Post-eruption precipitation anomalies are dominated by internal variability, not volcanic aerosol impacts

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April 11, 2024

Abstract

Aerosols from large volcanic eruptions are purported to cause significant global precipitation changes lasting up to several years. We here show that eruptions with very large stratospheric sulfur injections are, in fact, too weak to substantially alter precipitation at most land locations. Analyzing two climate model ensembles, we demonstrate that internal variability is the main driver of interannual precipitation anomalies even in the aftermath of the largest tropical eruptions of the last millennium. Further, observations show that post-eruption precipitation anomalies in post-eruption years are indistinguishable from anomalies in non-volcanic years. Reports of statistically significant post-eruption precipitation anomalies have relied on metrics that remove internal variability in order to inflate the volcanic signal. Such metrics are not suitable to assess the importance of volcanic eruptions on local-scale precipitation.

Supporting information for

Post-eruption precipitation anomalies are dominated by internal variability, not volcanic aerosol impacts

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Figure S1. Precipitation response over Africa in CESM-LME, showing precipitation anomalies in all CESM LME ensemble members (rows) and their average (bottom row), for all 12 assessed eruptions (columns). Anomalies are shown in the January-December year of the eruption, which is the year of maximum impact over this continent.

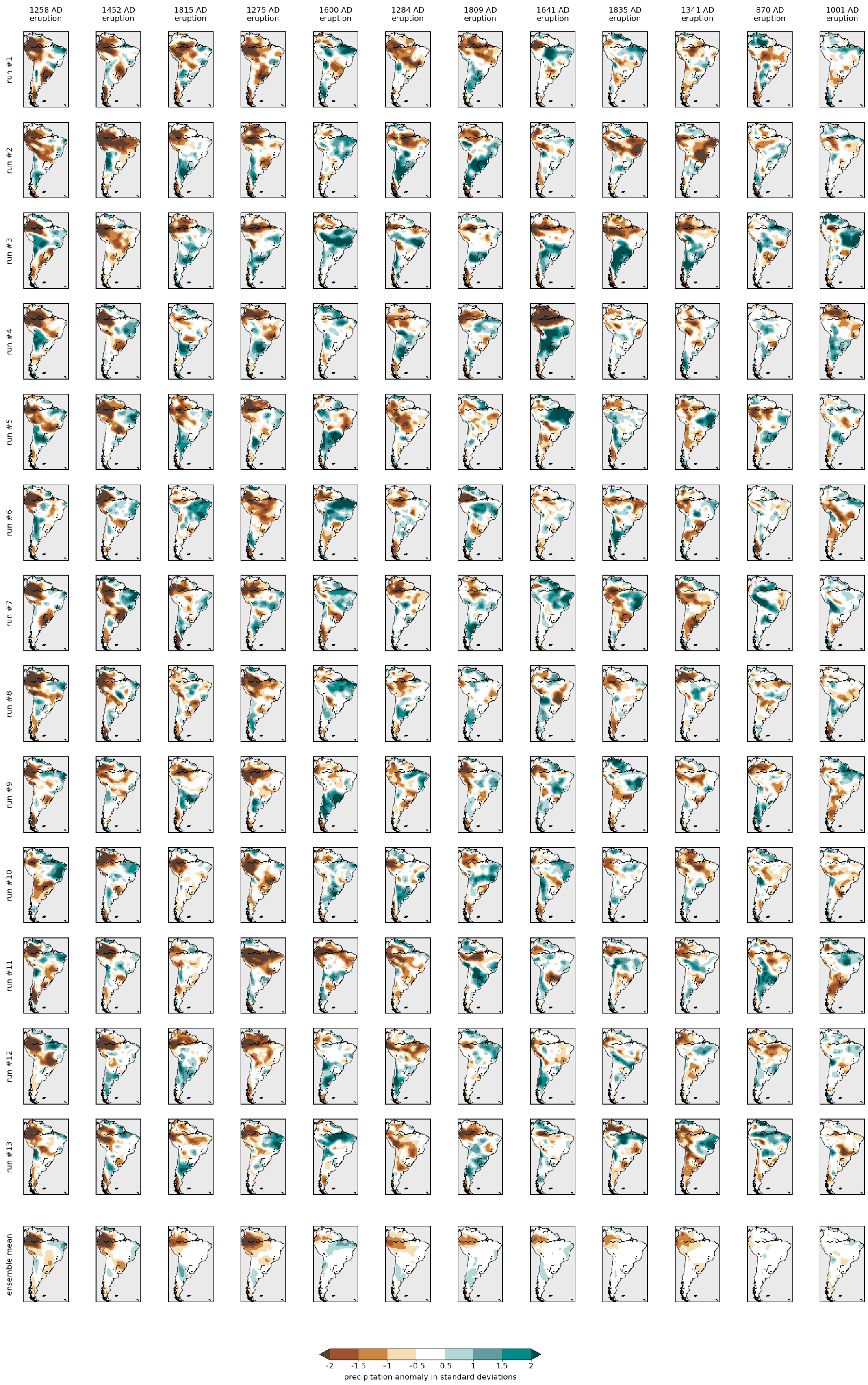

Figure S2. As in Figure S1 for showing precipitation response over South America in CESM-LME.

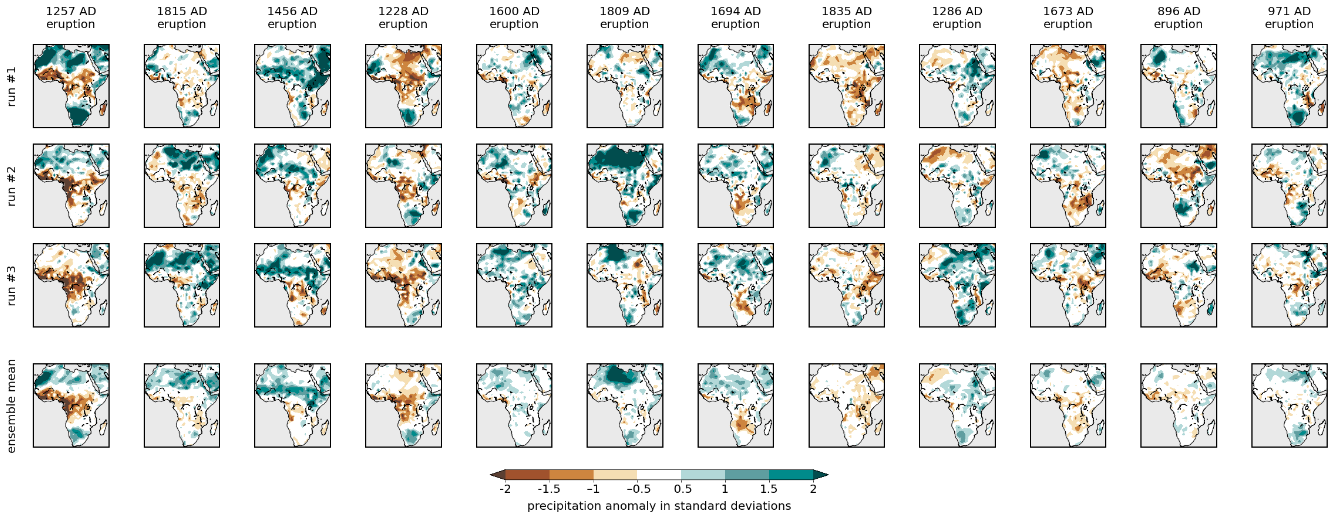

Figure S3. As in Figure S1 but in GISS LME, with the exception that for GISS LME the strongest response is in the year *after* the eruption, which we show here.

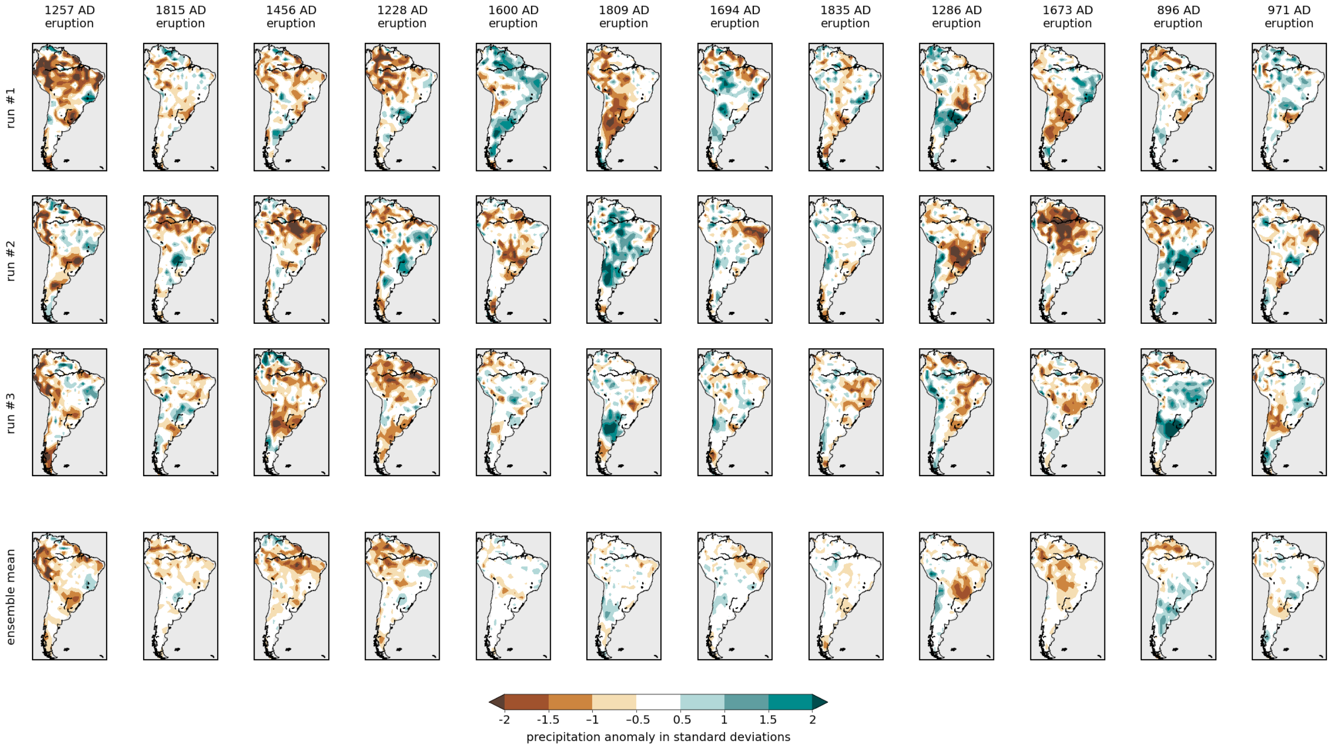

Figure S4. As in Figure S3 but in GISS LME, with the exception that for GISS LME the strongest response is in the year *after* the eruption, which we show here.

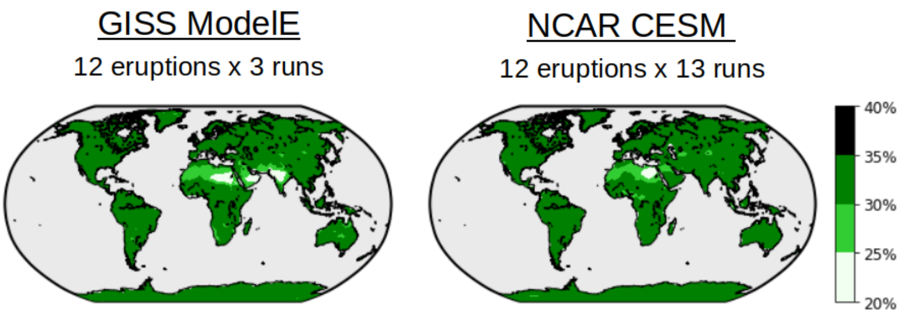

Figure S5. Proportion of years in last millennial ensembles that have more anomalous precipitation than ±1 $\sigma_{P,\ell}$. It is here evident that only the most precipitation-starved regions are outside the range of 30-35%, which includes the 32% value of a normally-distributed variable. Note that the $\sigma_{P,\ell}$ values were calculated without long-term variability, as described in Section 2.1.

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Abstract

Aerosols from large volcanic eruptions are purported to cause significant global precipitation changes lasting up to several years. We here show that eruptions with very large stratospheric sulfur injections are, in fact, too weak to substantially alter precipitation at most land locations. Analyzing two climate model ensembles, we demonstrate that internal variability is the main driver of interannual precipitation anomalies even in the aftermath of the largest tropical eruptions of the last millennium. Further, observations show that post-eruption precipitation anomalies in post-eruption years are indistinguishable from anomalies in non-volcanic years. Reports of statistically significant post-eruption precipitation anomalies have relied on metrics that remove internal variability in order to inflate the volcanic signal. Such metrics are not suitable to assess the importance of volcanic eruptions on local-scale precipitation.

Keywords: volcanic impacts, aerosols, climate change

1. Introduction

Numerous studies have reported that large volcanic eruptions significantly alter precipitation around the world (e.g. Fischer *et al* 2007, Iles *et al* 2013, Manning *et al* 2017, Robock and Liu 1994, Tejedor *et al* 2021). Large eruptions often generate volcanic sulfate aerosol that spreads throughout the stratosphere for roughly two years, where it reflects and absorbs radiation and through this can influence global climate and the water cycle. A considerable literature has reported identifiable patterns of volcanic hydroclimate sensitivity in climate model simulations (e.g. Manning *et al* 2017, Tejedor *et al* 2021) as well as observations (e.g. Gillett *et al* 2004, Iles and Hegerl 2014).

It is important to assess post-eruption hydroclimate anomalies given their potential threats to food and water security (Manning *et al* 2017, Tejedor *et al* 2021). Scientific evaluations guide policy recommendations for future eruption preparedness, as well as interpretations of volcanic climate impacts on past societies. However, whether volcanic aerosol impacts are sufficient to cause substantial precipitation anomalies at local scales has not been the focus of scientific studies. Instead, the end result of prior studies – via *statistical significance tests* – is overwhelmingly that volcanic hydroclimate responses are unlikely to match a zero-effect null hypothesis. While statistical significance can be a useful metric in explorations of physical mechanisms, it does not convey whether the eruption's impacts are actually large and thus important (Wasserstein and Lazar 2016). Hence, despite dozens of reports of a *significant* volcanic response, whether the response is sufficient to cause substantial hydroclimate anomalies – and the threat these would pose – remains to be established.

In this study, we reevaluate climate model simulations and observations that formed the basis of prior studies on post-eruption precipitation. While we do not dispute that volcanic response can achieve measures of statistical significance, our focus is to bring the previously reported impacts into a context more indicative of their anomalous nature and threat. Here we use simple statistical metrics to diagnose whether exceptional post-eruption precipitation-induced damages might be expected, free from the complexities of crop damage simulations (e.g. Fan *et al* 2021) or societal vulnerability conceptual models (Degroot *et al* 2021). Primarily we compare forced eruption response to the standard deviation of internal variability, in what is known as a *signal-to-noise ratio*. This metric conveys the degree to which a signal, in our case forced precipitation change, is capable of driving conditions outside the range that people and ecosystems are adapted to endure (Hegerl 2011, Mahlstein *et al* 2011).

With this framework, we demonstrate that volcanic impacts on precipitation are in fact weak compared to typical variations, and hence are unlikely to pose a comparable threat. We also examine the statistical metrics used in previous studies on volcanic precipitation response. Through this, we explain the apparent contradiction between our conclusions and the claims of past studies, while providing insights on the statistical methods used to deem a forced climate response noteworthy.

2. Methods

2.1 GISS ModelE and NCAR CESM last millennium ensembles

Here we assess volcanic precipitation impacts in two climate model ensembles that have previously been used as the basis for studies on this topic. The first is the last millennium ensemble (LME) of the Goddard Institute for Space Studies (GISS) Model-E2 (*GISS* hereafter), used in Colose et al. (2016) and described therein. The second is the last millennial ensemble of the National Center for Atmospheric Research (NCAR) Community Earth System Model (*CESM* hereafter) v 1.1, described in Otto-Bliesner et al. (2016) and used in several studies of volcanic hydroclimate impacts (e.g. Colose *et al* 2016, Stevenson *et al* 2016, Tejedor *et al* 2021). Both ensembles cover the period 850-1850 AD. Millennium-length ensembles are useful because they provide a large number of volcanic eruptions for analysis. The two climate models have similar horizontal resolutions, being 2.0°x2.5° for GISS and 1.9°x2.5° for CESM. GISS has 40 vertical levels up to 0.1 hPa while CESM has 30 levels up to ~2 hPa.

We specifically focus on simulations with all known forcings present, including volcanic aerosols that are read in from files based on estimates of sulfate in ice cores. For GISS 3 ensemble members each with the Gao *et al* (2008) and Crowley and Unterman (2013) volcanic forcing datasets are available, and for CESM 13 ensemble members all having the Gao *et al* (2008) forcing. However, as an error substantially exaggerated the strength of volcanic forcing in the Gao *et al* (2008) GISS experiments (Colose *et al* 2016), we here only analyze the 3 Crowley and Unterman (2013) simulations. For CESM we analyze all 13 ensemble members available, forced with the Gao *et al* (2008) dataset.

For our analysis we chose the 12 largest tropical eruptions in each ensemble that had a clear influence on global mean perturbation, encompassing most tropical eruptions Pinatubo-scale or larger. The input volcanic aerosol datasets are for many eruptions similar but for others differ substantially in onset year and strength. The events we analyze in the GISS ensemble members – ordered by descending sulfur mass – are simulated to erupt in years 1257, 1815, 1456, 1228, 1600, 1809, 1694, 1835, 1286, 1673, 896, and 971. For CESM we analyze eruptions in simulated years 1258, 1452, 1815, 1275, 1600, 1284, 1809, 1641, 1835, 1341, 870, and 1001. Between the 3 GISS simulations and 13 CESM simulations, we use a total of 36 and 156 eruptions in our analysis, respectively.

2.2 Global Precipitation Climatology Project dataset

To assess the extent to which volcanic influence on precipitation is evident in observations we examine version 2.3 of the Global Precipitation Climatology Project (GPCP) dataset (Adler *et al 2018)*. This dataset was formed by integrating satellite retrievals and rain gauge observations, and has previously been used for assessing volcanic impacts on precipitation (Iles *et al 2013, Iles and Hegerl 2014)*. Only two large Plinian eruptions have occurred within the 1979-2017 duration of this dataset. These are the eruptions of El Chicón in March-April of 1982 and Pinatubo in June of 1991.

2.3 Analysis methods

For our assessment we focus on volcano-induced precipitation anomalies during the January-December year in which the eruption occurs, and the year that follows. In GISS LME this occurs in the year after the eruption, while in CESM LME this occurs in the eruption year itself (as will be shown in Section 3.2). For simplicity we do not distinguish winter and summer impacts as in prior works (Fischer *et al*

2007, Iles *et al* 2013), as seasonal impacts show roughly similar extent and magnitude as the annual mean response (Tejedor *et al* 2021). We assess precipitation impacts only over continental land, to focus on areas containing most of the world's people and biomass. The volcanic impacts we present here are of similar magnitudes and extents as reported in other studies (Colose *et al* 2016, Iles *et al* 2013, Stevenson *et al* 2016, Tejedor *et al* 2021), though noticeable differences exist due to choices of analyzed eruptions, assessed post-eruption time period, and model, as well as some studies' reporting of anomalies in drought index rather than precipitation.

For each of the two climate model ensembles, we create an eruption composite by averaging all events together. This method is known as *superposed epoch analysis* and has been used to obtain a clear signal in most studies of precipitation using eruption events. As in previous studies, we calculate post-eruption anomalies by subtracting the average across a reference period, typically of a few years preceding each eruption. This allows us to avoid any long-term variations that are not our focus. In our analysis, the reference period contains the 5 January-December years prior to that in which the eruption occurs. Where we evaluate anomalies in the year before eruptions, this pre-eruption base period is shifted one year backward so as not to include the target years. As GPCP observations begin only 3 years before the El Chicón eruption, for our analysis of this dataset we instead use a 3-year period. For comparison, standard deviations of precipitation anomalies are calculated from all years of the millennium-long integrations at each land location (hereafter $\sigma_{P,\ell}$), after subtracting from each year a reference period of the same number of preceding years as in the eruption analysis.

3. Results

3.1 Anomalous precipitation is rarely attributable to volcanic aerosol, even following major eruptions

First we demonstrate that post-eruption precipitation is – over nearly all land areas – *not* anomalous compared to non-volcanic periods. This refutes the expectation that eruptions would be the cause of precipitation anomalies during their aftermath. For this task, we first define years with *anomalous* precipitation as those years when the annual anomalies are in excess of $\sigma_{P,\ell}$, i.e. one standard deviation. Then, to see if the eruptions are able to affect precipitation in a substantial way, we examine the probability of anomalous precipitation occurring before and after the eruption, in both the GISS and CESM last millennium ensembles.

As is shown in Fig. 1 (ii) and (iii), in years including and directly following major volcanic eruptions anomalous precipitation occurs roughly one-third of the time. However, years *before* the eruptions show very similar occurrence of anomalous precipitation, as seen in Fig. 1 (i). This clearly demonstrates that eruption years are for the most part *indistinguishable* from the pre-eruption years. To bring out the volcanic signal, in the bottom half of Fig.1 we plot the differences from the pre-eruption years. Nearly all locations experience a similar probability of anomalous precipitation before the eruptions as after. The bulk of anomalous precipitation occurrence in the post-eruption years would hence be expected to occur even without the eruption.

The only regions that stand out as undergoing volcanically forced responses on par with internal variability are northwestern South America and equatorial Africa. Precipitation changes over these equatorial land regions may be due to volcanic aerosols weakening convection, through a mechanism proposed in Khodri et al. (2017), but we do not explore the mechanism further here. We note also that these regions are not a typical focus for studies on remote volcanic climate impacts on societies, which tend to focus on Europe and the Mediterranean basin given their breadth of available written records (though tropical eruption impacts may influence extratropical societies as in Manning et al., 2017). In Figs. S1-S4 we show precipitation anomalies in South America and Africa during the years of the major eruptions. Only for the largest eruption of the millennium (Mount Samalas in the 1250s) do both models and all realizations clearly agree on any local features. In CESM, precipitation anomalies have a robust sign over a small portion of these continents after several of the largest eruptions, though this robustness is not present in the GISS simulations. While we do not evaluate why volcanic impacts are stronger in the CESM ensemble, this may relate to a bias in CESM LME whereby potentially 3x more cooling was simulated than supported by tree ring proxies (Wade *et al* 2020) and hence the precipitation response to this cooling would also be overestimated. For the large majority of locations, neither model shows post-eruption precipitation to be anywhere near as susceptible to the eruptions as to internal variability. Hence, even under exceptionally strong volcanic forcing, post-eruption precipitation anomalies are primarily controlled by internal variability.

Further, we wish to highlight that the rarity of large eruptions should also to be taken into account. In the time span between each of the major eruptions used in Fig. 1, internal variability causes many years to be anomalous by our $\pm 1\,\sigma_{P,\ell}$ criterion. Large eruptions occur roughly once every century, and primarily affect precipitation for only a few years, while internal variability causes anomalous precipitation roughly once every 3 years at each location (see Fig. S5). Precipitation anomalies of volcanic origin, therefore, are a minor contributor to precipitation variability and as we have shown *rarely* accounts for anomalous precipitation even in the aftermath of major eruptions.

3.2 Despite strong global signals, volcanic precipitation influence is weak at nearly all locations

A number of studies (e.g. Iles *et al* 2013, Robock and Liu 1994) have pointed to highly anomalous post-eruption changes in global mean precipitation as evidence of eruptions' importance for Earth's hydroclimate. Here we demonstrate that the global mean signal is a misleading indicator (i.e. a *red herring*), as volcanic influence is in fact weak at nearly every location. Climate models do indeed show large volcanic eruptions to cause substantial global mean precipitation anomalies, compared to the standard deviation of global mean precipitation anomalies $\sigma_{P,g}$. In Fig. 2a, we show post-eruption precipitation anomalies averaged over all global land and across all ensemble members. Further averaging across the 12 largest eruptions of the assessed millennium, these eruptions cause peak anomalies of -2.5 $\sigma_{P,g}$ in GISS and -1.8 $\sigma_{P,g}$ in CESM.

However, in Fig. 2b we see that comparing local anomalies to local variability reveals precipitation anomalies to be within ±0.5 $\sigma_{P,\ell}$ at most locations during the year of peak volcanic impact. If the global mean volcanic signal is so strong, why don't large eruptions produce substantial local anomalies? The key is that global mean precipitation is far less variable than local-scale precipitation. As shown in Fig. 2c, variability of global mean precipitation $\sigma_{P,g}$ is far smaller than the global average of the local variability $\sigma_{P,\ell}$ (compare orange bars). This is because the spatial averaging used to calculate the global mean precipitation removes most internal variability. Hence, even though internal variability has a huge influence locally it has far less influence on spatially averaged precipitation. Precipitation anomalies averaged globally – or over large regions – are hence *not* representative of local anomalies, and are thus of limited practical relevance.

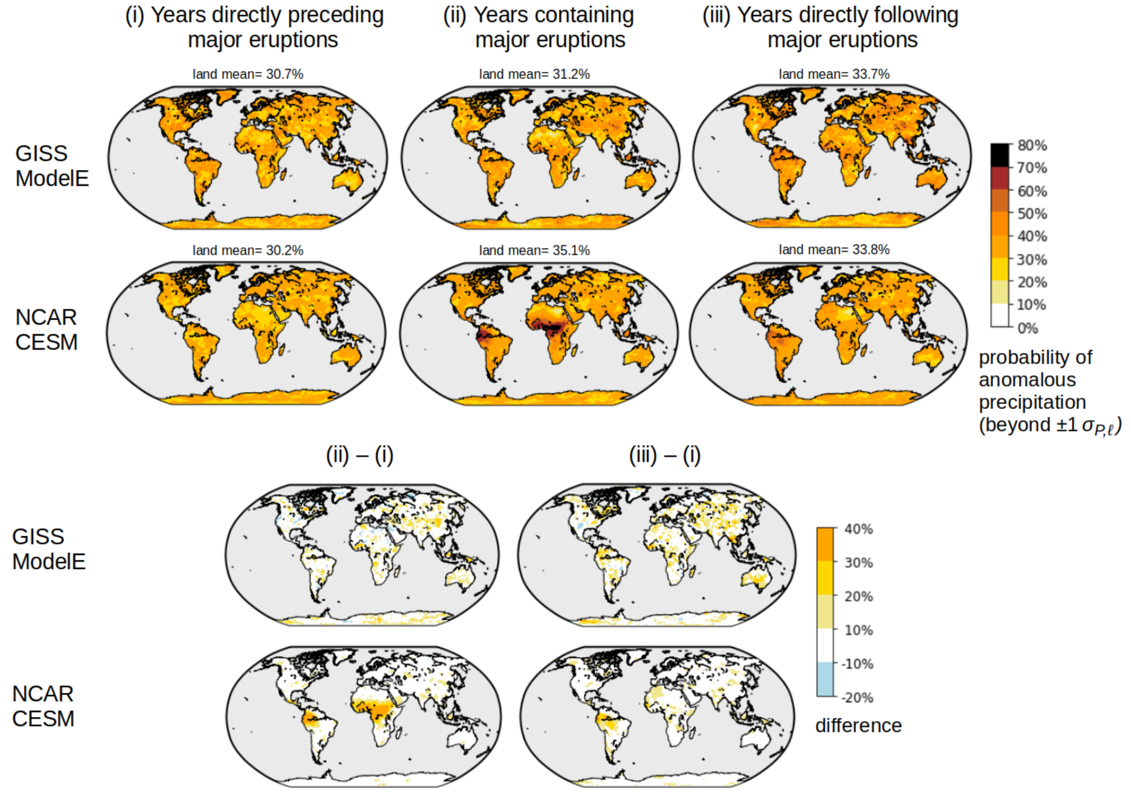


Figure 1. Precipitation is often anomalous in the aftermath of major eruptions, but about as often as before the eruptions occur. Plots show the probability of annual mean precipitation anomalies being more than standard deviation (i.e. beyond ±1 $\sigma_{P,\ell}$) at all land locations, for the years directly before (i), containing (ii), and directly following (iii) major eruptions, in both GISS Model and NCAR CESM last millennium ensembles. The probability of anomalous precipitation is computed as the fraction of ensemble members with anomalous precipitation for each year of interest.

3.3 Statistical significance does not indicate strong anomalies

Here we examine how earlier studies have reported noteworthy eruption impacts on precipitation at many locations, in contrast to the weak anomalies we have shown. The apparent contradiction is largely due to those studies' reliance on statistical significance tests, which are not designed to convey whether a signal causes strong anomalies (Wasserstein and Lazar 2016). Instead they test for rejection of a null hypothesis, typically whether, given a number of samples (here eruption realizations), one may confidently claim a non-zero effect (that eruptions alter precipitation). Statistical significance is the gold standard for reportable effects rather than strength or anomalous nature. The degree of overlap between these criteria is hence worth examining.

An anomaly can be both statistically significant and strong relative to typical fluctuations. After all, significance tests convey the size of a signal relative to random behavior. However, as we demonstrate here, this overlap breaks down in cases where one averages across many events to reach reportable criteria such as a 90% significance level. This averaging smooths over internal variability before the signal to random behavior comparison is made. When applied to volcanic precipitation influence, this creates an apparent discrepancy: the same post-eruption anomalies we have in the previous sections shown to be at most locations indistinguishable from non-eruption anomalies can by previous studies' methods be the basis for claims of positive effects nearly anywhere.

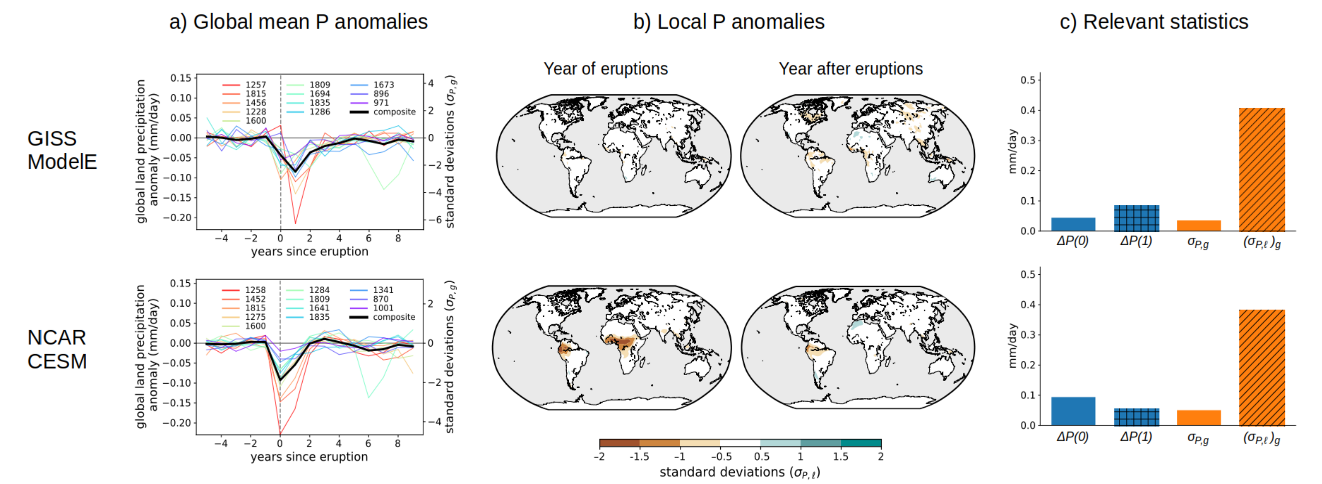


Figure 2. Strong global anomalies, yet weak anomalies nearly everywhere. Shown are the time series of global mean precipitation anomalies (ΔP) averaged across all assessed eruptions **(a)**, maps of post-eruption precipitation anomalies in units of $\sigma_{P,\ell}$ **(b)**, and a comparison ΔP to global and local-scale variability **(c)**. In (a), eruption events are listed in descending order of SO_2 mass, according to the volcanic forcing datasets used as model input. In (c), *ΔP(0)* indicates the global mean precipitation anomalies in the year of the eruptions, *ΔP(1)* the same quantity in the first year after the eruption, $\sigma_{P,g}$ is the standard deviation of global mean precipitation, and $(\sigma_{P,\ell})_g$ is the global mean of the standard deviation of local precipitation.

Figure 3 demonstrates that two distinct significance tests can evidence >90% confidence over most land locations using the same model output as we analyzed in the previous section. Let us start by considering the results from a Monte Carlo based test used in several volcanic precipitation studies (Iles *et al* 2013, Iles and Hegerl 2014, Rao *et al* 2017, Tejedor *et al* 2021). In this method, the average anomalies among volcanic years are compared to distributions of random *pseudo-eruption composite* means. Many sets of random years are chosen, and for each random year precipitation anomalies are calculated relative to the same pre-eruption period as for the volcanic signal. Composite means are then constructed by averaging over the same number of these *pseudo-eruptions* as used for the volcanic signal. This averaging across events severely smooths over internal variability's influence. Our evaluation uses 1000 pseudo-eruption composite means, each being an average over the same number of eruption realizations as used to construct the volcanic signal (12x3 for GISS, and 12x13 for CESM). With this test, statistical significance means that the eruption signal is more extreme than either the 5th or 95th annual precipitation percentiles at each location. As seen in Fig. 3, even in locations where the eruption signal is substantially weaker than typical variations (c.f. Fig. 2b), statistical significance can be attained.

Even though the Monte Carlo significance test is free from assumptions on the underlying probability distribution function, it gives extremely similar results to the far less computationally intensive Student's t-test (see Fig. 3), which has also been used in volcanic precipitation studies (e.g. Yang *et al* 2022, Zhuo *et al* 2021). In this test, the data is assumed to be normally distributed, with variability estimated based on *standard error*, in this case defined as

$$\sigma_{P,\ell} / \sqrt{n} \qquad \text{Equation 1}$$

Here n is sample size (12x3 for GISS, and 12x13 for CESM). In this test, internal variability is again greatly suppressed (this time implicitly) as the number of assessed eruptions is increased. Dependence on sample size also affects the Mann–Whitney–Wilcoxon test (not shown), a third test utilized in volcanic precipitation assessments (Fischer *et al* 2007, Stevenson *et al* 2016). Statistical significance can hence be achieved with a sufficiently large sample size, rendering this an attainable outcome rather than an innate property of the assessed phenomenon. Significance hence does not on its own imply a strong or important volcanic effect. Though volcanic influence on precipitation can be deemed stronger than no effect at most locations, for confidence in this meager criteria to require thousands of years' worth of major eruptions – even in simulations that substantially exaggerate the cooling driving much of the precipitation response (Wade *et al* 2020) – suggests that this effect has limited practical relevance.

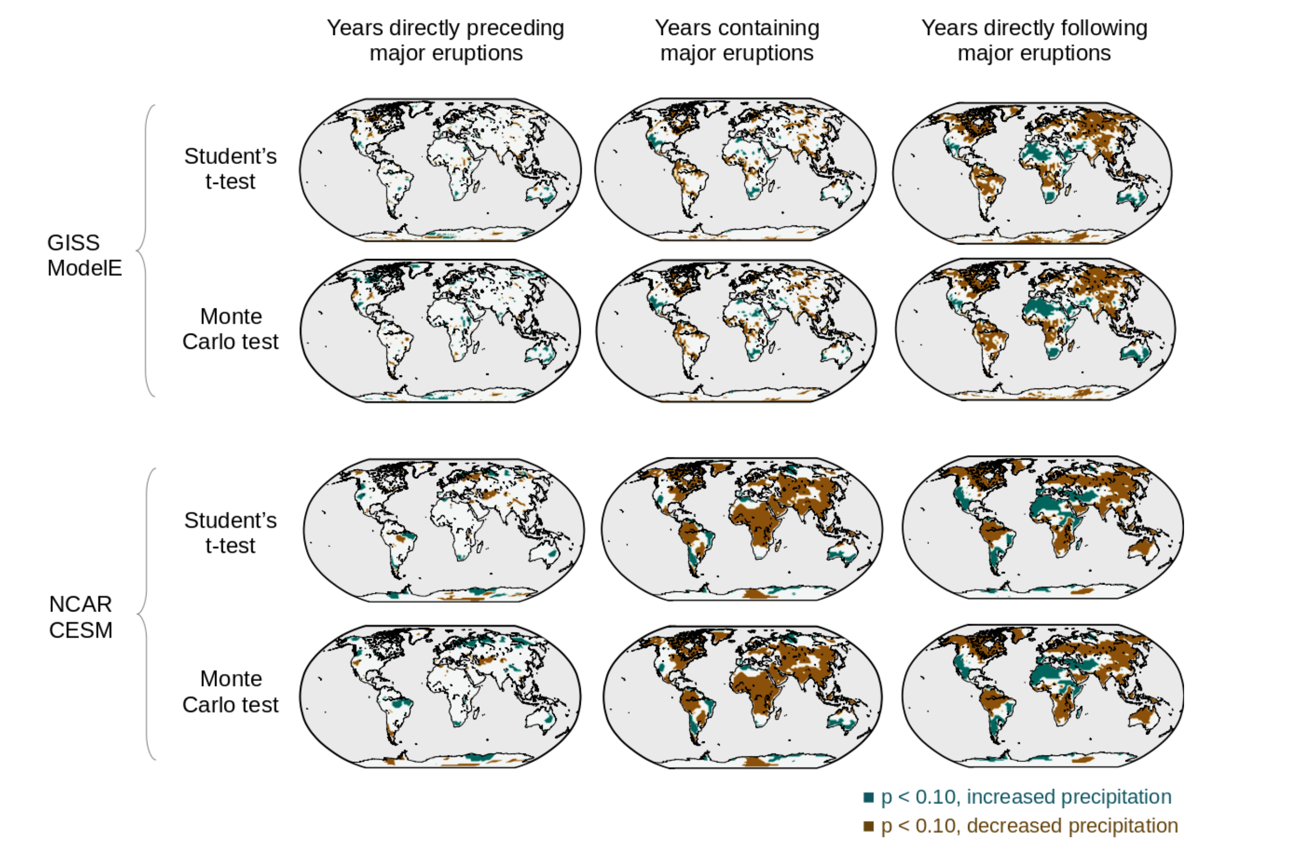


Figure 3. Weak volcanic precipitation impacts, but "statistically significant". Shown are the results of two standard tests for statistically significant volcanic precipitation impacts across the assessed eruption ensembles. Areas highlighted have p-values below 0.10, and are further distinguished by the sign of the anomaly.

3.4 No clear observational evidence of eruption-induced precipitation anomalies

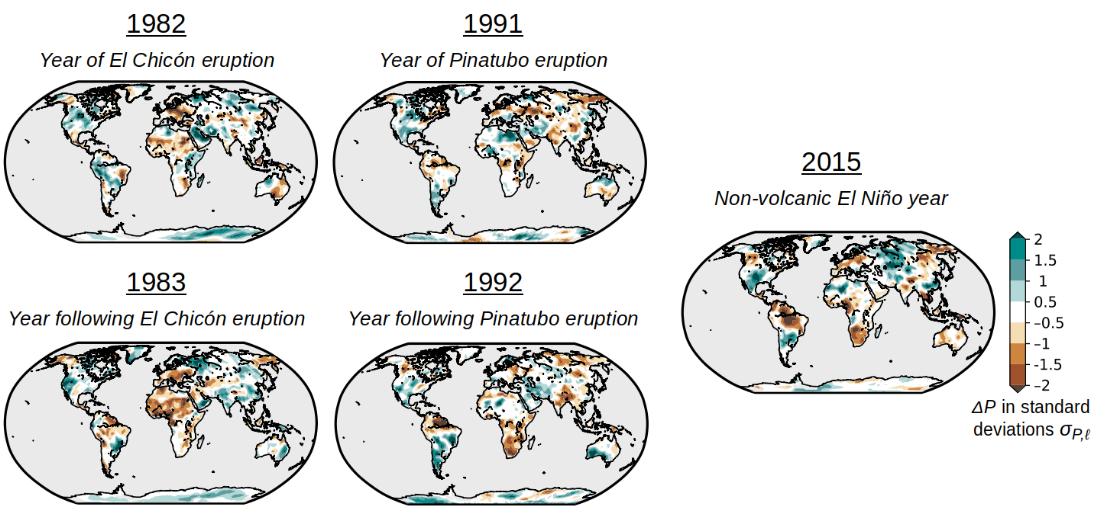
Now that we have evaluated precipitation statistics in model simulations, we demonstrate that observations also do *not* show substantial volcanic impacts on precipitation. Here we examine precipitation anomalies following the eruptions of El Chicón in 1982 and Pinatubo in 1991 in the GPCP observational dataset (described in Section 2.3). These anomalies are shown in Fig. 4, where we illustrate both the year of the eruption and the first post-eruption year.

Many strong anomalies can be seen. However, this does not in itself convey atypical years, not that the eruption is the cause. In fact, the post-eruption anomalies shown in Fig. 4 are overall not atypical. Metrics across all land areas, which are tabulated at the bottom of Fig. 4, show only very slight anomalies compared to the average values across all usable years (1983 to 2017, as 1979-82 lack sufficient pre-eruption periods). While the spatial average of the anomaly magnitude ($|\Delta P|$) is $0.88\,\sigma_{P,\ell}$ and $0.82\,\sigma_{P,\ell}$ in the two post-eruption years, it is on average $0.80\,\sigma_{P,\ell}$ across all years. This result closely matches expectations if we approximate internal variability as producing normally distributed annual anomalies. In this approximation the magnitude would follow a *half-normal distribution*, with its mean as follows (Ahsanullah *et al* 2014):

$$\text{mean}(|\Delta P|) = \sqrt{2/\pi} \times \sigma_{P,\ell} \approx 0.80\,\sigma_{P,\ell} \qquad \text{Equation 2}$$

where ΔP is the volcano-induced precipitation anomaly. As in Section 3.1, these results again suggest that most anomalies would be present even without the eruptions.

Even more interesting, we now show that key features of the volcanic years can exist in years that do *not* follow sizable eruptions. For both post-eruption first years (1983 and 1992), this includes slightly lower-than-usual spatial mean ΔP, slightly higher mean anomaly magnitude ($|\Delta P|$), and a slightly heightened proportion of land areas where $|\Delta P| > \sigma_{P,\ell}$. As is shown in Fig. 4, the year 2015 has similar anomalies as the two post-eruption years. In fact, 2015's precipitation anomalies have an r=0.21 spatial correlation (land only, calculated in terms of standard deviations) with those in 1992, substantially closer than 1992's weak 0.10 correlation to the other post-eruption year of 1983. Eruptions may slightly promote El Niño conditions, yet such an effect is far too weak to be confidently apparent in two eruptions (Dee *et al* 2020). Hence, no clear spatial signature (*fingerprint*) of the volcanic eruption is evident in precipitation observations.



	1982	1983	1991	1992	2015	1983-2017 mean
mean(ΔP)	$+0.04\,\sigma_{P,\ell}$	$-0.08\,\sigma_{P,\ell}$	$-0.06\,\sigma_{P,\ell}$	$-0.11\,\sigma_{P,\ell}$	$-0.17\,\sigma_{P,\ell}$	$0.00\,\sigma_{P,\ell}$
mean($|\Delta P|$)	$0.81\,\sigma_{P,\ell}$	$0.88\,\sigma_{P,\ell}$	$0.78\,\sigma_{P,\ell}$	$0.82\,\sigma_{P,\ell}$	$0.86\,\sigma_{P,\ell}$	$0.80\,\sigma_{P,\ell}$
% of land where $|\Delta P| > 1\,\sigma_{P,\ell}$	32 %	36 %	31 %	33 %	35 %	32 %

Figure 4. Observed annual precipitation anomalies in the years containing and after El Chicón and Pinatubo. For comparison we also show a separate El Niño year (2015) with a similar spatial pattern as followed Pinatubo. A statistical analysis of precipitation anomalies across all land areas is displayed at the bottom of the figure.

4. Discussion

We have demonstrated that volcanic aerosol is generally a minor contributor to precipitation variability over land, even in the aftermath of large tropical eruptions. Instead, internal variability is – at nearly all locations – the dominant control on post-eruption precipitation. Our conclusion is based on a detailed reexamination of datasets and methods that had been used in studies reporting noteworthy volcanic hydroclimate impacts. We are not claiming that volcanic aerosol cannot cause anomalous precipitation anywhere, but that such occurrences are exceptionally rare and cannot adequately be deduced from data averaged across large regions or many events. We note that our analysis identifies precipitation reduction over equatorial Africa and South America when simulating some of the strongest eruptions of the last millennium. However, in all other cases local-scale precipitation statistics are found to be similar after major eruptions to before the eruptions occur. This result is in line with the finding that seasonal precipitation forecast skill is in most land areas not appreciably affected by inclusion of a dense volcanic aerosol layer (Aquila *et al* 2021).

Our analysis demonstrates that metrics smoothing over internal variability fail to convey the anomalous extent of a forced response. Instead, a more appropriate comparison between a signal and random behavior keeps both sides of this comparison intact. Simulation ensembles are valuable tools for assessing the relative contributions of forced response and internal variability. The ratio between volcanic signal and local variability, as used here, is simplistic yet provides a straightforward measure of the signal's anomalous nature in a particular time period. We encourage more thorough attempts to convey the probability of exceptional climate damage based on standard climate model output.

Our analyses imply that volcanic aerosol impacts on precipitation are very rarely substantial enough to induce societal change. The abundance of research claiming eruption-induced impacts on human history may reflect that a) these case studies are truly rare instances or b) at least some evaluations follow an oversimplified causation bias that is endemic in the field of climate and society (Degroot *et al* 2021). Internal variability is rarely seen as a suitable focus for historical case studies, in spite of its great importance for past societies (Degroot *et al* 2022). One example is offered by the 1783 Laki eruption, whose impacts have been reassessed as potentially driven by a combination of El Niño and Northern Annular Mode conditions rather than volcanic aerosols (e.g. D'Arrigo *et al* 2011). We note that, even in the rare cases where models do simulate eruptions as altering hydroclimate substantially outside its typical range, this might not be strong evidence for eruption-induced society change theories. For one, model experiments – including those used in our analysis – substantially overestimate volcanic aerosol-induced cooling (Wade *et al* 2020), so likely also overestimate the precipitation response to this cooling. Second, climate models can at most provide an estimate of climate anomalies, with no rigorous method for translating climate anomalies into impacts on society. Adding further difficulty, the relatively short duration of eruption-induced climate anomalies makes these incommensurate to those caused by other forcings (e.g. greenhouse gas emissions). Societies have a level of inbuilt ability to absorb temporary shocks, e.g. through food storage, unlike prolonged anomalies that build stress over time and hence are more likely to induce conflicts (Ulus and Ellenblum 2021). Rigorously establishing the influence of volcanic aerosols continues to be a challenge.

Acknowledgments

The authors thank Kevin Dallasanta, Christopher Colose, and Allegra LeGrande for helpful discussions. LMP is funded, in part, by an award from the US National Science Foundation to Columbia University. This assessment has been based entirely on publicly available datasets. Output from the last millennium ensembles of NCAR CESM and GISS ModelE is available online at https://www.cesm.ucar.edu/community-projects/lme and https://esgf-node.llnl.gov/search/esgf-llnl/, respectively. The GPCC precipitation dataset is at https://psl.noaa.gov/data/gridded/data.gpcp.html.

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