https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

Modelling compounding global climate extremes following the Mazama eruption of Crater Lake 7600 years ago

Evelien JC van Dijk[1,2,3], Felix Riede[3], Claudia Timmreck[4], Kirstin Krüger[1], and Michael Sigl[1,2]

[1]Department of Geosciences, University of Oslo, Oslo, Norway
[2]Department of Physics and the Oeschger Center for Climate Change Research, University of Bern, Bern, Switzerland
[3]Department of Archaeology and Heritage Studies, Aarhus University, Aarhus, Denmark
[4]Max Planck Institute for Meteorology, Hamburg, Germany

Correspondence: Evelien van Dijk (e.van.dijk@geo.uio.no)

Abstract. The Mount Mazama eruption (Crater Lake, USA) c. 7600 years ago counts among the largest eruptions of the Holocene, yet its impact on contemporaneous climate, environment, and humans remains incompletely understood. Here, we simulate the Mazama eruption using the Max Planck Institute Earth System Model with a volcanic stratospheric sulfur injection of 162 Tg S based on estimates from ice core records, to project potential impacts on global climate and society. The model simulations reveal severe and diverging surface climate anomalies in different regions of the world. We investigate specifically the regions of the Mediterranean and Near East, and southeast Asia distal from the eruption source, for which we project compounding extreme events. We argue that the compound occurrence of severe cooling and precipitation extremes likely had a significant impact on these main regions of human settlements and spread of agricultural practices, with crop failures due to drought, and potential flooding in areas experiencing extreme precipitation increase. Our study illustrates how very large volcanic eruptions can alter surface climate with varying and contrasting compound anomalies affecting much of the land surface. A volcanic event similar to the Mazama eruption may well occur in the next decades to centuries. Today, an eruption of this magnitude would pose substantial risks of multiple breadbasket failures, impacting food security globally, which in turn may lead to further societal upheaval. Studying very large past eruptions is imperative for better understanding the risks associated with low-likelihood, high-impact events – that global society is patently ill-prepared for.

1 Introduction

Studies of the Common Era (CE) demonstrate that large volcanic eruptions have considerable effects on global climate, often leading to crop failures, which in turn impact food security, health, and socio-political systems (Büntgen et al., 2020; Guillet et al., 2017; Newhall et al., 2018; Oppenheimer, 2003; van Dijk et al., 2023). In considering these societal impacts, temperature and precipitation responses have been in focus, as these are known to affect crop yield and, therefore, living conditions (Luterbacher and Pfister, 2015). Eruptions over the last two millennia cover only a limited range of eruption sizes, with very large 1815 Tambora (volcanic explosivity index (VEI) of 7, c.30 Tg S (Self et al., 2004; Gao et al., 2008) strength and larger being rare (between 1 and 2 eruptions every 1000 years) (Newhall et al., 2018; Meredith et al., 2025).

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

Technological advances based on real-time continuous flow analysis techniques of ice-cores have been instrumental in unraveling the global volcanic eruption history of such high-magnitude eruptions. These analytical improvements have facilitated new insights into their impact on climate (Sigl et al., 2014, 2015). Several extremely large eruptions have been identified between 7000 and 5000 Before Common Era (BCE) in ice-cores from both Greenland and Antarctica (Sigl et al., 2022) in close agreement with the independent geological eruption record (Brown et al., 2014; Newhall et al., 2018). By analyzing the geochemical composition of tephra shards entrapped in the ice (Davies et al., 2024), one of these eruptions is firmly associated with the cataclysmic eruption of Mount Mazama (in the following called Mazama).

Mazama was located in the Northern Hemisphere (NH) mid-latitudes (43°N) in the Cascades mountain range in Oregon (USA) and today consists of Crater Lake. This is a caldera remnant, the relic of a major volcanic eruption that occurred c. 7600 years ago (in the following called 5600 BCE, with an estimated bulk eruption volume of > 150 km^3, a magnitude (M) of 7.1, and a VEI of 7 (Buckland et al., 2020). Petrological analyses reveal minimum estimates of 34 Tg S and 2170 Tg Cl releases to the atmosphere (Mandeville et al., 2009). The Mazama tephra-fall was widespread (Buckland et al., 2020; Pyne-O'Donnell et al., 2012), covering most of North America from the Cascades to the Atlantic seaboard at variable depths. Some of the erupted material traveled as far as Greenland, where it was deposited as a crypto-tephra layer within the polar ice sheets, alongside large quantities of volcanic sulfuric acid and chloride (Davies et al., 2024; Zdanowicz et al., 1999). From sulfuric acid deposition in the ice, a volcanic stratospheric sulfur injection (VSSI) of 162 Tg S ($\pm 94, 2\sigma$)) (or 320 Tg SO_2 ($\pm 188, 2\sigma$)) was recently estimated for this eruption (Sigl et al., 2022). This ranks among the greatest stratospheric gas releases of the Holocene and the last glacial period (Dunbar et al., 2017; Lin et al., 2022, 2023; Innes et al., 2025). Vettoretti et al. (2026) estimated a return period of 5,000 years (2,700-12,300 years, 95% CI) for VSSI of 162 Tg S eruptions, meaning a chance of 1 to 3% of such an event to occur until 2100. While these are low-likelihood events, they may well occur in the next decades to centuries and pose a major risk for human society (Stoffel et al., 2024).

Less is known about Mazama's global and regional climatic and social impacts. The extremely large eruptions of Kikai, Kurile Lake, and Tao Rusyr (identified between 7000 and 5000 BCE, VEI $\geq$7, VSSI > 140 Tg S; Sigl et al. (2022)) have been linked to global glacier advances and distinct climate anomalies identified in Greenland ice cores and other climate proxies (Kobashi et al., 2017; Paine et al., 2026). Studies on more recent NH mid to high-latitude eruptions such as Aniakchak (1628 BCE, VEI 6, VSSI 52 Tg S), Okmok (43 BCE, VEI 6, VSSI 48 Tg S), Zavaritskii (1831, VEI $\leq$6, VSSI 12 Tg S), and Katmai (1912, VEI 6, VSSI 6 Tg S) all reveal extreme weather and climate conditions, as recorded in (early) instrumental observations, reanalysis, and proxy records (Andrews et al., 2025; McConnell et al., 2020a; Pearson et al., 2022; Hutchison et al., 2025).

Archaeological finds from around the Mazama eruptive center, as well as oral histories, indicate that communities living in the vicinity south of the volcano were directly affected by the ash fall (Harmon, 2002), as were proximal environments (Long et al., 2014). Palaeoecological and archaeological studies suggest that societies living on the Great Plains and in subarctic Canada at the time were directly affected by this ash-fall. There, the eruption is likely to have led to a temporary abandonment of the affected landscapes (Beaudoin and Oetelaar, 2006; Oetelaar and Beaudoin, 2005; Oetelaar, 2015, 2021; Rainville, 2016).

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

Volcanic eruptions also have the potential to affect a wider range of climate parameters beyond temperature. Despite the observation that compound events pose an extraordinary risk (Ridder et al., 2020; Zscheischler et al., 2018), the past societal impacts of multiple volcanically induced climate extremes have rarely been examined in detail. Compound events, first introduced by the Intergovernmental Panel for Climate Change in their Special Report for Climate Extremes (SREX, 2012), have been used to describe a combination of multiple drivers and/or hazards that contribute to societal or environmental risk (Zscheischler et al., 2018). Here, we will use the notion of compound events to consider how a large volcanic eruption such as Mazama may cause several impacts occurring at the same time.

In this study, we investigate the global and regional distal climatic impacts of the Mazama eruption in 5600 BCE utilizing Earth System Modelling and an ice core based VSSI estimate to shed more light on the potential impacts during a time period and in places where limited precisely-dated environmental and archaeological records exist. We use the Max Planck Institute Earth System Model (MPI-ESM) with an ensemble of ten simulations branched off the MPI-ESM Holocene run (Dallmeyer et al., 2021), using volcanic forcing corresponding to a VSSI of 162 Tg S, which is explained in more detail in Section 2. In Section 3 the results are presented and discussed, including the uncertainties of the study and the repercussion of a Mazama-like eruption in a present day setting. Section 5 contains the summary and conclusion.

2 Methods

2.1 The Max Planck Institute Earth System Model

The MPI-ESM Holocene experiments (Bader et al., 2020; Dallmeyer et al., 2021) were carried out using version 1.2 of the MPI-ESM (Mauritsen et al., 2019). The atmospheric component (ECHAM6) has a horizontal resolution of T63 (1.9° x 1.9°) and a vertical resolution of 47 levels between the surface and the top of the atmosphere at 80 km (0.01 hPa, Stevens et al. (2013)). The ocean component (MPIOM) has a horizontal resolution of 1.5° and 40 vertical levels (Jungclaus et al., 2013). The full carbon cycle is included in MPI-ESM with the subsystem models JSBACH (Reick et al., 2013) and HAMOCC (Ilyina et al., 2013). In the simulations, the atmospheric CO_2 concentration is prescribed. The dynamic vegetation module (in JSBACH) represents different plant functional types (trees, grass, and shrubs) responding to environmental thresholds (i.e., minimum temperature, net primary production, bare soil fraction) (Dallmeyer et al., 2021).

The MPI-ESM model has been consistently used for past, present, and future climate studies, including volcanic eruptions (Timmreck et al., 2021; Ward et al., 2021; Fang et al., 2022, 2023; van Dijk et al., 2022; Zanchettin et al., 2022). This MPI-ESM version has been shown to produce reliable results in studies of the climate effect of large volcanic eruptions during the Common Era (e.g. Timmreck et al. (2021); Ward et al. (2021); Fang et al. (2022, 2023); van Dijk et al. (2022)). Furthermore, observed global and hemispheric mean temperature anomalies from the HadCRUT5 dataset (Morice et al., 2021) fall within the range of Post-Pinatubo climate anomalies simulated by various CMIP models, including the MPI-ESM (Zanchettin et al., 2022). As has been shown by van Dijk et al. (2024) and Verkerk et al. (2025) the same model version also performs well further back in time during the Holocene, where the availability of high-resolution proxy reconstructions is limited.

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

2.2 Model experiments

The Holocene simulation is a transient simulation that spans the Middle and Late Holocene (6000 BCE to 1850 CE). It includes prescribed variations in orbital forcing (Berger, 1978) and greenhouse gas concentrations (Brovkin et al., 2019; Köhler, 2019) (the `orbital + GHG` run), as well as land-use change (Hurtt et al., 2020), stratospheric ozone which varies with solar irradiance (Bader et al., 2020), solar irradiance Krivova et al. (2011) and stratospheric volcanic aerosol (Sigl et al., 2022) (the `all forcing` run, see also section 2.3). The spin-up simulation was run with constant conditions at 6000 BCE. More information on the model setup and the Holocene run can be found in Dallmeyer et al. (2021) and van Dijk et al. (2024).

The Mazama ensemble was branched off the Holocene run. A series of ten simulations was carried out for the period around the eruption of Mazama, which is set to the year 5624 BCE, based on ice core data. The simulations are perturbed by slightly altering the atmospheric vertical diffusivity by $1 \cdot 10^{-5}$ m^2s^{-1} for a short time 5, 10 and 20 years prior to the eruption date to create a slightly different climate state for each ensemble member.

2.3 Volcanic forcing

The volcanic forcing used for the simulations in this study is the HolVol1.0 data set Sigl et al. (2022), which is based on sulfur and sulfate records from four ice cores in Greenland and Antarctica. January was taken as the eruption month as a plausible eruption scenario (see Section 4.2.2). The stratospheric sulfur estimates from the ice cores are converted to zonal mean aerosol radiative properties using the Easy Volcanic Aerosol (EVA) model (Toohey et al., 2016). EVA calculates wavelength-dependent aerosol extinction, single scattering albedo, and scattering asymmetry factor values, which were then used as input for the MPI-ESM radiation scheme. Aerosol extinction is assumed to be linearly proportional to mass for eruptions smaller than the 1815 Tambora eruption, and follows a two-thirds power-law scaling for eruptions larger than that (Crowley and Unterman, 2013). Each eruption in the model simulations gives an abrupt increase in aerosol optical depth (AOD), which is calculated using the previously mentioned aerosol properties (Fig. 1a,b). In the following, we use the stratospheric aerosol optical depth (AOD) at 550 nm as a measure of volcanic forcing.

2.4 Analysis

For the anomaly calculations, the mean of the years before the Mazama eruption in the Holocene run was taken as the reference period for each run (6000-5624 BCE). This 376-year mean was then subtracted from the absolute values of each variable in the ensemble runs to calculate an anomaly value for each time step. This pre-eruptive period was also used to calculate anomaly significance, taking twice the standard deviation (2σ).

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

3 Results

3.1 Global Climate Response

In our model simulations, the main stratospheric sulfate aerosol loading is mostly confined to the NH, with a duration of approximately four to five years (Fig. 1a-b). This leads to surface cooling with a peak global annual mean 2 m air temperature anomaly of -1.1 K in the second year after the eruption, while the NH peak annual temperature anomaly is -1.8 K. The temperature response lasts for about seven years before returning within the 2σ range (Fig.1c). Two additional events similar to a Pinatubo-size eruption occurred ten and sixteen years after the Mazama eruption. These result in a decrease in temperature, but this response is very small compared to the Mazama-like eruption, with a cooling of 0.2 and 0.1 K, respectively. The mean precipitation response after the Mazama eruption consists of a severe drying, both globally (7 mm month^{-1}) and in the NH (16 mm month^{-1}), which is also reflected in the global and NH mean runoff. The net primary production (NPP) also shows a decrease for both global and NH mean, with a reduction of up to 10% for the NH (Fig. 1f).

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

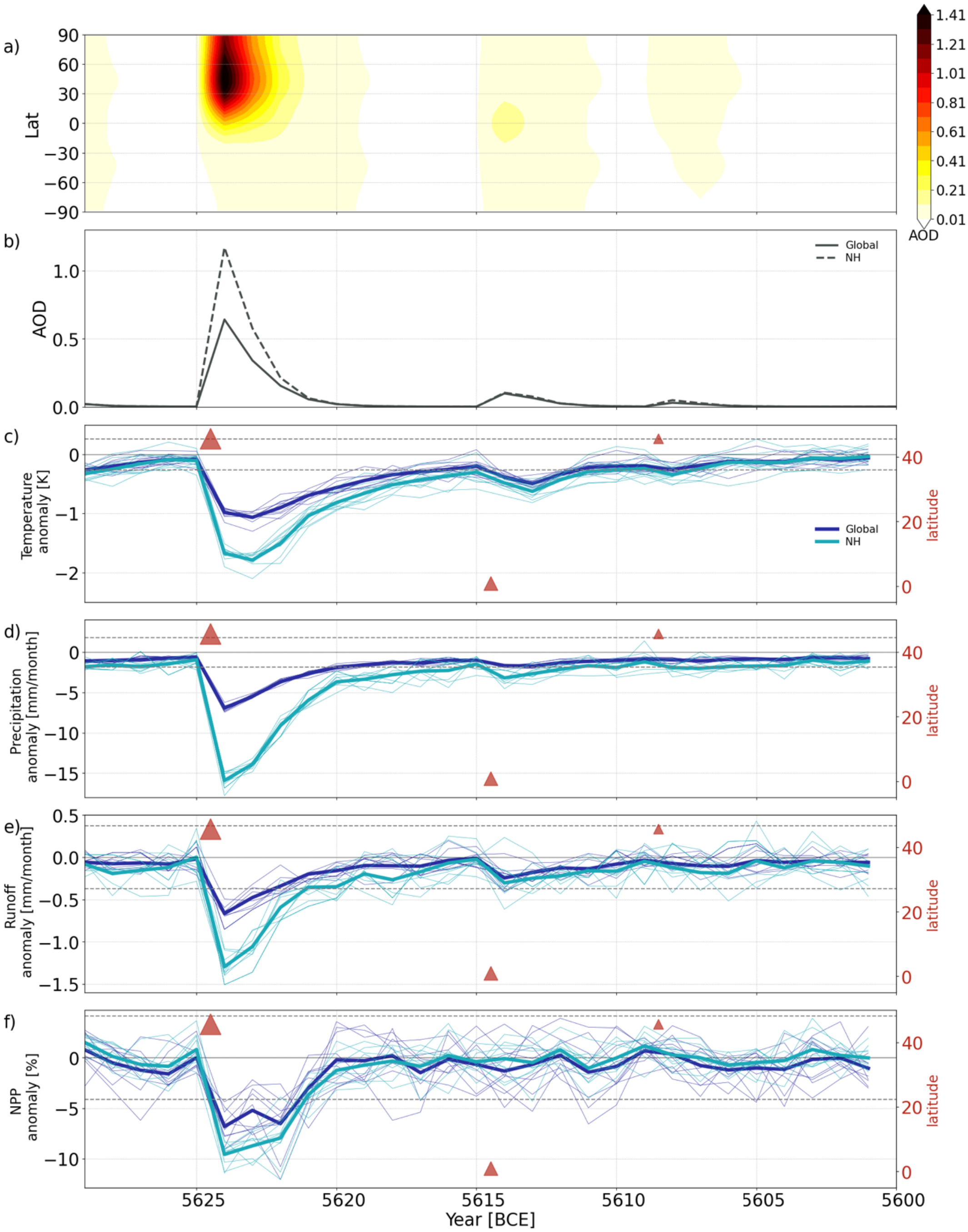

Figure 1. a) Latitudinal distribution of monthly mean Aerosol Optical Depth (AOD; volcanic forcing). Global and NH (0-90°N) mean annual mean anomalies for b) AOD, c) 2 m air temperature, d) precipitation, e) run-off, and f) net primary production (NPP). The right y-axes indicate the latitude (°N) of eruptions, marked with red triangles, whereas the size of the triangles mark the size of the eruptions. The gray dashed lines indicate the 2σ ranges.

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

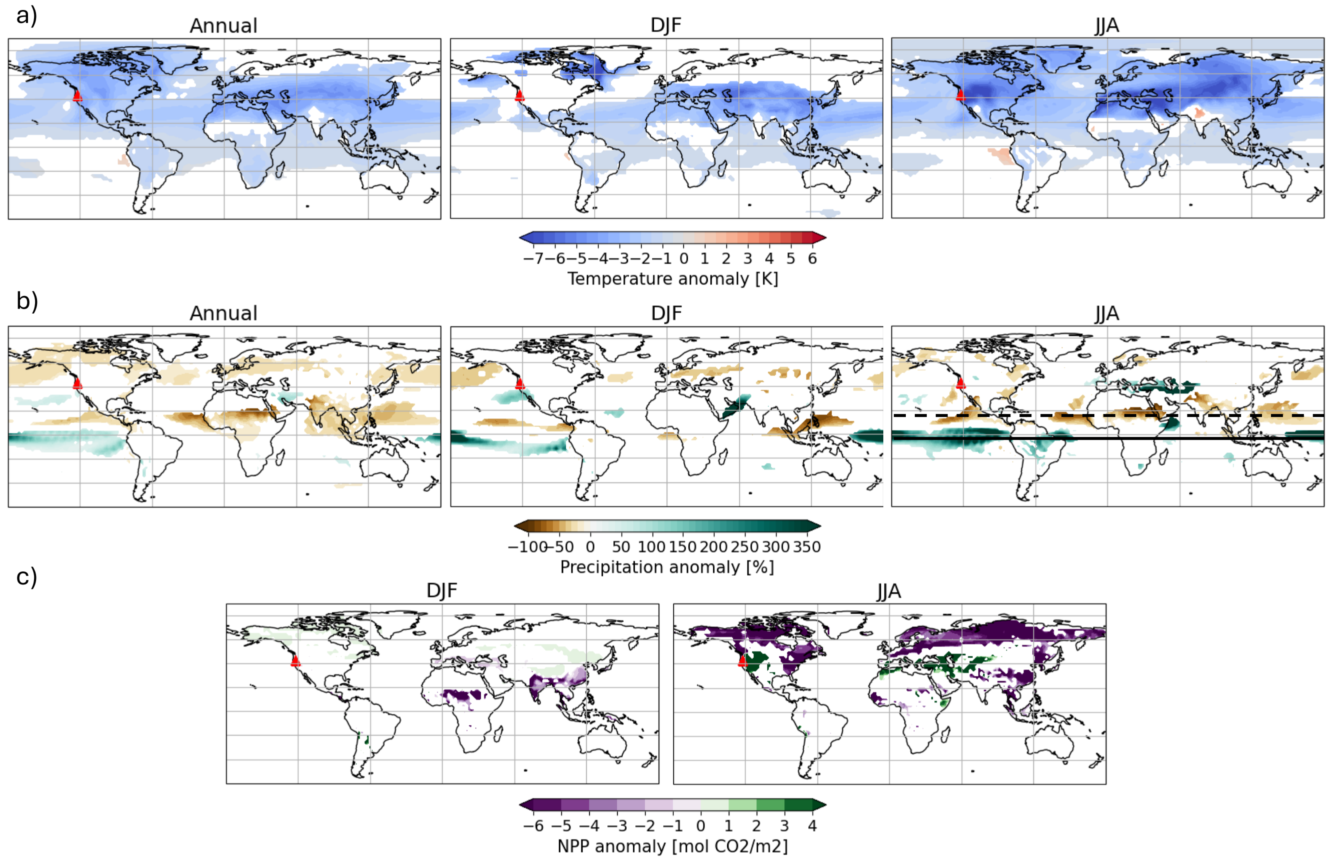

Figure 2. Global anomalies (with reference to years before the eruption in control run) for the 2-year mean annual, boreal winter (DJF), and boreal summer (JJA) a) 2 m air temperature, b) precipitation (in percent), and c) net primary production (NPP, only JJA and DJF). For precipitation (b), the original zonal maximum (dashed line) as well as the new zonal maximum (solid line) is given for the boreal summer months, representing the shift in ITCZ. Only data falling outside the 2σ range are shown.

The post-eruptive two-year mean volcanic cooling is strongest over NH continental areas (Fig. 2a). This is because land has a lower heat capacity than the ocean, which results in land masses experiencing a larger decrease in temperature than the oceans. Precipitation changes are largely mediated by the Inter-Tropical Convergence Zone (ITCZ) shifting into the Southern Hemisphere (SH) as a result of the aerosol loading and the attendant cooling occurring in the NH. This is a well-known effect of NH extra-tropical volcanic eruptions (Liu et al., 2016). In our simulations, this leads to a strong decrease in precipitation in monsoonal areas such as India and South East Asia. Simultaneously, a strong increase in precipitation occurs south of the dry regions in the South Pacific and the Amazon area (Fig. 2b), indicating a southward shift of the ITCZ by nearly 20° during NH monsoon season. The post-eruptive annual mean fluctuations in NPP are not significant (not shown), but analyzing their seasonal patterns reveals that there is a significant strong decrease in NPP in large areas of the Sahel, India, and East Asia from December to February, and in large parts of the high latitudes and North America from June to August. An increase in NPP

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

is simulated over the American Midwest and the Near East in boreal summer, both regions that also experience an increase in precipitation (Fig. 2c).

The Mediterranean and Near East regions stand out due to the strongest cooling in combination with an extreme increase in precipitation, as well as an increase in NPP in the summer months. In contrast, India and Southeast Asia experience a decrease in precipitation and NPP. We will use these regions to further illustrate the diverging extremes that in our model simulations occur in the years following the Mazama eruption.

3.2 Impacts in the Mediterranean and the Near East

The Mediterranean and the Near East are located on the border between the dry subtropical and wet European mid-latitude climate zones. Because of this, slight changes in atmospheric circulation such as those following large volcanic eruptions can lead to significant changes in the (hydro)climate of these regions. The southward shift in the ITCZ in the wake of a large NH extra-tropical eruption (Fig. 2) causes the Hadley and Ferrel cells to shift southward as well, resulting in wetter conditions in the Mediterranean and the Near East. This effect is strongest in boreal summer (Fig. 3 b) when the displacement of ITCZ is the most noticeable in comparison to its climatological presence in the NH at this time of year. Our model simulations project a $>$40 mm month^{-1} ($>$350%) increase in precipitation in areas such as present-day southern Turkey and around the southern and eastern parts of the Caspian Sea (Fig. 3b). This relative increase is so pronounced because these areas receive very little precipitation in the summer months.

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

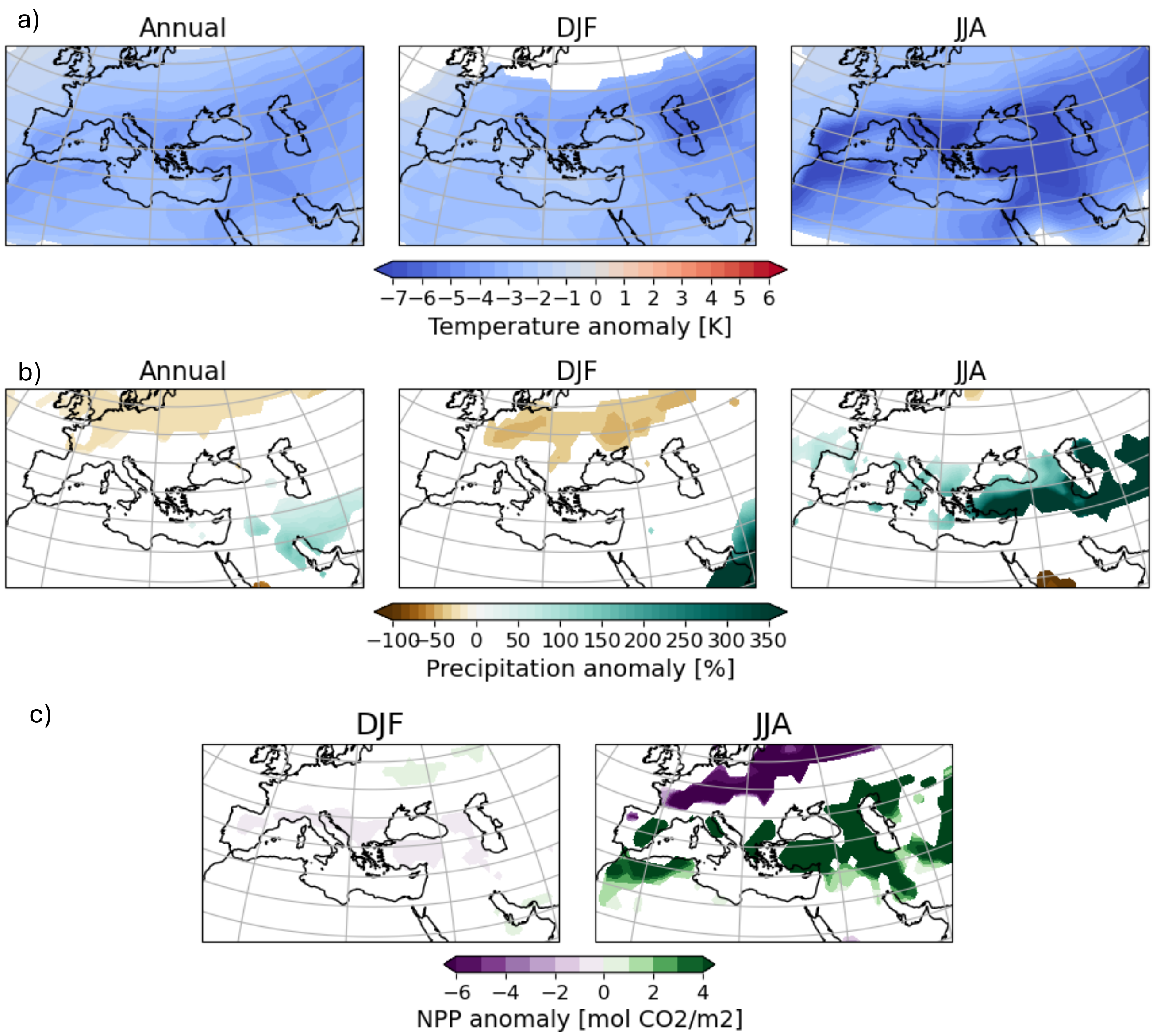

Figure 3. Anomalies (with reference to years before the eruption in control run) for the 2-year mean annual, boreal winter, and boreal summer a) 2 m air temperature, b) precipitation (in percent), and c) net primary production (NPP) for the Mediterranean and Near East. Only data falling outside the 2σ range are shown.

In our simulations, NPP increases by over 4 mol $CO_2\,m^{-2}$ (>300%) in the summers following the Mazama eruption due to the increase in precipitation (Fig. 3c). This is expected, and would also lead to an increase in agricultural yields. Yet, the extreme summer precipitation increase in this normally very arid area could also have had negative consequences for contem-

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

poraneous agricultural societies. Mesopotamian societies relied on rain-fed agriculture (Araus et al., 2014) around the time of the eruption, and with soil conditions and agricultural practices adapted to extremely dry conditions, this could potentially have led to severe flooding and destruction of summer crops. Using a major extra-tropical eruption in 626-27 CE as an historical analogue we argue in section 4.1 that the Mazama eruption may plausibly be linked to one of the largest historic floods of the Tigris/Euphrates rivers with adverse effects on contemporaneous human societies.

The Mazama eruption occurred around 5600 BCE, on the boundary between the Neolithic and the Chalcolithic (Copper Age, around 5.3 BCE) in the Iranian highlands (Kehl et al., 2023). Around the mid-sixth millennium BCE, a widespread abandonment of settlements and re-establishment of smaller communities at other locations occurred from Iran to Syria (Miller and Wetterstrom, 2000). This may have been due to overgrazing and inadequate fallowing (Miller and Wetterstrom, 2000). This area stands out in our simulations for the hydroclimatic fluctuations (Fig. 3b) in annual mean, with an increase of precipitation around 20 mm month^{-1}, and an increase in runoff of more than 10 mm month^{-1}. We propose that weather extremes such as frost occurrence and flooding linked to the simulated climate anomalies may have accelerated ongoing process of culture change by putting pressure on existing agricultural systems and associated power structures (Hoffman, 1999), although we acknowledge that such anomalies cannot be resolved in this region in paleoclimatic and archeological records.

3.3 Impacts in India and Southeast Asia

In contrast to the eastern Mediterranean, India experiences dry and warm conditions that exceed the 2σ threshold in the boreal summer months in our model simulations (Fig. 4a-b). This is consistent with other studies where the warming over India in the aftermath of an extremely large volcanic eruption is due to reduced cloud cover and soil moisture (Timmreck, 2012). Dry conditions in India caused by a failure of the summer monsoon as projected in our simulations are consistent with other studies of volcanic eruptions using climate models, proxy reconstructions, and observations (Anchukaitis et al., 2010; Man et al., 2014; Schneider et al., 2009; Warren, 2026). Precipitation deficits strongly affect traditional societies, regardless of whether they rely on agriculture or foraging (Benati and Guerriero, 2021; Manning et al., 2023; Ordonez and Riede, 2022). These very dry conditions prevail in a large area of India and parts of Southeast Asia, both in the annual mean and the summer mean precipitation for the two years after the Mazama eruption (Fig. 4b). Drought conditions such as these would also have reduced flow in the major monsoon-fed riverine arteries of these regions, which both in the past as well as in the present play a decisive role in structuring the economies and societies in the region (Shah and Mishra, 2018).

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

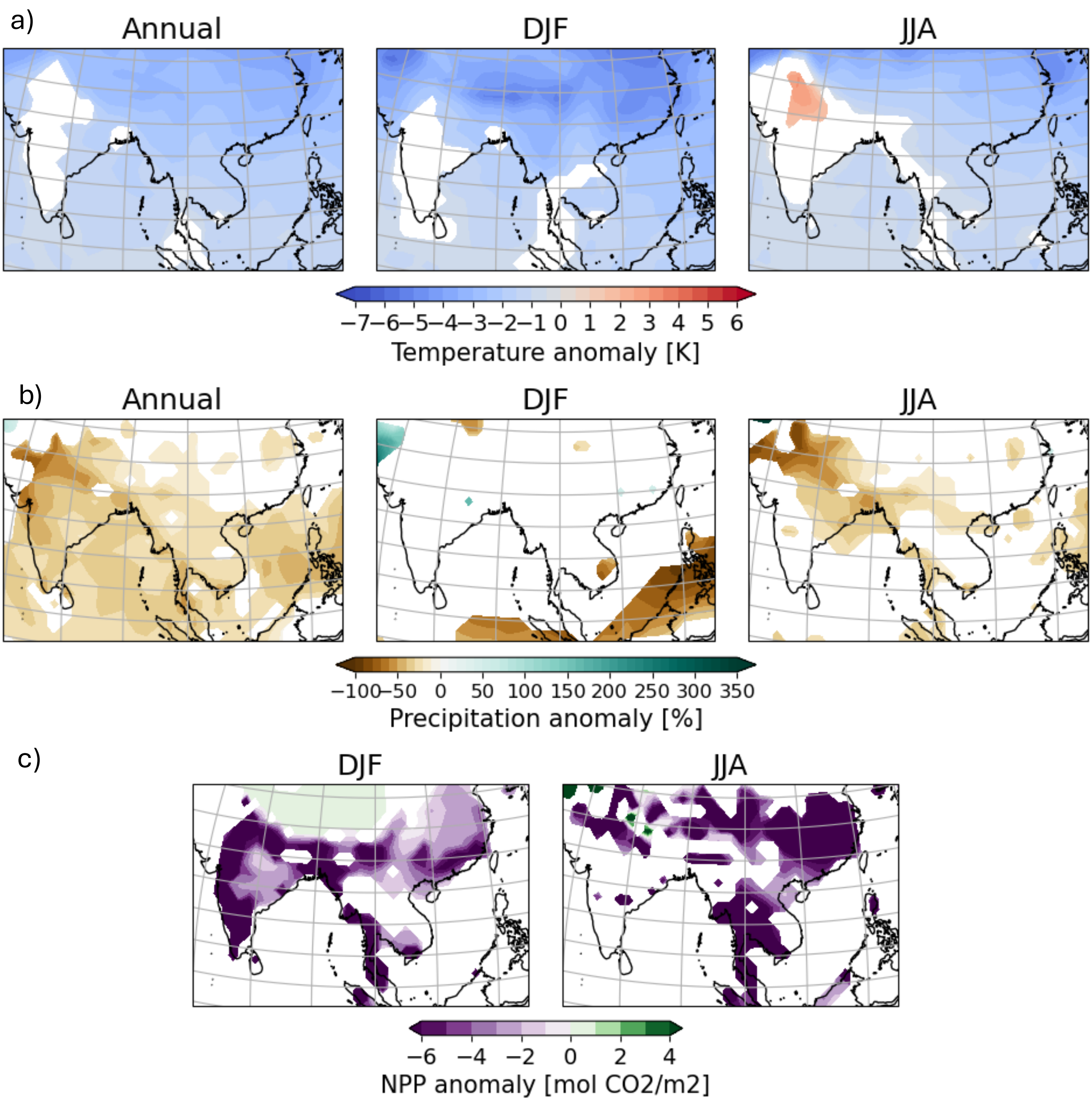

Figure 4. Anomalies (with reference to years before the eruption in control run) for the 2-year mean annual, boreal winter, and boreal summer a) 2 m air temperature, b) precipitation (in percent), and c) net primary production (NPP) for the India and Southeast Asia. Only data falling outside the 2σ range are shown.

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

This post-eruptive drought is reflected in the vegetation changes after the eruption with areas in Southeast Asia experiencing a strong decrease in NPP of over 6 mol CO_2 $m^{-}2$ in India during winter, and in eastern Asia in summer (Fig. 4c). This corresponds to a decrease of around 50% for India, and over 100% in Southeast Asia. Such drought conditions would likely have led to widespread harvest failure and food scarcity - known drivers of societal destabilization (Weiss, 2017).

3.4 Compound extremes

In line with earlier studies (e.g., Self, 2006), our model simulations demonstrate in a powerful and spatially explicit way the global climatic impacts that are expected after extremely large volcanic eruptions such as Mazama. In the same way, they also highlight the regionally diverse and even contrasting climatic impacts that may occur in different parts of the world after such an extreme event. Crucially, our analysis identifies hot-spots of compound risks emerging in the wake of large magnitude volcanic eruptions, some of which align with areas of risk in present-day as identified in the analyzes of Ridder et al. (2020).

Widespread cooling is the most robust response to the Mazama eruption, occurring over most land masses around the world (Figures 2-4). Yet, in regions such as the Mediterranean and the Near East, several concurrent extremes may co-occur. Anomalously wet and dry extremes take place simultaneously with a significant cooling - and more rarely a warming -, thus resulting in so-called compound extremes (Leonard et al., 2014). Such compound extremes have a high impact potential in relation to basic ecosystem services and agriculture, as both temperature and precipitation are key factors for plant growth. Figure 5a illustrates the significant (2σ) 2-year mean temperature and precipitation anomalies. In our simulations, large areas experience cooling as well as drying in the two years after the eruption, with certain areas (e.g., the Near East) experiencing cooling and wetting. In fact, almost 100% of the surface area in the low to mid-latitudes experiences at least one extreme climatic event in the two years after the eruption (Fig. 5a,c).

Around the time of the Mazama eruption, early (Neolithic) agricultural societies had emerged in the Near East and Eastern China (Stephens et al., 2019), with hunter-gatherer societies widespread elsewhere. Following complex impact pathways, large volcanic eruptions may have had significant climatic effects on people. These impacts were conditioned on prior vulnerabilities and would have depended on the capacity to accommodate the impacts of eruption-induced climate change and, in some regions, also ash-fall (van Dijk et al., 2023; Grattan and Torrence, 2010; Oppenheimer, 2011; Riede, 2015, 2016). An eruption the strength of Mazama is likely to have significantly impacted Mid-Holocene societies. Here we suggest that post-eruptive changes in temperature and precipitation could have impacted agricultural production leading to crisis responses (migration, economic adjustments or political adjustments (Halstead and O'Shea, 1989). These responses may be discernible in the archaeological record, as perturbations lasting $\geq$3 years are likely to exceed these traditional societies' buffering capacities (Luterbacher and Pfister, 2015; Manning et al., 2023; Ulus and Ellenblum, 2021). In contrast, not all climatic changes need to be negative, and complex eruption-induced climate changes may also generate more favorable conditions that allow societies to grow and expand. In general, there are winners and losers in any such disaster scenario (Scanlon, 1988). There is empirical

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

evidence of pronounced demographic boom-and-bust cycles during the Mid-Holocene (Kondor et al., 2024), yet inherent limitations conditioned on preservation and resolution exist in linking past climate change with societal changes (Cumming and Peterson, 2017; Degroot et al., 2021; Van Bavel et al., 2019).

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

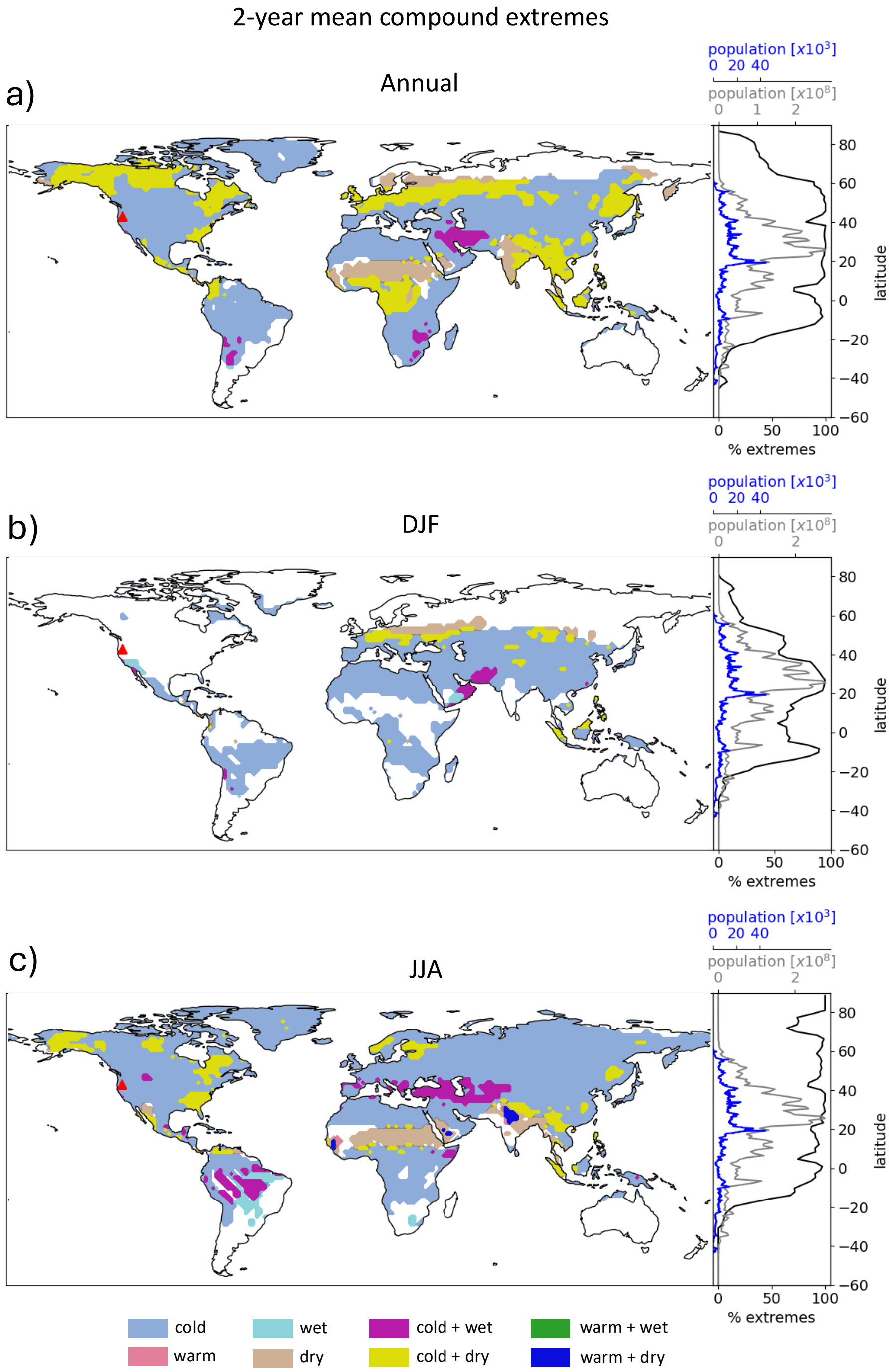

Figure 5. Occurring anomalies on the 2σ level for the 2-year mean after the Mazama-like eruption. a) Annual mean, b) boreal winter (DJF), and c) boreal summer (JJA). The latitudinal distribution of any anomaly in temperature or precipitation is represented by the black lines. Population per latitude for 5000 BCE is given by the blue lines (Klein Goldewijk (2024); see Klein Goldewijk et al. (2010) for uncertainties), and population per latitude for 2020 CE (CIESIN, 2018) is given by the grey lines.

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

4 Discussion

4.1 Comparison to other large explosive eruptions

The Mazama eruption was one of the largest eruptions in the Holocene. Here we discuss how this eruption compares to other large eruptions of the past.

The general patterns of the climate response after the Mazama eruption are as expected, as the direct impact of volcanic forcing in the stratosphere is a cooling of the Earth surface, which is generally stronger over land due to the larger heat capacity of the oceans. Likewise, the indirect impact of the changes in atmospheric circulation and, therefore, the changes in precipitation patterns follow the same pathway as is known from other large explosive eruptions. For example, the eruption of Okmok II (44/43 BCE, 48 Tg S; Table 1), located on the Aleutian islands, was simulated to have had a strong cooling over NH continents, as well as wetter conditions in the Mediterranean region. In addition, this eruption was suggested to be a contributing factor (next to warfare and others) to food scarcity and societal instability in the Mediterranean region in the years following the eruption (McConnell et al., 2020a). Similarly, the Samalas eruption (1258 CE, 59 Tg S; Table 1) has been found to have caused a cooling over the NH continents the year after the eruption (Büntgen et al., 2022), as well as slightly wetter conditions in the Near East (Hartmann et al., 2025). The eruption of Tambora in 1815 (28 Tg S; Table 1) is widely known to have caused 'the year without summer', with widespread cooling over the NH continents, resulting in crop failures, famine, and outbreak of disease (Oppenheimer, 2003). Although all of these well-studied eruptions had a cooling response and led to precipitation changes, the severity of the anomalies they caused was less strong than those modeled here for the Mazama eruption (see also Table 1). Although volcanic impacts do not necessarily scale linearly with the amount of sulfur injected by the eruption, our simulations suggest more severe climatic impacts than any of the other known large Holocene eruptions, in line with previous studies (Pinto et al., 1989; Hyde and Crowley, 2000; Timmreck et al., 2010; Metzner et al., 2014; Brenna et al., 2020). The maximum simulated cooling after Mazama reached more than 7 °C regionally (Fig. 2), compared to a maximum of 5 °C cooling simulated for the Okmok eruption (McConnell et al., 2020a), which is the closest analogue in terms of climatic impact.

Throughout the Holocene several other major stratospheric eruptions occurred in the NH mid-latitudes across all four seasons. Figure 6 summarizes the time evolution of estimated stratospheric AOD (SAOD) and effective radiative forcing (ERF) for Mazama and five comparative events in winter (Okmok, Alaska, 44/43 BCE), spring (Unidentified 536 CE), summer (Zavaristski, Kurils, 1831 CE and Pinatubo 1991) and autumn (Unidentified 626). Major temperature and precipitation anomalies have been linked to these mid-latitude eruptions of varying emissions strengths and seasons. These include heavy snowfall, frost, and flooding from the Near East to China and Japan in 627-30 CE (Stothers and Rampino, 1983; Fei et al., 2007; Di Cosmo et al., 2017; Imamura, 1947), monsoon failures and famines in India and Japan in 1832 CE (Imamura, 1947; Hutchison et al., 2025; Warren, 2026), and reduced Nile summer flooding in the wake of the Okmok eruption of 44/43 BCE (Manning et al., 2017; McConnell et al., 2020a), with potentially strong agricultural and societal implications (McConnell et al., 2020b). The as yet unidentified major eruption that produced a dust veil that persisted for nine months between October 626 and June 627

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

CE (Stothers and Rampino, 1983; Sigl et al., 2015) also preceded one of the largest historic floods of the Tigris and Euphrates river system.

For the years 627 and 628 CE, the Arabic chronicler al-Balādhurī wrote: “[There] was an enormous flood of the Euphrates and Tigris rivers, such as no one had ever seen before. Large dams opened, which [the Sasanian Great King] Chosrau [II] tried to close, but the water was stronger, reaching the lower areas and flooding villages, crops and several districts in the region. Chosrau personally arrived on the scene to stop the bursting of the dams; [...] but he could not stop the water masses. [...] From then on, the Persians were occupied with the war, so that the dam breaches grew larger without anyone caring" (Al-Baladhuri, 2002; Verkinderen, 2015).

This flood, which damaged irrigation infrastructure and dams, is considered one of the worst floods in Mesopotamian history. The lower reaches of the Tigris changed course and large swamps formed. It is widely linked to the fall of the Sassanid dynasty, destruction of crops, famines, and population displacement (Abdullah et al., 2020; Angelakis et al., 2023; Preiser-Kapeller, 2021).

Using the Community Earth System Model CESM version 1.2.2, positive precipitation anomalies are simulated for the mountains of Anatolia and Armenia – the headwaters of the Tigris / Euphrates system, for the years 536 and 540 CE (both unidentified eruptions) and 43-42 BCE (Okmok II) (McConnell et al., 2020a; Kim et al., 2021). In addition, the years 627, 536 and 43-42 BCE rank among the coldest years in the NH extratropics in the past 2500 years (Stothers, 1999; Sigl et al., 2015; McConnell et al., 2020a; Büntgen et al., 2025). Since the surface climate anomalies after the Manzama eruption are even more severe, we argue that the consequences of the eruption on the societies in these regions were at least on the same order of severity, and potentially more severe.

4.2 Uncertainties and limitations

Our model simulations present the potential impacts of the Mazama eruption (and comparably large NH extratropical eruptions) in 5600 BCE, based on stratospheric sulfur injection estimates using volcanic sulfate measurements in ice core records. The different components and methods used are subject to uncertainties related to less constrained emission source parameters (e.g. SO_2 mass, composition, eruption season) (Toohey et al., 2011, 2019; Marshall et al., 2020, 2021). One of the limitations of our study is that the SO_2 injected into the atmosphere is represented in terms of zonal mean volcanic forcing (AOD), which may impact the duration and pattern of the response. Thus, there are no interactive aerosol microphysics and chemistry processes included in our model and no other volcanic material was injected, such as ash, water vapor and halogens, which likely would have impacted air quality, environment, and human health as well. Especially for eruptions as large as the Mazama eruption, where ash fall has been found up to 1300 km away for similar size eruptions. Depending on the precise location of the eruption, this could affect millions of people (Meredith et al., 2025).

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

4.2.1 Magnitude of the SO_2 injection

Similar ensemble approaches for smaller (yet still very powerful) historical eruptions, such as Okmok II 43 BCE (McConnell et al., 2020a), and the 536-540 CE double event (van Dijk et al., 2022) have evaluated post-eruption climate changes. These existing model simulations can be considered as analogues for the lower bound estimates of SO_2 for Mazama (130-510 Tg SO_2, 2σ) and Okmok (40-160 Tg SO_2, 2σ) overlapping within the stated errors. The Okmok model ensemble (CESM1.2.2) projected climate effects similar to our study, with strong NH cooling overlapping with low precipitation in South Asia and South East Asia, and increased precipitation in the Mediterranean and the Near East (McConnell et al., 2020a). This pattern occurs especially during summer and autumn, supporting the notion of a compound impact.

4.2.2 Seasonal dependency

As the exact timing and duration of the Mazama eruption is unknown, the eruption was set to occur in January in the volcanic forcing data set. The only published information about the Mazama eruption season we know of states that: “volcanic ash from a major eruption of Mazama [...] first fell in the autumn and 4.6 centimeters of ash was deposited before the following spring” (Mehringer et al., 1977). Taking this into account, January seems plausible for a Mazama eruption in the model simulation, as the atmospheric circulation is rather similar for these months. Figure 6 shows a similar time evolution of SAOD and ERF for October (autumn) rather than January as the eruption month in the EVA module (Toohey et al., 2016) to calculate the volcanic forcing (Toohey and Sigl, 2017).

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

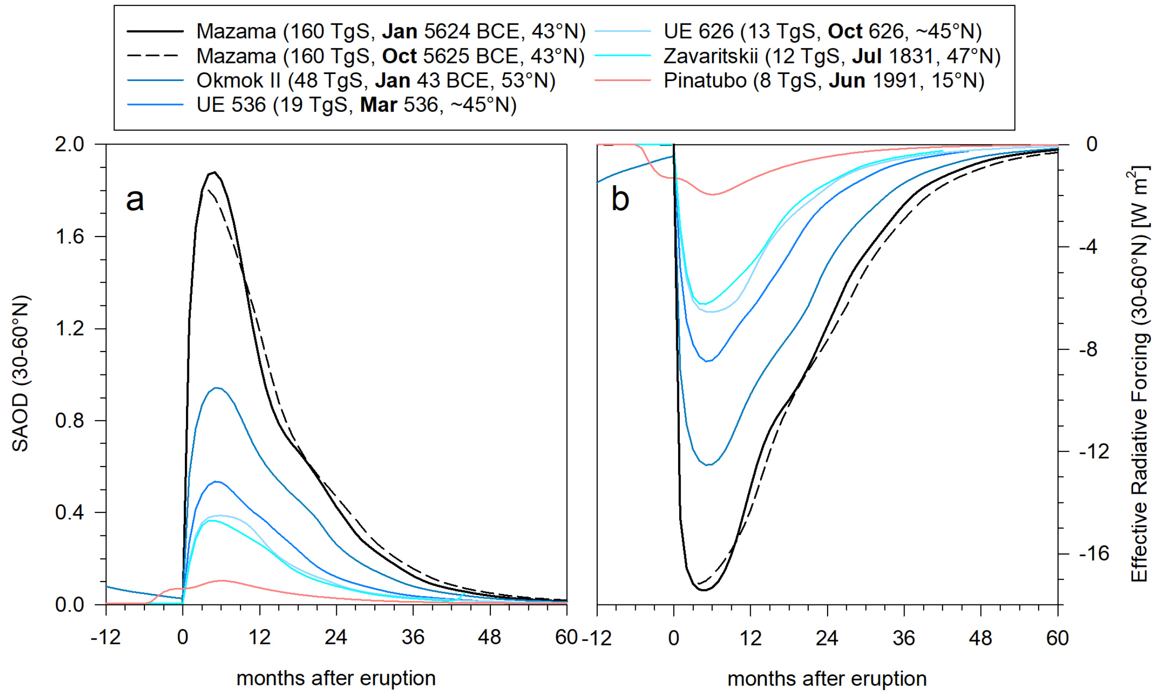

Figure 6. Estimated stratospheric aerosol optical depth (SAOD) between 30-60°N for six major eruptions of different sulfur injections, latitudes and seasons using ice core records (Sigl et al., 2015, 2022; Toohey and Sigl, 2017; Sigl and Toohey, 2024); b: estimated changes in effective radiative forcing (ERF) between 30-60°N using the Marshall et al. (2021) forcing scaling factor of $ERF = -20.7 \times (1 - e^{-SAOD})$.

4.2.3 Background conditions

310 The background state of the climate and the atmosphere impacts the effect of large volcanic eruptions (Zanchettin et al., 2022). The surface atmospheric dynamics, as well as ocean dynamics can evolve differently for different background conditions (Zanchettin et al., 2013; Dutta et al., 2025). Starting from different initial atmospheric conditions for a NH extra-tropical Pinatubo-like eruption, Fuglestvedt et al. (2024) showed that the AOD evolution for sulfur and halogen rich eruptions such as Mazama was within the spread of varying eruption source parameters of two different climate aerosol models (CESM2(WACCM6) and MAECHAM5HAM). In Figure 7, the relative SST (RSST, Khodri et al. (2017)) index is presented for the five years before the Mazama eruption as well as for the 25 years after. There is a pre-conditioning to La Nina and neutral ENSO cases during the pre-Mazama eruption years. Following, all ensembles simulate a significant El Nino response after the Mazama eruption, as expected from high latitude eruptions from previous model studies (Oman et al., 2006; Pausata et al., 2016; Fang et al., 2025).

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

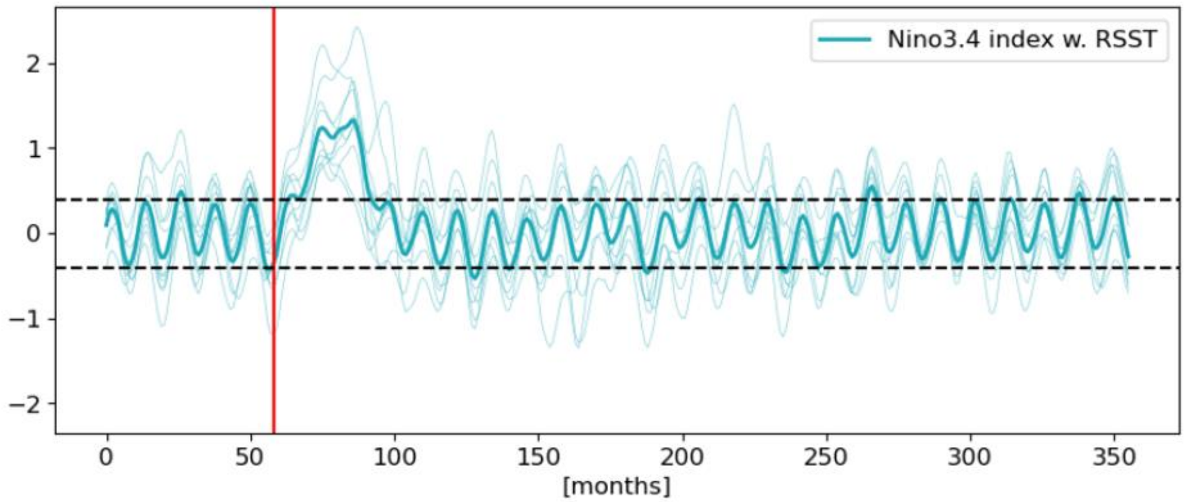

Figure 7. The Nino 3.4 index with relative sea surface temperature (RSST, bottom panel) after the Mazama-like eruption (timing indicated by the red line).

4.3 A Mazama-like eruption in present or future conditions

In addition to the potential impact on past societies, the impact of an eruption such as Mazama is also highly relevant for present-day society. Today, a very large number of people live in the vicinity of volcanoes (Chester et al., 2000; Barclay et al., 2019; Brown et al., 2014). Notably, the areas with a high likelihood of post-eruptive climate anomalies in our model simulations also correspond to the areas where most of the world's population resides today (Fig. 5). The human niche space is concentrated along the low and middle latitudes and is sensitive to shifts in temperature and precipitation (Lenton et al., 2023; Xu et al., 2020). Should a Mazama-like event occur in the present or under projected climate change futures, most of the world's population would experience more than one climatic extreme, in addition to those already likely to occur in a warmer world (Thiery et al., 2021). Additional impacts may be mediated - as in the Mid-Holocene but on a globally expanded scale - by perturbations of agricultural systems. At present, only five countries supply much of the world's food: China, India, the USA, Russia, and Brazil (Ritchie et al., 2023). The USA and Brazil experience significant cooling in our model simulations. Close to the eruptive centre - in North America, for instance, assuming an eruption at or near present-day Crater Lake - agriculture as well as critical infrastructure and population health would additionally have suffered from ash fall. Parts of China, India, and Russia would all experience compound extremes with significant drought and cooling. With drought as a main driver of crop failure, this could potentially result in large-scale and simultaneous breadbasket failures. This, in turn, would likely have serious consequences, with potentially global ripple effects (Bailey et al., 2015; Goulart et al., 2021), including population displacements, economic downturns, and conflicts - also far removed from those regions experiencing the greatest actual climatic perturbations (IDMC, 2018; Barriopedro et al., 2011; Johnstone and Mazo, 2011; Reichstein et al., 2021; Von Uexkull et al., 2016).

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

5 Summary and conclusion

One of the largest eruptions in the Holocene was the 5600 BCE eruption of Mazama, Crater Lake. In this study, we have investigated how an eruption like this would have forced a range of climatic anomalies including extreme fluctuations in individual climate parameters, as well as compound events where temperature and precipitation extremes co-occur in given regions. The main regions that stand out are the Mediterranean and the Near East as well as India. Here, precipitation and temperature extremes could have caused severe flooding in the Near East, with droughts having the opposite effect in India.

While the occurrence of a Mazama-like eruptive event is of low likelihood, it would likely have considerable impacts on food security and critical infrastructure - and it would interact with ongoing climate change that is already putting high pressure on many societies around the world. Focusing on compound extremes, we illustrate how combinations of temperature and precipitation anomalies could occur, with diverging and heterogeneous responses for different areas. In addition to directly impacting human populations, compounding extremes affect food availability through increased risk of crop failure. Against the backdrop of our simulations, renewed eruptive activity at Crater Lake - or similar eruptive activity elsewhere - is projected to disrupt multiple key food-producing regions globally, with downstream implications for food security and political stability. Studying these extremely large past eruptions is thus key for better understanding the nature of and risks associated with low-likelihood, high-impact events – events that global society is patently ill-prepared for. Therefore, it is imperative that we improve our understanding of the consequences these types of events and that we develop scenarios regarding their potential future impacts.

Code and data availability. The model data used to produce the figures will be archived on the NIRD Research Data Archive (https://archive.sigma2.no/), DOI will follow. The code for producing the figures will be available on a public Github repository (https://github.com/EvelienvanDijk/Mazama_public)

Author contributions. CT, KK, and MS developed the research idea. CT provided the model simulations. EvD processed the model data, performed the analysis, designed the corresponding figures, and led the writing of the manuscript. CT, KK, FR, and MS contributed to the interpretation of the results. All authors discussed the results and helped writing the manuscript.

Competing interests. The authors declare no competing interests.

Acknowledgements. Evelien van Dijk and Felix Riede received funding from the European Research Council under the European Union's Horizon 2020 research and innovation program (CLIOARCH, grant agreement no. 817564). Evelien van Dijk and Michael Sigl received funding from the European Research Council under the European Union's Horizon 2020 research and innovation program (THERA, grant

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

agreement no. 820047). Michael Sigl also received funding from the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract no. MB22.00030, as well as from the NORCLI UIO:TRG project. Claudia Timmreck acknowledges support by the Deutsche Forschungsgemeinschaft Research Unit VolImpact (FOR2820 (grant no. 398006378)). Kirstin Krüger would like to acknowledge support from the Max Planck Institute for Meteorology for a scientific guest stay where the idea for the Mazama model experiments was born, in addition to funding from the RCN TOPPFORSK project VIKINGS (grant no. 275191), and the UIO:EE convergent environment project 'ClimSHOCK' at the University of Oslo. This work also benefited from participation by some authors in the Past Global Changes Volcanic Impacts on Climate and Society working group. Computations, analysis, and model data storage were mainly performed on the computer of the Deutsches Klima Rechenzentrum (DKRZ) and partly on Sigma2 the National Infrastructure for High-Performance Computing and Data Storage in Norway. The authors thank Stephan Lorenz for his work in performing the Mazama ensemble and Matthew Toohey, and Johannes Preiser-Kapeller for their valuable feedback.

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

References

Abdullah, M., Al-Ansari, N., Adamo, N., Sissakian, V. K., and Laue, J.: Floods and flood protection in Mesopotamia, Journal of Earth Sciences and Geotechnical Engineering, 10, 155–173, 2020.

Al-Baladhuri, A.-l. A. i.-j.: The Origins of the Islamic State: Being a Translation of kitaab futu al-buldaan of Abul-l Abbas Ahmad ibm Jabir al-Baladhuri, by Philip K. Hitti, 2002.

Anchukaitis, K., Buckley, B., Cook, E., Cook, B., D'Arrigo, R., and Ammann, C.: Influence of volcanic eruptions on the climate of the Asian monsoon region, Geophysical Research Letters, 37, 2010.

Andrews, B. J., Venzke, E., Cottrell, E., Sennert, S. S., Bennis, K. L., and Crafford, A.: The Volcanoes of the World database, Bulletin of Volcanology, 87, 34, 2025.

Angelakis, A. N., Capodaglio, A. G., Valipour, M., Krasilnikoff, J., Ahmed, A. T., Mandi, L., Tzanakakis, V. A., Baba, A., Kumar, R., Zheng, X., et al.: Evolution of floods: from ancient times to the present times (ca 7600 BC to the present) and the future, Land, 12, 1211, 2023.

Araus, J. L., Ferrio, J. P., Voltas, J., Aguilera, M., and Buxó, R.: Agronomic conditions and crop evolution in ancient Near East agriculture, Nature communications, 5, 3953, 2014.

Bader, J., Jungclaus, J., Krivova, N., Lorenz, S., Maycock, A., Raddatz, T., Schmidt, H., Toohey, M., Wu, C.-J., and Claussen, M.: Global temperature modes shed light on the Holocene temperature conundrum, Nature communications, 11, 1–8, 2020.

Bailey, R., Benton, T., Challinor, A., Elliott, J., Gustafson, D., Hiller, B., Jones, A., Jahn, M., Kent, C., Lewis, K., et al.: Extreme weather and resilience of the global food system (2015). Final project report from the UK-US Taskforce on extreme weather and global food system resilience, The Global Food Security programme, UK., Extreme weather and resilience of the global food system (2015). Final project report from the UK-US Taskforce on extreme weather and global food system resilience, The Global Food Security programme, UK., 2015.

Barclay, J., Few, R., Armijos, M. T., Phillips, J. C., Pyle, D. M., Hicks, A., Brown, S. K., and Robertson, R. E.: Livelihoods, wellbeing and the risk to life during volcanic eruptions, Frontiers in Earth Science, 7, 205, 2019.

Barriopedro, D., Fischer, E. M., Luterbacher, J., Trigo, R. M., and García-Herrera, R.: The hot summer of 2010: redrawing the temperature record map of Europe, Science, 332, 220–224, 2011.

Beaudoin, A. B. and Oetelaar, G. A.: The day the dry snow fell: the record of a 7627-year-old disaster, Alberta formed Alberta transformed, 1, 36–53, 2006.

Benati, G. and Guerriero, C.: Climate change and state evolution, Proceedings of the National Academy of Sciences, 118, e2020893 118, 2021.

Berger, A. L.: Long-Term Variations of Caloric Insolation Resulting from the Earth's Orbital Elements 1, Quaternary research, 9, 139–167, 1978.

Brenna, H., Kutterolf, S., Mills, M. J., and Krüger, K.: The potential impacts of a sulfur- and halogen-rich supereruption such as Los Chocoyos on the atmosphere and climate, Atmos. Chem. Phys., 20, 6521–6539, 2020.

Brovkin, V., Lorenz, S., Raddatz, T., Ilyina, T., Stemmler, I., Toohey, M., and Claussen, M.: What was the source of the atmospheric CO_2 increase during the Holocene?, Biogeosciences, 16, 2543–2555, 2019.

Brown, S. K., Crosweller, H. S., Sparks, R. S. J., Cottrell, E., Deligne, N. I., Guerrero, N. O., Hobbs, L., Kiyosugi, K., Loughlin, S. C., Siebert, L., et al.: Characterisation of the Quaternary eruption record: analysis of the Large Magnitude Explosive Volcanic Eruptions (LaMEVE) database, Journal of Applied Volcanology, 3, 1–22, 2014.

Buckland, H. M., Cashman, K. V., Engwell, S. L., and Rust, A. C.: Sources of uncertainty in the Mazama isopachs and the implications for interpreting distal tephra deposits from large magnitude eruptions, Bulletin of Volcanology, 82, 23, 2020.

Büntgen, U., Arseneault, D., Boucher, É., Churakova, O. V., Gennaretti, F., Crivellaro, A., Hughes, M. K., Kirdyanov, A. V., Klippel, L., Krusic, P. J., et al.: Prominent role of volcanism in Common Era climate variability and human history, Dendrochronologia, 64, 125 757, 2020.

Büntgen, U., Smith, S. H., Wagner, S., Krusic, P., Esper, J., Piermattei, A., Crivellaro, A., Reinig, F., Tegel, W., Kirdyanov, A., et al.: Global tree-ring response and inferred climate variation following the mid-thirteenth century Samalas eruption, Climate Dynamics, 59, 531–546, 2022.

Büntgen, U., Cosmo, N. D., Esper, J., Frachetti, M., Khalidi, L., Mauelshagen, F., Rohland, E., and Oppenheimer, C.: Volcanoes, Climate, and Society, Annual Review of Earth and Planetary Sciences, 54, 2025.

Chester, D. K., Degg, M., Duncan, A. M., and Guest, J. E.: The increasing exposure of cities to the effects of volcanic eruptions: a global survey, Global Environmental Change Part B: Environmental Hazards, 2, 89–103, 2000.

CIESIN, Center For International Earth Science Information Network, C. U.: Gridded Population of the World, Version 4 (GPWv4): Population Count, Revision 11, https://doi.org/10.7927/H4JW8BX5, 2018.

Cumming, G. S. and Peterson, G. D.: Unifying research on social–ecological resilience and collapse, Trends in ecology & evolution, 32, 695–713, 2017.

Dallmeyer, A., Claussen, M., Lorenz, S. J., Sigl, M., Toohey, M., and Herzschuh, U.: Holocene vegetation transitions and their climatic drivers in MPI-ESM1. 2, Climate of the Past, 17, 2481–2513, 2021.

Davies, S. M., Albert, P. G., Bourne, A. J., Owen, S., Svensson, A., Bolton, M. S., Cook, E., Jensen, B. J., Jones, G., Ponomareva, V. V., et al.: Exploiting the Greenland volcanic ash repository to date caldera-forming eruptions and widespread isochrons during the Holocene, Quaternary Science Reviews, 334, 108 707, 2024.

Degroot, D., Anchukaitis, K., Bauch, M., Burnham, J., Carnegy, F., Cui, J., de Luna, K., Guzowski, P., Hambrecht, G., Huhtamaa, H., et al.: Towards a rigorous understanding of societal responses to climate change, Nature, 591, 539–550, 2021.

Di Cosmo, N., Oppenheimer, C., and Büntgen, U.: Interplay of environmental and socio-political factors in the downfall of the Eastern Türk Empire in 630 CE, Climatic change, 145, 383–395, 2017.

Dunbar, N. W., Iverson, N. A., Van Eaton, A. R., Sigl, M., Alloway, B. V., Kurbatov, A. V., Mastin, L. G., McConnell, J. R., and Wilson, C. J.: New Zealand supereruption provides time marker for the Last Glacial Maximum in Antarctica, Scientific Reports, 7, 12 238, 2017.

Dutta, D., Hopcroft, P. O., Andreasen, L. S., Aubry, T. J., Timmreck, C., Zanchettin, D., Zhang, X., and Muschitiello, F.: State-dependent North Atlantic response to volcanic eruption clusters, Geophysical Research Letters, 52, e2025GL117 582, 2025.

Fang, S.-W., Timmreck, C., Jungclaus, J., Krüger, K., and Schmidt, H.: On the additivity of climate responses to the volcanic and solar forcing in the early 19th century, Earth System Dynamics, 13, 1535–1555, 2022.

Fang, S.-W., Sigl, M., Toohey, M., Jungclaus, J., Zanchettin, D., and Timmreck, C.: The role of small to moderate volcanic eruptions in the early 19th century climate, Geophysical Research Letters, 50, e2023GL105 307, 2023.

Fang, S.-W., Pausata, F. S., D'agostino, R., Khodri, M., Zanchettin, D., and Timmreck, C.: Seasonal ITCZ control on enso responses to extratropical volcanic forcing, Journal of Climate, 38, 6061–6079, 2025.

Fei, J., Zhou, J., and Hou, Y.: Circa AD 626 volcanic eruption, climatic cooling, and the collapse of the Eastern Turkic Empire, Climatic Change, 81, 469–475, 2007.

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

Fuglestvedt, H. F., Zhuo, Z., Toohey, M., and Krüger, K.: Volcanic forcing of high-latitude Northern Hemisphere eruptions, Npj Climate and Atmospheric Science, 7, 10, 2024.

Gao, C., Robock, A., and Ammann, C.: Volcanic forcing of climate over the past 1500 years: an improved ice core-based index for climate models, J. Geophys. Res., 113, D23 111, 2008.

Goulart, H. M., Van Der Wiel, K., Folberth, C., Balkovic, J., and Van Den Hurk, B.: Storylines of weather-induced crop failure events under climate change, Earth System Dynamics, 12, 1503–1527, 2021.

Grattan, J. and Torrence, R.: Living under the shadow: cultural impacts of volcanic eruptions, vol. 53, Left Coast Press, 2010.

Guillet, S., Corona, C., Stoffel, M., Khodri, M., Lavigne, F., Ortega, P., Eckert, N., Sielenou, P. D., Daux, V., Churakova, O. V., et al.: Climate response to the Samalas volcanic eruption in 1257 revealed by proxy records, Nature geoscience, 10, 123–128, 2017.

Halstead, P. and O'Shea, J.: Bad year economics: cultural responses to risk and uncertainty, Cambridge Univ. Press, 1989.

Harmon, R.: Crater lake national park: A history, Oregon State University Press, 2002.

Hartmann, E., Zhang, M., Wagner, S., Adakudlu, M., Luterbacher, J., and Xoplaki, E.: On the implementation of external forcings in a regional climate model–a sensitivity study around the Samalas volcanic eruption in the Eastern Mediterranean/Middle East, Climate of the Past, 21, 1699–1724, 2025.

Hoffman, S. M.: After Atlas shrugs: cultural change or persistence after a disaster, in: The Angry Earth, pp. 316–340, Routledge, 1999.

Hurtt, G. C., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B. L., Calvin, K., Doelman, J. C., Fisk, J., Fujimori, S., Klein Goldewijk, K., et al.: Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6, Geoscientific Model Development, 13, 5425–5464, 2020.

Hutchison, W., Sugden, P., Burke, A., Abbott, P., Ponomareva, V. V., Dirksen, O., Portnyagin, M. V., MacInnes, B., Bourgeois, J., Fitzhugh, B., et al.: The 1831 CE mystery eruption identified as Zavaritskii caldera, Simushir Island (Kurils), Proceedings of the National Academy of Sciences, 122, e2416699 122, 2025.

Hyde, W. and Crowley, T.: Probability of future climatically significant volcanic eruptions, J Clim, 13, 1445–1450, 2000.

IDMC: GRID: global report on internal displacement 2018., Technological report, http://www.internal-displacement.org/global-report/grid2018/, 2018.

Ilyina, T., Six, K. D., Segschneider, J., Maier-Reimer, E., Li, H., and Núñez-Riboni, I.: Global ocean biogeochemistry model HAMOCC: Model architecture and performance as component of the MPI-Earth system model in different CMIP5 experimental realizations, Journal of Advances in Modeling Earth Systems, 5, 287–315, 2013.

Imamura, A.: Volcanoes driving volcanic dust abundantly to an extraordinary altitude, Proceedings of the Japan Academy, 23, 105–110, 1947.

Innes, H. M., Hutchison, W., Sigl, M., Crick, L., Abbott, P. M., Bigler, M., Chellman, N. J., Davies, S. M., Kutterolf, S., McConnell, J. R., et al.: Ice core evidence for the Los Chocoyos supereruption disputes millennial-scale climate impact, Communications Earth & Environment, 6, 137, 2025.

Johnstone, S. and Mazo, J.: Global warming and the Arab Spring, Survival, 53, 11–17, 2011.

Jungclaus, J. H., Fischer, N., Haak, H., Lohmann, K., Marotzke, J., Matei, D., Mikolajewicz, U., Notz, D., and Von Storch, J.: Characteristics of the ocean simulations in the Max Planck Institute Ocean Model (MPIOM) the ocean component of the MPI-Earth system model, Journal of Advances in Modeling Earth Systems, 5, 422–446, 2013.

Kehl, M., Rafiei-Alavi, B., Lahijani, H., Bernbeck, R., Eberhardt, G., and Pollock, S.: Holocene paleoenvironmental change and phases of drought in the Iranian Highlands. A review, 2023.

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

Khodri, M., Izumo, T., Vialard, J., Janicot, S., Cassou, C., Lengaigne, M., Mignot, J., Gastineau, G., Guilyardi, E., Lebas, N., et al.: Tropical explosive volcanic eruptions can trigger El Niño by cooling tropical Africa, Nature communications, 8, 778, 2017.

Kim, W. M., Blender, R., Sigl, M., Messmer, M., and Raible, C. C.: Statistical characteristics of extreme daily precipitation during 1501 BCE–1849 CE in the Community Earth System Model, Climate of the Past, 17, 2031–2053, 2021.

Klein Goldewijk, K.: History Database of the Global Environment 3.3, https://doi.org/10.24416/UU01-94FNH0, 2024.

Klein Goldewijk, K., Beusen, A., and Janssen, P.: Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1, The Holocene, 20, 565–573, 2010.

Kobashi, T., Menviel, L., Jeltsch-Thommes, A., Vinther, B. M., Box, J. E., Muscheler, R., Nakaegawa, T., Pfister, P. L.and Doring, M., Leuenberger, M., Wanner, H., and Ohmura, A.: Volcanic influence on centennial to millennial Holocene Greenland temperature change, Sci Rep, 7, 2017.

Köhler, P.: Interactive comment on “What was the source of the atmospheric CO_2 increase during the Holocene?” by Victor Brovkin et al., Biogeosciences Discussions, 16, SC1, 2019.

Kondor, D., Bennett, J. S., Gronenborn, D., and Turchin, P.: Landscape of Fear: Indirect effects of conflict can account for large-scale population declines in non-state societies, Journal of the Royal Society Interface, 21, 20240 210, 2024.

Krivova, N., Solanki, S., and Unruh, Y.: Towards a long-term record of solar total and spectral irradiance, Journal of Atmospheric and Solar-Terrestrial Physics, 73, 223–234, 2011.

Lenton, T. M., Xu, C., Abrams, J. F., Ghadiali, A., Loriani, S., Sakschewski, B., Zimm, C., Ebi, K. L., Dunn, R. R., Svenning, J.-C., et al.: Quantifying the human cost of global warming, Nature Sustainability, 6, 1237–1247, 2023.

Leonard, M., Westra, S., Phatak, A., Lambert, M., van den Hurk, B., McInnes, K., Risbey, J., Schuster, S., Jakob, D., and Stafford-Smith, M.: A compound event framework for understanding extreme impacts, Wiley Interdisciplinary Reviews: Climate Change, 5, 113–128, 2014.

Lin, J., Svensson, A., Hvidberg, C. S., Lohmann, J., Kristiansen, S., Dahl-Jensen, D., Steffensen, J. P., Rasmussen, S. O., Cook, E., Kjær, H. A., et al.: Magnitude, frequency and climate forcing of global volcanism during the last glacial period as seen in Greenland and Antarctic ice cores (60–9 ka), Climate of the Past, 18, 485–506, 2022.

Lin, J., Abbott, P. M., Sigl, M., Steffensen, J. P., Mulvaney, R., Severi, M., and Svensson, A.: Bipolar ice-core records constrain possible dates and global radiative forcing following the 74 ka Toba eruption, Quaternary Science Reviews, 312, 108 162, 2023.

Liu, F., Chai, J., Wang, B., Liu, J., Zhang, X., and Wang, Z.: Global monsoon precipitation responses to large volcanic eruptions, Scientific reports, 6, 24 331, 2016.

Long, C. J., Power, M. J., Minckley, T. A., and Hass, A. L.: The impact of Mt Mazama tephra deposition on forest vegetation in the Central Cascades, Oregon, USA, The Holocene, 24, 503–511, 2014.

Luterbacher, J. and Pfister, C.: The year without a summer, Nature Geoscience, 8, 246–248, 2015.

Man, W., Zhou, T., and Jungclaus, J. H.: Effects of large volcanic eruptions on global summer climate and East Asian monsoon changes during the last millennium: Analysis of MPI-ESM simulations, Journal of Climate, 27, 7394–7409, 2014.

Mandeville, C. W., Webster, J. D., Tappen, C., Taylor, B. E., Timbal, A., Sasaki, A., Hauri, E., and Bacon, C. R.: Effects of large volcanic eruptions on global summer climate and East Asian monsoon changes during the last millennium: Analysis of MPI-ESM simulations, Geochimica et Cosmochimica Acta, 73, 2978–3012, 2009.

Manning, J. G., Ludlow, F., Stine, A. R., Boos, W. R., Sigl, M., and Marlon, J. R.: Volcanic suppression of Nile summer flooding triggers revolt and constrains interstate conflict in ancient Egypt, Nature communications, 8, 900, 2017.

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

Manning, S. W., Kocik, C., Lorentzen, B., and Sparks, J. P.: Severe multi-year drought coincident with Hittite collapse around 1198–1196 BC, Nature, 614, 719–724, 2023.

Marshall, L. R., Smith, C. J., Forster, P. M., Aubry, T. J., Andrews, T., and Schmidt, A.: Large variations in volcanic aerosol forcing efficiency due to eruption source parameters and rapid adjustments, Geophysical Research Letters, 47, e2020GL090 241, 2020.

Marshall, L. R., Schmidt, A., Johnson, J. S., Mann, G. W., Lee, L. A., Rigby, R., and Carslaw, K. S.: Unknown eruption source parameters cause large uncertainty in historical volcanic radiative forcing reconstructions, Journal of Geophysical Research: Atmospheres, 126, e2020JD033 578, 2021.

Mauritsen, T., Bader, J., Becker, T., Behrens, J., Bittner, M., Brokopf, R., Brovkin, V., Claussen, M., Crueger, T., Esch, M., et al.: Developments in the MPI-M Earth System Model version 1.2 (MPI-ESM1. 2) and its response to increasing CO2, Journal of Advances in Modeling Earth Systems, 11, 998–1038, 2019.

McConnell, J. R., Sigl, M., Plunkett, G., Burke, A., Kim, W. M., Raible, C. C., Wilson, A. I., Manning, J. G., Ludlow, F., Chellman, N. J., et al.: Extreme climate after massive eruption of Alaska's Okmok volcano in 43 BCE and effects on the late Roman Republic and Ptolemaic Kingdom, Proceedings of the National Academy of Sciences, 117, 15 443–15 449, 2020a.

McConnell, J. R., Sigl, M., Plunkett, G., Wilson, A. I., Manning, J. G., Ludlow, F., and Chellman, N. J.: REPLY TO STRUNZ AND BRAECKEL: Agricultural failures logically link historical events to extreme climate following the 43 BCE Okmok eruption, Proceedings of the National Academy of Sciences, 117, 32 209–32 210, 2020b.

Mehringer, P. J., Blinman, E., and Petersen, K. L.: Pollen influx and volcanic ash: The pollen content of Mazama and Glacier Peak ashes reveals details of their depositional chronologies., Science, 198, 257–261, 1977.

Meredith, E. S., Handley, H., Jenkins, S. F., Chim, M. M., and Gregg, C.: High-impact low-probability events: Exposure to potential large-magnitude explosive volcanic eruptions, 2025.

Metzner, D., Kutterolf, S., Toohey, M., Timmreck, C., Niemeier, U., Freundt, A., and Krüger, K.: Radiative forcing and climate impact resulting from SO2 injections based on a 200,000 year record of Plinian eruptions along the Central American Volcanic Arc, American Volcanic Arc, Int J Earth Sci, 103(7), 2063–2079, 2014.

Miller, N. F. and Wetterstrom, W.: The beginnings of agriculture: the ancient near East and North Africa, The Cambridge World history of food, 2, 1123–39, 2000.

Morice, C. P., Kennedy, J. J., Rayner, N. A., Winn, J. P., Hogan, E., Killick, R. E., Dunn, R. J., Osborn, T. J., Jones, P. D., and Simpson, I. R.: An updated assessment of near-surface temperature change from 1850: The HadCRUT5 data set, Journal of Geophysical Research: Atmospheres, 126, e2019JD032 361, 2021.

Neely III, R. R. and Schmidt, A.: VolcanEESM: Global volcanic sulphur dioxide (SO2) emissions database from 1850 to present, 2016.

Newhall, C., Self, S., and Robock, A.: Anticipating future Volcanic Explosivity Index (VEI) 7 eruptions and their chilling impacts, Geosphere, 14, 572–603, 2018.

Oetelaar, G. A.: The days of the dry snow: vulnerabilities and transformations related to the Mazama ash fall on the northern Plains, Past Vulnerability: Vulcanic eruptions and human vulnerability in traditional societies past and present, 2015.

Oetelaar, G. A.: Natural disasters and interregional interactions: La Longue Durée in Northern Plains historical developments, Plains Anthropologist, 66, 1–33, 2021.

Oetelaar, G. A. and Beaudoin, A. B.: Darkened Skies and sparkling grasses: the potential impact of the Mazama Ash fall on the northwestern plains, Plains Anthropologist, 50, 285–305, 2005.

Oman, L., Robock, A., Stenchikov, G. L., and Thordarson, T.: High-latitude eruptions cast shadow over the African monsoon and the flow of the Nile, Geophysical Research Letters, 33, 2006.

Oppenheimer, C.: Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815, Progress in physical geography, 27, 230–259, 2003.

Oppenheimer, C.: Eruptions that shook the world, Cambridge University Press, 2011.

Ordonez, A. and Riede, F.: Changes in limiting factors for forager population dynamics in Europe across the last glacial-interglacial transition, Nature Communications, 13, 5140, 2022.

Paine, A. R., Baldini, J. U. L., Rex, C. L., Sigl, M., Pausata, F. S. R., and Brown, R. J.: Evidence for volcanic forcing of Holocene cold events, Nat Commun, doi: 10.1038/s41467-026-73492-4, 2026.

Pausata, F. S., Karamperidou, C., Caballero, R., and Battisti, D. S.: ENSO response to high-latitude volcanic eruptions in the Northern Hemisphere: The role of the initial conditions, Geophysical Research Letters, 43, 8694–8702, 2016.

Pearson, C., Sigl, M., Burke, A., Davies, S., Kurbatov, A., Severi, M., Cole-Dai, J., Innes, H., Albert, P. G., and Helmick, M.: Geochemical ice-core constraints on the timing and climatic impact of Aniakchak II (1628 BCE) and Thera (Minoan) volcanic eruptions, PNAS nexus, 1, pgac048, 2022.

Pinto, J. P., Turco, R. P., and Toon, O. B.: Self-limiting physical and chemical effects in volcanic eruption clouds, Journal of Geophysical Research: Atmospheres, 94, 11 165–11 174, 1989.

Preiser-Kapeller, J.: Die erste Ernte und der große Hunger: Klima, Pandemien und der Wandel der Alten Welt bis 500 n. Chr., (No Title), 2021.

Pyne-O'Donnell, S. D., Hughes, P. D., Froese, D. G., Jensen, B. J., Kuehn, S. C., Mallon, G., Amesbury, M. J., Charman, D. J., Daley, T. J., Loader, N. J., et al.: High-precision ultra-distal Holocene tephrochronology in North America, Quaternary Science Reviews, 52, 6–11, 2012.

Rainville, R. A.: Effects of the White River and Mazama tephras on terrestrial and aquatic palaeoenvironments in western Subarctic Canada, and implications for past human populations, Ph.D. thesis, University of Calgary (Canada), 2016.

Reichstein, M., Riede, F., and Frank, D.: More floods, fires and cyclones—plan for domino effects on sustainability goals, Nature, 592, 347–349, 2021.

Reick, C., Raddatz, T., Brovkin, V., and Gayler, V.: Representation of natural and anthropogenic land cover change in MPI-ESM, Journal of Advances in Modeling Earth Systems, 5, 459–482, 2013.

Revell, L. E., Stenke, A., Luo, B., Kremser, S., Rozanov, E., Sukhodolov, T., and Peter, T.: Impacts of Mt Pinatubo volcanic aerosol on the tropical stratosphere in chemistry–climate model simulations using CCMI and CMIP6 stratospheric aerosol data, Atmospheric Chemistry and Physics, 17, 13 139–13 150, 2017.

Ridder, N. N., Pitman, A. J., Westra, S., Ukkola, A., Do, H. X., Bador, M., Hirsch, A. L., Evans, J. P., Di Luca, A., and Zscheischler, J.: Global hotspots for the occurrence of compound events, Nature communications, 11, 5956, 2020.

Riede, F.: Past vulnerability: vulcanic eruptions and human vulnerability in traditional societies past and present, Aarhus Universitetsforlag, 2015.

Riede, F.: Volcanic activity and human society, Quaternary International, 394, 1–5, 2016.

Ritchie, H., Rosado, P., and Roser, M.: Agricultural Production, Our World in Data, https://ourworldindata.org/agricultural-production, 2023.

Scanlon, J.: Winners and losers: Some thoughts about the political economy of disaster, International Journal of Mass Emergencies & Disasters, 6, 47–63, 1988.

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

Schneider, D. P., Ammann, C. M., Otto-Bliesner, B. L., and Kaufman, D. S.: Climate response to large, high-latitude and low-latitude volcanic eruptions in the Community Climate System Model, Journal of Geophysical Research: Atmospheres, 114, 2009.

Self, S.: The effects and consequences of very large explosive volcanic eruptions, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 364, 2073–2097, 2006.

Self, S., Gertisser, R., Thordarson, T., Rampino, M. R., and Wolff, J. A.: Magma volume, volatile emissions, and stratospheric aerosols from the 1815 eruption of Tambora, Geophys. Res. Lett., 31, L20 608, 2004.

Shah, S. and Mishra, V.: Climate change impacts on streamflow in India, in: Climate Change and Water Resources in India, Edition: 24th Conference of the Parties (COP24) to the United Nations Framework Convention on Climate Change (UNFCCC), pp. 39–52, Ministry of Environment, Forest and Climate Change (MOEFCC), 2018.

Sigl, M. and Toohey, M.: Volcanic stratospheric sulfur injections from 500 BCE to 1900 CE, eVolv2k_version4, (No Title), 2024.

Sigl, M., McConnell, J. R., Toohey, M., Curran, M., Das, S. B., Edwards, R., Isaksson, E., Kawamura, K., Kipfstuhl, S., Krüger, K., et al.: Insights from Antarctica on volcanic forcing during the Common Era, Nature Climate Change, 4, 693–697, 2014.

Sigl, M., Winstrup, M., McConnell, J. R., Welten, K. C., Plunkett, G., Ludlow, F., Büntgen, U., Caffee, M., Chellman, N., Dahl-Jensen, D., et al.: Timing and climate forcing of volcanic eruptions for the past 2,500 years, Nature, 523, 543–549, 2015.

Sigl, M., Toohey, M., McConnell, J. R., Cole-Dai, J., and Severi, M.: 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, 3167–3196, 2022.

Stephens, L., Fuller, D., Boivin, N., Rick, T., Gauthier, N., Kay, A., Marwick, B., Armstrong, C. G., Barton, C. M., Denham, T., et al.: Archaeological assessment reveals Earth's early transformation through land use, Science, 365, 897–902, 2019.

Stevens, B., Giorgetta, M., Esch, M., Mauritsen, T., Crueger, T., Rast, S., Salzmann, M., Schmidt, H., Bader, J., Block, K., et al.: Atmospheric component of the MPI-M Earth system model: ECHAM6, Journal of Advances in Modeling Earth Systems, 5, 146–172, 2013.

Stoffel, M., Corona, C., and St. George, S.: The next massive volcano eruption will cause climate chaos — and we are unprepared, Nature, 635, 286–289, 2024.

Stothers, R. B.: Volcanic dry fogs, climate cooling, and plague pandemics in Europe and the Middle East, Climatic change, 42, 713–723, 1999.

Stothers, R. B. and Rampino, M. R.: Volcanic eruptions in the Mediterranean before AD 630 from written and archaeological sources, Journal of Geophysical Research: Solid Earth, 88, 6357–6371, 1983.

Thiery, W., Lange, S., Rogelj, J., Schleussner, C.-F., Gudmundsson, L., Seneviratne, S. I., Andrijevic, M., Frieler, K., Emanuel, K., Geiger, T., et al.: Intergenerational inequities in exposure to climate extremes, Science, 374, 158–160, 2021.

Timmreck, C.: Modeling the climatic effects of large explosive volcanic eruptions, Wiley Interdisciplinary Reviews: Climate Change, 3, 545–564, 2012.

Timmreck, C., Graf, H.-F., Lorenz, S. J., Niemeier, U., Zanchettin, D., Matei, D., Jungclaus, J. H., and Crowley, T. J.: Aerosol size confines climate response to volcanic super-eruptions, Geophysical Research Letters, 37, 2010.

Timmreck, C., Toohey, M., Zanchettin, D., Brönnimann, S., Lundstadt, E., and Wilson, R.: The unidentified volcanic eruption of 1809: why it remains a climatic cold case, Climate of the Past Discussions, 2021, 1–39, 2021.

Toohey, M. and Sigl, M.: Volcanic stratospheric sulfur injections and aerosol optical depth from 500 BCE to 1900 CE, Earth System Science Data, 9, 809–831, 2017.

Toohey, M., Krüger, K., Niemeier, U., and Timmreck, C.: The influence of eruption season on the global aerosol evolution and radiative impact of tropical volcanic eruptions, Atmospheric Chemistry and Physics, 11, 12 351–12 367, 2011.

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

Toohey, M., Stevens, B., Schmidt, H., and Timmreck, C.: Easy Volcanic Aerosol (EVA v1. 0): an idealized forcing generator for climate simulations, Geoscientific Model Development, 9, 4049–4070, 2016.

Toohey, M., Krüger, K., Schmidt, H., Timmreck, C., Sigl, M., Stoffel, M., and Wilson, R.: Disproportionately strong climate forcing from extratropical explosive volcanic eruptions, Nature Geoscience, 12, 100–107, 2019.

Ulus, T. and Ellenblum, R.: How long and how strong must a climatic anomaly be in order to evoke a social transformation? Historical and contemporaneous case studies, Humanities and Social Sciences Communications, 8, 1–12, 2021.

Van Bavel, B. J., Curtis, D. R., Hannaford, M. J., Moatsos, M., Roosen, J., and Soens, T.: Climate and society in long-term perspective: Opportunities and pitfalls in the use of historical datasets, Wiley Interdisciplinary Reviews: Climate Change, 10, e611, 2019.

van Dijk, E., Jungclaus, J., Lorenz, S., Timmreck, C., and Krüger, K.: Was there a volcanic-induced long-lasting cooling over the Northern Hemisphere in the mid-6th–7th century?, Climate of the Past, 18, 1601–1623, 2022.

van Dijk, E., Gundersen, I. M., de Bode, A., Høeg, H. I., Loftsgarden, K., Iversen, F., Timmreck, C., Jungclaus, J., and Krüger, K.: Climate and societal impacts in Scandinavia following the 536 and 540 CE volcanic double event, Climate of the Past, 19, 357–398, 2023.

van Dijk, E. J., Jungclaus, J., Sigl, M., Timmreck, C., and Krüger, K.: High-frequency climate forcing causes prolonged cold periods in the Holocene, Communications Earth & Environment, 5, 242, 2024.

Verkerk, M., Aubry, T. J., Smith, C., Hopcroft, P. O., Sigl, M., Tierney, J. E., Anchukaitis, K., Osman, M., Schmidt, A., and Toohey, M.: Using reduced-complexity volcanic aerosol and climate models to produce large ensemble simulations of Holocene temperature, Clim. Past, 21, 1755–1778, 2025.

Verkinderen, P.: Waterways of Iraq and Iran in the early Islamic period: changing rivers and landscapes of the Mesopotamian plain, 2015.

Vettoretti, G., Hu, R.-J., Bethke, I., Krüger, K., Sigl, M., Outten, S., Lin, J., Nuterman, R., Svensson, A., Ditlevsen, P., et al.: Volcanism-induced collapse and recovery of the Atlantic meridional overturning circulation under glacial conditions, Science Advances, 12, eadx2124, 2026.

Von Uexkull, N., Croicu, M., Fjelde, H., and Buhaug, H.: Civil conflict sensitivity to growing-season drought, Proceedings of the National Academy of Sciences, 113, 12 391–12 396, 2016.

Ward, B., Pausata, F. S., and Maher, N.: The sensitivity of the El Niño–Southern Oscillation to volcanic aerosol spatial distribution in the MPI grand ensemble, Earth System Dynamics, 12, 975–996, 2021.

Warren, R.: Climate, crisis, and colonialism: Volcanic eruptions and the causes of famine in British India, 1831 to 1838, Journal of Historical Geography, 91, 18–36, 2026.

Weiss, H.: Megadrought and collapse: from early agriculture to Angkor, Oxford University Press, 2017.

Xu, C., Kohler, T. A., Lenton, T. M., Svenning, J.-C., and Scheffer, M.: Future of the human climate niche, Proceedings of the National Academy of Sciences, 117, 11 350–11 355, 2020.

Zanchettin, D., Bothe, O., Graf, H. F., Lorenz, S. J., Luterbacher, J., Timmreck, C., and Jungclaus, J. H.: Background conditions influence the decadal climate response to strong volcanic eruptions, Journal of Geophysical Research: Atmospheres, 118, 4090–4106, 2013.

Zanchettin, D., Timmreck, C., Khodri, M., Cole, J. N., Tsigaridis, K., Abe, M., and Mann, G.: VolMIP volc-pinatubo-full field-average GL TR NH SH ENSO NAO monthly time series, 2022.

Zdanowicz, C. M., Zielinski, G. A., and Germani, M. S.: Mount Mazama eruption: Calendrical age verified and atmospheric impact assessed, Geology, 27, 621–624, 1999.

Zscheischler, J., Westra, S., Van Den Hurk, B. J., Seneviratne, S. I., Ward, P. J., Pitman, A., AghaKouchak, A., Bresch, D. N., Leonard, M., Wahl, T., et al.: Future climate risk from compound events, Nature climate change, 8, 469–477, 2018.

https://doi.org/10.5194/egusphere-2026-3266
Preprint. Discussion started: 16 June 2026

Table 1. SO_2, SAOD, and ERF for selected past major eruptions, as well as the corresponding ratios between Mazama and Tambora (Mazama/Tambora), and Mazama and Okmok (Mazama/Okmok).

Eruption	VSSI (Tg S)	1σ	Latitude (°N)	Max monthly NH30-60°N SAOD-EVA	Min monthly NH30-60°N ERF (W/m^2)	Max annual NH30-60°N SAOD-EVA	Min annual NH30-60°N ERF (W/m^2)	References
Pinatubo (1991 CE)	9		15	0.10	-2.1	0.09	-1.8	EESM (Neely III and Schmidt, 2016) and CMIP6 (Revell et al., 2017)
Katmai (1912 CE)	6		58	0.18	-3.3	0.15	-2.8	EESM (Neely III and Schmidt, 2016) and CMIP6 (Revell et al., 2017)
Zavaritskii (1831 CE)	12	7	47	0.37	-6.3	0.32	-5.6	Hutchison et al. (2025)
Tambora (1815 CE)	28	4	-8	0.34	-6.0	0.28	-5.1	Toohey and Sigl (2017)
Samalas (1257 CE)	59	11	-8	0.61	-9.5	0.52	-8.4	Toohey and Sigl (2017)
Okmok II (44/43 BCE)	48	15	53	0.94	-12.6	0.81	-11.5	McConnell et al. (2020a)
Aniachak (1628 BCE)	52	17	56	0.98	-13.0	0.85	-11.8	Pearson et al. (2022)
Mazama (5600 BCE)	162	47	43	1.80	-17.3	1.54	-16.3	Sigl et al. (2022)
Mazama/Tambora	5.8			5	3	5	3	
Mazama/Okmok	3.4			2	1.4			
	see references			Based on EVA	$ERF = -20.7(1 - e^{-SAOD})$	Based on EVA	$ERF = -20.7(1 - e^{-SAOD})$	
				Toohey et al. (2016)	Marshall et al. (2020)	Toohey et al. (2016)	Marshall et al. (2020)	