring paleoproxies recorded summer cooling on the order of 1°C for 1–3 years over Northern Hemisphere (NH) extratropical land but varying widely across temperature reconstruction methodologies (Büntgen et al., 2021; Guillet et al., 2017; L. Schneider et al., 2015; Wilson et al., 2016). Further understanding of post-eruption climates has relied on climate model estimates of volcanic sulfur impacts. These models have been used to show that volcanic impacts on hydroclimate are strong (e.g., Iles & Hegerl, 2014; Iles et al., 2013; Man et al., 2014; Paik & Min, 2018; Paik et al., 2020; D. P. Schneider et al., 2009; Tejedor et al., 2021), as evidence that eruptions caused historical crises (e.g., Kandlbauer et al., 2013; McConnell et al., 2020; Schurer et al., 2019; Singh et al., 2023; Van Dijk et al., 2023), and to convey severe global threats of future eruptions (e.g., Freychet et al., 2023; Man et al., 2021).

Climate models have long been known to produce stronger volcanic cooling than tree ring temperature reconstructions convey (e.g., Mann et al., 2012; Zhu et al., 2020). This mismatch has led some to question the reliability of the reconstructions for these large eruption cases, citing issues involving methodological choices, floor effects on tree growth, and a lack of modern analogs for validation (Büntgen et al., 2021; Esper et al., 2015; Mann et al., 2012; Zhu et al., 2020). However, whereas models thoroughly rely on representations of poorly constrained physical processes (Anchukaitis et al., 2012; LeGrande et al., 2016; McGraw et al., 2024; Timmreck et al., 2009), tree rings capture at least some component of the real-world climate response—and denunciations of their reliability have themselves been challenged (Anchukaitis et al., 2012; D'Arrigo et al., 2013). Importantly, Timmreck et al. (2009) showed that adjusting models within plausible aerosol microphysics scenarios can reconcile the simulated and tree ring cooling, suggesting that discrepancies may lie more with the models than the proxies.

Notwithstanding these uncertainties, many historical catastrophes have been attributed to climate anomalies caused by aerosols from distant volcanic eruptions. For instance, the spring and summer of 1816 AD (the "year without a summer") was marked by exceptionally wet conditions in Central Europe, followed by famines and violent antisemitic riots, in a sequence of crises popularly attributed to the 1815 AD eruption of Mt. Tambora in Indonesia (Behringer, 2019; Brönnimann & Krämer, 2016; Klingaman & Klingaman, 2013; Post, 1977; Stommel & Stommel, 1983; Wood, 2015). Similarly, the first global cholera pandemic has been attributed to a Tambora-induced drought in Bengal (Post, 1977; Stommel & Stommel, 1983), even though meteorological records show no abnormal monsoon conditions at the time (Oppenheimer, 2003). Further case studies report eruption-linked crises in medieval Europe, Scandinavia, and Mesoamerica (Gill & Keating, 2002; Guillet et al., 2017; Stothers, 2000; Van Dijk et al., 2023). While volcanic cooling within 1°C might stress food systems, most theories of historical eruption impacts instead focus on wet and dry conditions. Yet precipitation-sensitive tree rings from Europe and North America show no unusual signals after the 1257 AD eruption of Mt. Samalas in Indonesia (Büntgen et al., 2022)—the most sulfur-rich eruption of the past 6,000 years (Sigl et al., 2022). Nonetheless, the idea that large eruptions pose an existential threat to societies worldwide remains popular (Papale & Marzocchi, 2019; Stoffel et al., 2024).

Here we carefully evaluate climate model output of temperature and precipitation anomalies after the largest eruptions of the last millennium. We ask: *Do climate models give reliable evidence that large eruption impacts are more extreme than indicated by tree ring records*, *which show only modest cooling and ordinary precipitation*? As shown below, the answer is negative: climate simulations are broadly inconsistent with one another, and may be exaggerating volcanic signals more than has previously been appreciated.

2. Methods

2.1. Eruptions Analyzed and Anomaly Definitions

As we are seeking modeling evidence for potentially catastrophic events, we confine our analysis to the three largest eruptions of the last millennium ranked by sulfur mass in ice cores (Toohey & Sigl, 2017). These events include the aforementioned eruptions of Samalas in 1257 AD and Tambora in 1815 AD, as well as a 1458 AD tropical eruption often attributed to Mt. Kuwae in Vanuatu yet still of unknown origin (Hartman et al., 2019). For each eruption, we calculate temperature and precipitation anomalies in models and tree ring temperature reconstructions relative to mean conditions during a 5-year pre-eruption reference period. For the 1257 AD eruption the reference period is 1251–1256 AD. For the remaining two eruptions we shifted the reference period 6 years forward to avoid impacts of earlier eruptions in 1452 and 1809 AD, using 1447–1451 and 1804–1808 AD.

2.2. Climate Model Simulations

The simulations we examine include 4 models from the Paleoclimate Model Intercomparison Project 4 (PMIP4) experiment *past1000* (Jungclaus et al., 2017) that accompanied the Coupled Model Intercomparison Project Phase 6 (CMIP6). We also examine the CESM Last Millennium Ensemble (LME), which has 13 ensemble members and hence is useful for identifying the role of internal variability (Otto-Bliesner et al., 2016). To explore the potential influence of bias in volcanic forcing, we examine two 5-member ensembles from McGraw et al. (2024) with the NASA GISS ModelE2.2 (Rind et al., 2020). These ensembles simulate the 1257 AD eruption of Mt. Samalas with two distinct aerosol size assumptions, chosen to produce dissimilar volcanic forcing strengths that are both consistent with a 120 Tg SO_2 eruption. As we will show, one ensemble shows volcanic cooling similar to that in the PMIP4 models (hereafter *GISS A*), while the second ensemble shows a more moderate cooling consistent with tree ring records (*GISS B*). For more details on the simulations, see Text S1 and Table S1 in Supporting Information S1.

2.3. Tree Ring Proxy Records

To place the simulated post-eruption impacts in the context of temperature reconstructions, we will also examine tree ring records of post-eruption cooling in the NH extratropics. Specifically, we analyze three tree ring

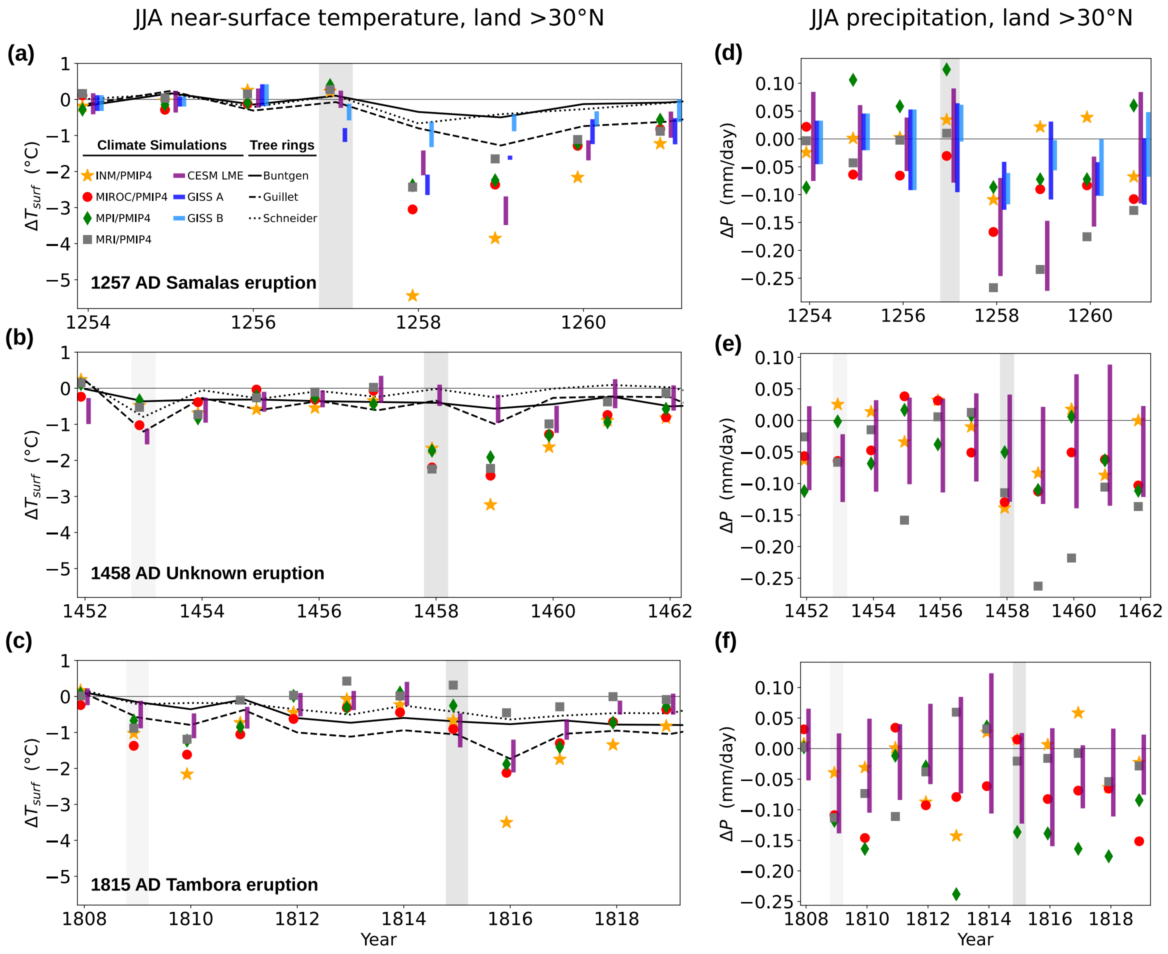

Figure 1. (a–c) Summer surface air temperature and (d–f) precipitation anomalies over Northern Hemisphere extratropics (>30°N) across the 3 largest eruption events of the last millennium. Results are shown for model simulations (markers and vertical lines), while temperatures are also shown in tree ring reconstructions (lines across time). For the CESM and GISS simulations, vertical distance denotes spread between minimum and maximum anomalies within each ensemble of simulations. The year of each major eruption is indicated as a medium gray shaded bar, while smaller eruptions are represented in light gray.

temperature reconstructions: Büntgen et al. (2022), Guillet et al. (2017), and L. Schneider et al. (2015). The Büntgen et al. (2022) and L. Schneider et al. (2015) reconstructions are calibrated to represent land >30°N during summer, and hence for comparison we spatially average model output over all land >30°N. The Guillet et al. (2017) reconstruction is instead calibrated to land >40°N.

3. Results

3.1. Inconsistent Post-Eruption Cooling in Climate Simulations and Tree Ring Records

We first examine post-eruption cooling in tree ring records of the three largest eruption events of the last millennium. These are shown in Figures 1a–1c as black lines. The reconstructed temperature anomalies, which were calibrated to reveal summer conditions over NH extratropics, convey that cooling is a robust feature of post-eruption climate over this region. However, quantitatively this cooling varies considerably across the reconstructions. Reconstructed summer cooling after each eruption generally falls within 1°C, in some cases peaking as moderately as 0.5°C. An outlier is the Guillet et al. (2017) reconstruction (dashed line) for 1816 AD, which shows 1.7°C of cooling. However, 1°C of this cooling appears before the eruption, suggesting a known issue whereby tree rings store memory from earlier years (Esper et al., 2015), in this case carrying effects of an 1809 AD eruption (Toohey & Sigl, 2017).

Partly because of the inconsistent tree ring results, one is led to use climate models as an alternative estimate of post-eruption cooling. However, as is apparent from the simulations denoted by markers and vertical lines in Figures 1a–1c, models show even less agreement in post-eruption cooling over NH extratropical summer than the tree ring reconstructions. As has been pointed out previously (e.g., Marshall et al., 2025; Wade et al., 2020), simulations tend to estimate stronger cooling than the moderate anomalies in tree ring records, in some cases by several times. One PMIP4 model even exceeds 5°C cooling after the 1257 AD Samalas eruption.

Part of the intermodel spread is due to dissimilar magnitudes of volcanic aerosol radiative forcing. Examining the top-of-atmosphere (TOA) radiative flux anomalies in PMIP4 simulations (Figure S1 in Supporting Information S1), we find that the models poorly agree on volcanic radiative forcing. This is in spite of the fact that most of the PMIP4 simulations (i.e., MIROC, MPI, INM) are forced by identical volcanic aerosol inputs. While the remaining PMIP4 model (MRI) based its volcanic forcing on interactive aerosol microphysics, we showed in McGraw et al. (2024) that contemporary interactive aerosol models can immensely disagree on volcanic signals. Altogether, we conclude that one would be hard-pressed to trust quantitative results from simulated post-eruption temperatures.

3.2. Probing Climate Simulations for Insights on Volcanic Cooling Not Available From Paleoproxies

We now examine whether climate models give useful information on volcanic cooling where tree ring records have little availability. In Figure 2a, we compare simulated post-eruption temperature anomalies averaged over NH land >30°N to the same metric over all remaining land areas (<30°N), each during the summer of peak cooling within 4 years of the eruption year. The models indicate that some level of cooling occurs in the latter region, but with no consistent magnitude. Most simulations show post-eruption cooling over land outside the NH extratropics to be half as strong as inside this region, suggesting that the most studied region is also anomalously sensitive to volcanic phenomenon. However, some simulations show both land regions to experience similar cooling. The large spread among the 13-member CESM LME ensemble for each eruption (purple dots of each size) conveys that this ratio hinges on internal variability. However, comparing to other simulated results with a strong volcanic signal (e.g., the 5-member ensemble of *GISS A* Samalas simulations) reveals that these models considerably disagree on the ratio of cooling between the two regions.

We next check whether climate models consistently reveal how much cooling occurs outside the summer growing season covered by tree ring records. In Figure 2b we contrast NH extratropical impacts in summer (JJA) and winter (DJF). While the simulation spread is around the 1-to-1 line of equal cooling in each season, the scatter reflects too much internal variability to anticipate whether a large eruption would be experienced in winter with substantially less or more cooling than in summer.

Without examining any models, one might expect that eruptions that prompt summer cooling in tree rings at NH extratropical locations would cause roughly similar cooling elsewhere and in other seasons. In these two analyses of volcanic cooling, climate models are found to offer no useful quantitative information beyond this unsophisticated hypothesis. Despite tree ring records of volcanic cooling having considerable uncertainties and limited regional extent (Büntgen et al., 2021; D'Arrigo et al., 2013; Esper et al., 2015), our analyses indicate that climate models fail to reliably add clarity where proxy records are unavailable or unclear.

3.3. Examining Why Precipitation Impacts of Historical Eruptions Are Difficult to Pinpoint

We now begin to examine volcanic aerosol influence on precipitation, which is often cited in claims of global eruption-induced catastrophes. Contradicting this, a study of 79 precipitation-sensitive tree ring records primarily in North America and Europe found no unusual precipitation pattern after the exceptionally large Samalas eruption (Büntgen et al., 2022). Here, we examine simulated post-eruption precipitation responses and offer two potential explanations for the lack of tree-ring signals.

The most robust precipitation response across models is that global mean precipitation decreases (Iles et al., 2013; McGraw & Polvani, 2024). However, in Figures 1d–1f we demonstrate that simulated precipitation effects are difficult to discern across the NH extratropics (>30°N). While both models and tree rings show robust cooling across this region, only a single summer (1258 AD) undergoes a regional precipitation reduction that is robust across models. Models do, however, agree on a reason for this lack of clear precipitation signal: the global

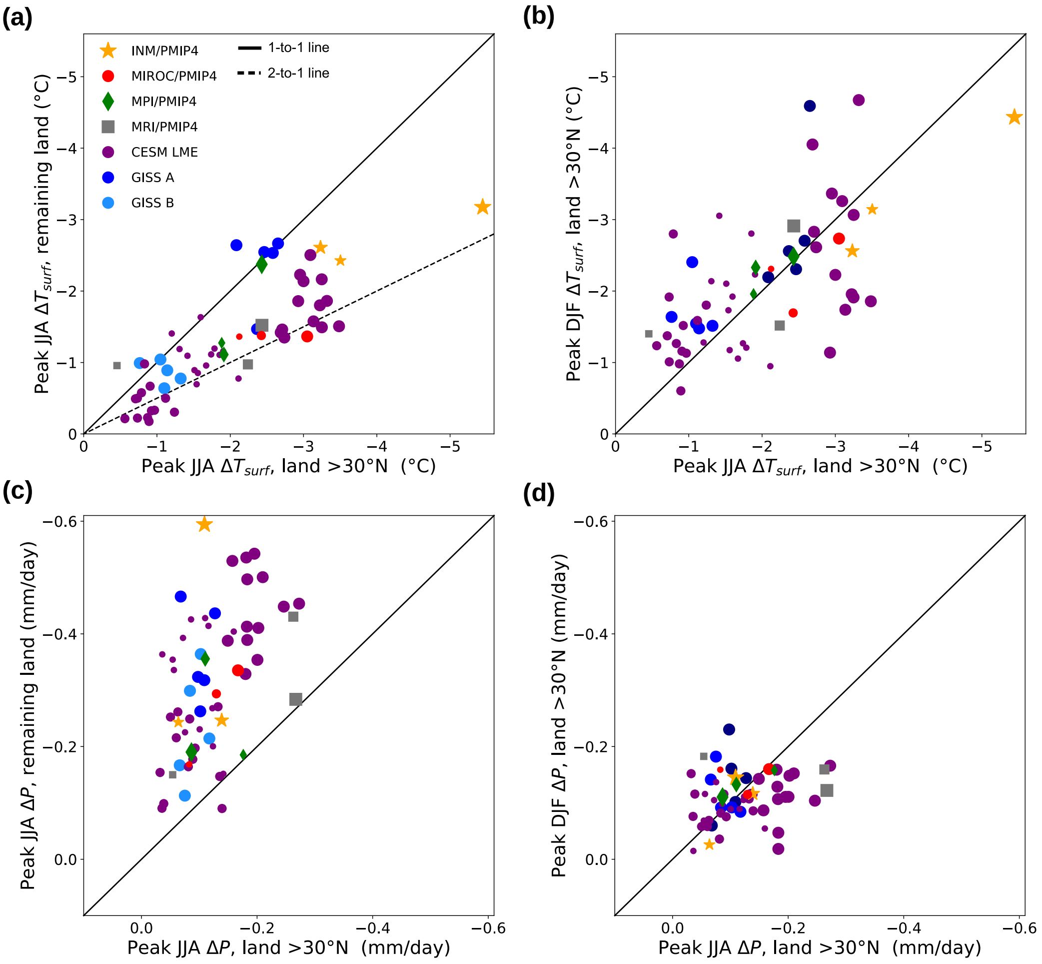

Figure 2. Climate model results of post-eruption anomalies over Northern Hemisphere (NH) extratropics in summer (JJA) compared to (a, c) summer impacts over remaining land areas and (b, d) NH extratropical impacts in winter (DJF). Comparisons of post-eruption temperatures are in panels (a, c) and precipitation in panels (b, d), showing the minimum values reached within 4 years after each of the 3 largest eruptions of the millennium. Eruptions are indicated by the size of markers, with the largest markers for each model representing climate after the 1257 AD eruption, medium markers for 1458 AD, and small markers for 1815 AD.

precipitation reduction is instead predominantly experienced outside the NH extratropics. This is apparent in Figure 2c, which compares simulated anomalies averaged over land above and below 30°N.

A second reason for the lack of clear precipitation signal in the NH extratropics relates to the spatial variability of volcanic precipitation effects. Unlike eruption impacts on temperature—which are predominantly in one direction (i.e., cooling), enabling volcanic impacts to be extracted via spatial averaging that removes noise—eruptions induce wet conditions in some locations and dry conditions in others (Iles et al., 2013; McGraw & Polvani, 2024). Averaging precipitation anomalies across the NH extratropics can hence instead dilute the volcanic impact. This starkly contrasting degree of spatial heterogeneity is apparent when comparing surface temperature (Figure S2 in Supporting Information S1) and precipitation (Figure S3 in Supporting Information S1) anomalies averaged over the 3 largest eruptions of the millennium in each PMIP4 model. We will in the next sections argue a third explanation: precipitation impacts are weak at nearly every location compared to typical interannual fluctuations from internal variability.

We next examine whether models give consistent quantitative information on precipitation effects. As with temperature, the answer is no. The magnitude of the precipitation reductions from each eruption (Figure 2c) is poorly constrained across models. Further, models show no consistent relationship between precipitation in summer and winter in the NH extratropical focus area (Figure 2d). We have also mapped the post-eruption climate

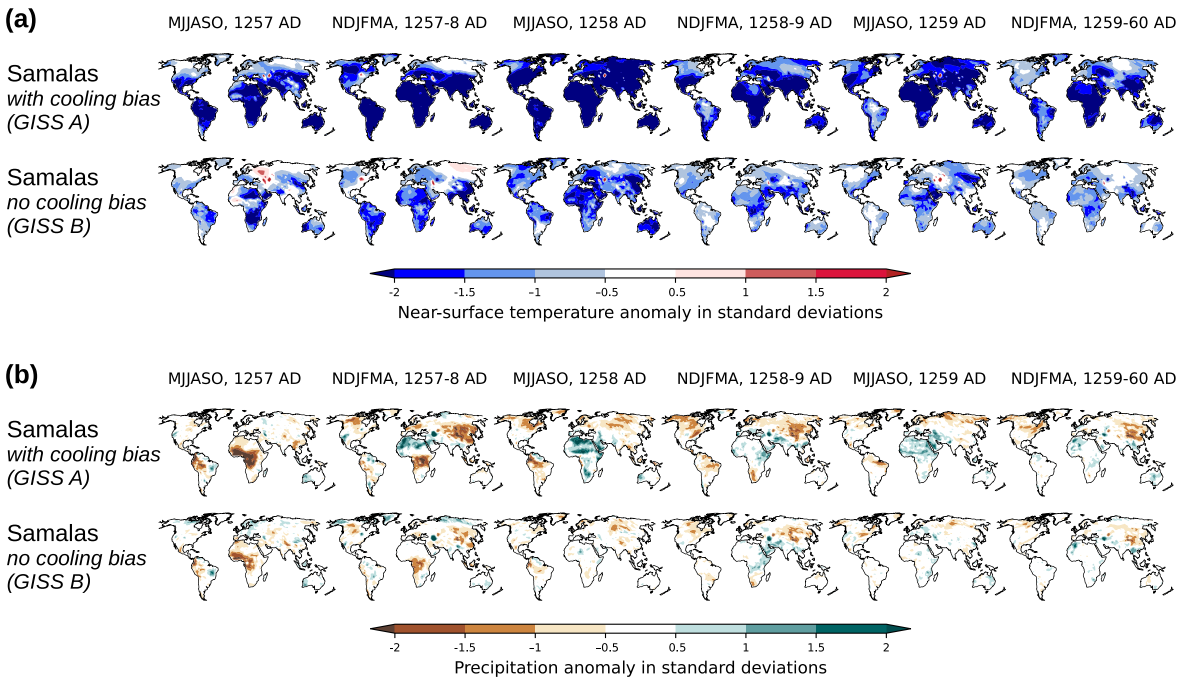

Figure 3. Simulated impacts of the Mt. Samalas eruption on near-surface temperature and precipitation in two ensembles of the NASA GISS climate model, calculated as ensemble-mean anomalies. Here we assess the proportion of global land that undergoes seasonal temperature (panel a) and precipitation (b) states more extreme than in any of the previous 100 years.

anomalies over every land location to seek robust regional patterns among PMIP4 models. Whereas all PMIP4 models show cooling nearly everywhere (Figure S2 in Supporting Information S1), these models poorly agree on the sign of regional precipitation impacts (Figure S3 in Supporting Information S1). The only intermodel agreement over sizable regions is a temporary precipitation reduction in parts of equatorial Africa and South America. Even here the simulations disagree on magnitude, timing, and precise area. While models hence indicate volcanic risks over these regions are worth study, they once again provide little consistent quantitative information.

3.4. Potential for Models to Overestimate Regional Temperature and Precipitation Impacts

Now we demonstrate that climate models are potentially exaggerating volcanic impacts on temperature and precipitation across the globe. To do so, we present two ensembles of NASA GISS ModelE2.2 simulations with distinct representations of the Samalas eruption. As shown Figures 1a–1c, the first ensemble (*GISS A*, dark blue) has volcanic cooling representative of PMIP4 models but stronger than in tree ring reconstructions, while the second (*GISS B*, light blue) replicates the moderate cooling recorded in the tree rings.

In Figure 3, we map ensemble-mean anomalies in MJJASO and NDJFMA seasons across the eruption event. We here normalize these anomalies by their standard deviation across years as derived from the unforced pre-industrial equilibrium climate state. Plotting such signal-to-noise ratios helps convey whether volcanic signals are strong compared to typical fluctuations caused by internal variability. As is apparent in Figure 3a, *GISS A* simulates much stronger cooling than *GISS B*, indicating exaggerated volcanic cooling practically everywhere if the NH extratropical cooling in tree ring reconstructions is accepted as a reasonable benchmark. The signal-to-noise ratios indicate that post-eruption temperatures are abnormally cold in many regions, even on examining the more moderate *GISS B* simulations.

The key point of Figure 3, which to the best of our knowledge has not been previously appreciated, is that biased cooling also leads to exaggerated post-eruption precipitation anomalies. This can be seen by comparing rows of Figure 3b. This conclusion based on the GISS ensembles is corroborated by the PMIP4 models in Figure S3 in Supporting Information S1, which shows that the INM model, which has the strongest volcanic forcing (Figure S1 in Supporting Information S1) and cooling (Figures 1a–1c and Figure S2 in Supporting Information S1), also

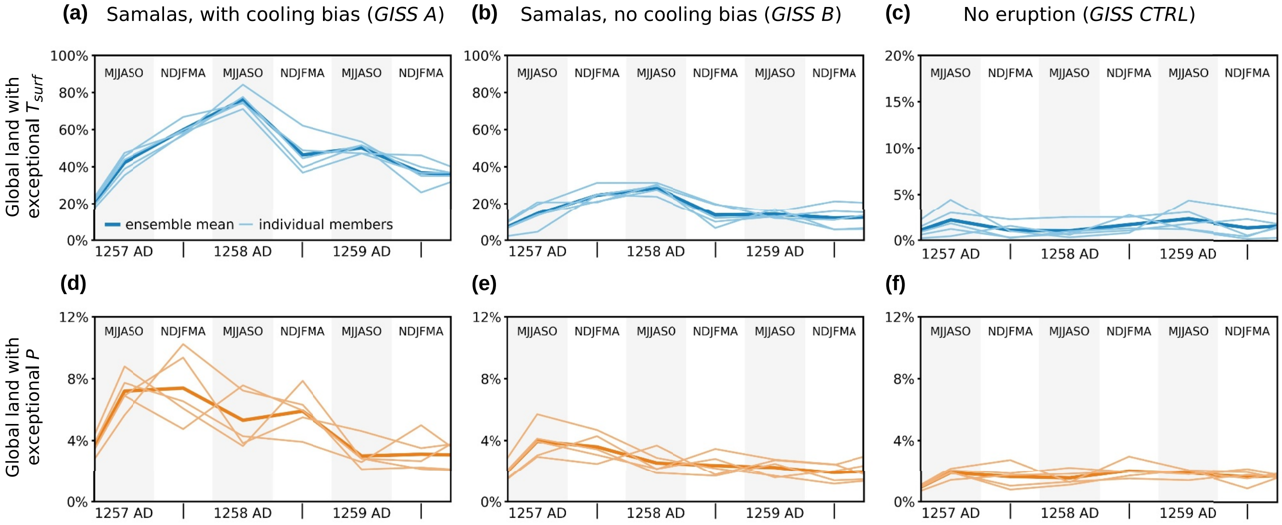

Figure 4. The proportion of global land that undergoes seasonal temperature and precipitation states beyond any in the 100 years preceding the eruption, as simulated in the GISS ensembles of the 1257 AD Mt. Samalas eruption.

shows the strongest regional precipitation signals. This is not surprising, as we have shown in a previous study (McGraw & Polvani, 2024) that volcanic cooling is a major driver of post-eruption precipitation anomalies. If the volcanic signals in the paleoproxy-consistent ensemble (*GISS B*) are reliable, even the largest eruption of the millennium would not clearly alter precipitation in most regions. We note the exception of drying over equatorial Africa, which we had noted is also a robust result in PMIP4 simulations.

3.5. Examining the Risk of Global Catastrophe Following Large Eruptions

As a final component of our analysis, we probe whether volcanic climate impacts qualify as a *global catastrophe*, broadly defined as an event causing serious harm to human well-being on a global scale (Bostrom & Ćirković, 2011). As our focus is on climate simulation results, we limit our focus to whether post-eruption climate anomalies exceed typical variability across a large proportion of global land. This approach sidesteps the complexity of determining precise climate thresholds for catastrophe in each region and society, while remaining relevant: humans and their crops are generally adapted to cope with ordinary year-to-year fluctuations, while being vulnerable to more extreme conditions (White et al., 2018).

In Figure 4 we show the fraction of global land area that experiences MJJASO or NDJFMA seasonal mean value outside this season's bounds (minimum and maximum) in the 100 years preceding the Samalas eruption. Post-eruption temperatures are found to be exceptional at most locations in *GISS A* (Figure 4a), while exceptional surface temperatures occur in up to ~30% of global land even in our proxy-consistent simulations (*GISS B*, Figure 4b). Cooling on the order of 1°C hence produces atypical temperatures at many locations, suggesting that impacts of this cooling may be worth evaluating.

However, the proportion of land showing exceptional post-eruption precipitation is far smaller than the proportion showing exceptional cooling. Focusing on the ensemble mean of the paleoproxy-consistent *GISS B* ensemble (thick line in Figure 4e), one can see that the exceedingly strong Samalas eruption is simulated to double the occurrence of exceptional precipitation states during one MJJASO and one NDJFMA season before resembling the same analysis with the control simulation containing no eruptions (Figure 4f, with methods described in Text S1 in Supporting Information S1). This volcanic enhancement is much weaker than in the *GISS A* ensemble with exaggerated cooling (Figure 4d), suggesting that most exceptional precipitation states therein stem from model bias in volcanic cooling. Further, one of the five members of the control ensemble (thin orange lines in Figure 4f) undergoes two seasons with 1.5x occurrence of exceptional precipitation despite *no simulated eruption*, conveying that internal variability enhances the occurrence of exceptional precipitation states far more frequently than such exceedingly rare eruptions as Samalas. These results suggest that, contrary to the results of many climate simulations, even the largest eruption of the last several thousand years had limited ability to induce severe precipitation.

4. Conclusion

We have examined recent simulations of the last millennium's largest eruptions and shown that these do not give reliable evidence of strong post-eruption climate anomalies. Further, we examined paleoproxy-consistent simulations indicating that even the Mt. Samalas eruption only moderately affected precipitation, with few regional exceptions. These model results supplement tree ring records of unexceptional post-Samalas precipitation (Büntgen et al., 2022) to suggest a consistent picture: *Even the largest eruption of the last several thousand years was incapable of strongly disrupting global precipitation patterns*. This speaks against theories of global volcanic catastrophes, which claim strong eruption-induced wet and dry anomalies (see Section 1).

That said, we raise two questions that remain worth exploring:

- *Can a temporary global cooling of* 1°C *pose a severe global threat*? We have shown that volcanic cooling can place temperatures outside their usual range in many regions. The common focus of historical studies on volcanic hydroclimate impacts may reflect that a 1°C temporary temperature anomaly seems non-catastrophic from the standpoint of a world that has undergone what is now 1.5°C of sustained global warming (Jarvis & Forster, 2024). While future eruptions might temporarily ease the effects of greenhouse gas warming, historical societies were likely more vulnerable to global cooling on the order of 1°C.
- *How vulnerable are equatorial Africa and South America to eruption-induced drying*? The only regional precipitation anomalies robust across the analyzed models affect equatorial Africa and South America, suggesting a need to evaluate impacts in these regions in particular. Surprisingly, records of African climate show no clear drying in the aftermath of Tambora despite identifying a continent-wide drought a decade after the eruption (Nicholson, 2018).

Our analysis adds evidence to a recent stream of studies pointing to inconsistencies in climate simulations of large eruption impacts (e.g., Clyne et al., 2020; Marshall et al., 2025; McGraw et al., 2024; Timmreck et al., 2009; Wade et al., 2020). Climate models remain prone to depicting more exceptional post-eruption climate conditions than paleoproxies indicate, an issue that had not previously been explored in regards to precipitation. It is difficult to know why model results remain inconsistent without comprehensively examining choices in the model physics and relating these to differences in volcanic forcing, aerosol rapid adjustments, radiative feedbacks, and hydrological sensitivity. Model intercomparisons offer a pathway to understand and evaluate these differences (e.g., Clyne et al., 2020; Zanchettin et al., 2022). Our findings suggest continued effort is needed.

Data Availability Statement

Output from PMIP is publicly available at the CMIP archive, https://pcmdi.llnl.gov/CMIP6/, while output from the CESM LME is at https://www.cesm.ucar.edu/community-projects/lme. We have placed output from the NASA GISS ModelE2.2 simulations online at DallaSanta et al. (2025).

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