Climatic and Societal Impacts of Volcanic Eruptions in the Western Han Dynasty (206 BCE- 8 CE): A Comparative Study

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Abstract. The Western Han dynasty (206 BCE-8 CE) experienced periods of extreme climate, accompanied by the evolving concept of the "mandate of heaven" that shaped societal response to disasters. While recent studies suggest that certain climate anomalies during the Han era are related to the atmospheric impacts of explosive volcanic eruptions, this paper employs both quantitative and qualitative methods to establish these associations more systematically. It categorizes and quantifies climatic stressors and selected societal events and applies superposed epoch analysis to examine the timing and statistical significance of their potential associations with ice-core-based dates of explosive eruptions. The paper then selects two historical periods, 180-150 BCE and 60-30 BCE, and offers a comparative analysis of recorded climatic and societal stresses, atmospheric optical anomalies, and societal responses to consecutive natural disasters. These periods are chosen because of the occurrence of massive volcanic eruptions known from polar ice-cores. For instance, in 43 BCE, when the Okmok volcano in Alaska erupted, a pale-blue sun and extreme summer cold are documented. Similarly, ice-cores identify a cluster (previously termed the "volcanic quartet") of substantial eruptions in 168 BCE, 164 BCE, 161 BCE and 158 BCE that may have heavily impacted societies such as Egypt. Comparing the responses to the disasters of these periods also allows us to incorporate historical materials not suitable for quantification and to evaluate the effectiveness of Han dynasty disaster prevention and mitigation measures, thereby ~~identifying~~ suggesting factors that may contribute to better resilience to sudden and drastic environmental changes.

1 Introduction

He went out East Gate,
no hope to return;
he came in the gate,
he was shaken with grief.
No food in the kettle;
no clothes on the rack.
He drew his sword,
he went out the gate,
his children wept and wife pulled at his clothes.
"Other wives want wealth and honour,
I gladly share gruel with you,
share gruel with you:
By broad Heaven above,
by our babies here below,
this is wrong!"
"Get out of my way! I go!
I've waited far too long!

Already my hair hangs white,
I cannot stay here forever!"[1]

This conversation from “Parting and Going off, East Gate” (東門行), a classic piece of Yuefu (folk song style poem) possibly dated to the Eastern Han period (Owen, 1996), portrays how the hardship of lower-class livelihoods could promote societal instability. Given the poem’s historical background, repeated disasters were likely one plausible trigger to the husband’s taking up arms in the face of the family’s poverty. Environmental change is long considered a potential (if controversial) contributor to societal stress and collapse (e.g., Butzer, 2012; deMenocal, 2001; Fei and Zhou, 2016; Weiss and Bradley,2001; Haldon et al., 2020). Recent work suggests that climatic shocks have been persistently associated with Chinese dynastic collapse (or transition), with large shocks potentially acting more independently, and smaller shocks more often effective when dynasties were already experiencing notable stress (Gao et al., 2021). These shocks were inferred from ice-core-based evidence for explosive volcanic eruptions, which are a known agent of abrupt regional to global climatic change. Our paper stages its research in the Western Han Dynasty (206 BCE- 8CE) to examine whether climatic and societal stresses recorded in Chinese sources are associated with explosive volcanic eruptions. As stated by Butzer (2012), academics have often overlooked “the intricate interplay of environmental, political, and sociocultural resilience” that can allow societies to rebound after impacts from climatic changes. We thus also explore how Han society responded to consecutive disasters.

The short-lived but sudden and severe climatic impacts potentially wrought by explosive eruptions start with the sulfur-rich gases they can inject into the stratosphere, which there oxidize to form sulfate aerosols that backscatter incoming shortwave radiation, resulting in net surface cooling (Ludlow and Manning, 2021; Singh et al., 2023; Robock and Mao, 1992). This is the direct radiative impact of explosive volcanism, but dynamical impacts are also regionally important. For tropical eruptions, the resulting concentration of aerosols in the stratosphere at lower latitudes (where they can induce high-altitude heating by absorbing outgoing long-wave radiation) may induce a north-south heating asymmetry that resolves itself partly by altering atmospheric circulation (e.g., enhancing westerly winter-time airflow in the Northern Hemispheric (NH) high latitudes (Robock and Mao,1992;Robock,2000; Zambri et al., 2017, Singh et al., 2023)). Extra-tropical eruptions, such as those in the NH higher latitudes, are usually considered less impactful, but recent research suggests they can cause strong hemispheric cooling (Toohey et al., 2019). Radiative cooling from explosive volcanism can also induce precipitation anomalies that result in net global drying (though varying by region). One way is by reducing evaporation from waterbodies, reducing later precipitation potential (Iles et al., 2013). Another (this time dynamical) mechanism (particularly effective when eruptions occur in higher latitudes) is by restricting the summer season migration of the inter-tropical convergence zone into the hemisphere most heavily loaded with aerosols, thereby diminishing associated monsoon rainfall (Robock 2020, Peterson et al., 2000; Fasullo et al., 2019). Volcanic aerosols and other particulates can also produce atmospheric optical anomalies that include diminished sunlight, a discoloured solar disk, unusually red “volcanic” sunsets, Bishop’s Rings or volcanic coronae (Deirmendjian, 1973; Ludlow and Manning, 2021; Guillet et al., 2020). Such phenomena are documented ~~through time~~on multiple occasions across Eurasia (Scuderi, 1990; Wittmann and Xu,1987; Sigl et al., 2015).

Volcanically induced hydroclimatic extremes, especially cold and drought, can promote agricultural pest populations, land degradation, crop damage or bad harvests and human and animal mortality (Gao et al., 2021; Robock, 2020). Instances of h~~H~~uman mortality following major volcanic eruptions include diseases and high mortality in England and France after the Icelandic Laki eruption in 1783-1784 CE (Stothers,1999), the surge in diarrhoea cases in Bima, Dompo, and Sang’ir after the

[1] Translated by Stephen Owen. The original text is, 出東門，不顧歸。來入門，悵欲悲。盎中無鬥米儲，還視架上無懸衣。拔劍東門去，舍中兒母牽衣啼：“他家但願富貴，賤妾與君共哺糜。上用倉浪天故，下當用此黃口兒。今非！” “咄！行！吾去爲遲！白髮時下難久居。

1815 CE Tambora eruption (Oppenheimer, 2003), and the regional measles outbreak after the Mt. Pinatubo (Philippines) eruption in 1991 CE ~~Philippines~~ (Floret et al., 2006); all merit further examination regarding the mechanisms of disease spread after volcanic eruptions (Fei et al., 2016). Because some sulfate ultimately settles out of the atmosphere over polar regions and is captured in ice cores (Sigl et al., 2015), the climate forcing potential of past explosive volcanism can be investigated. Other archives such as tree-rings and historical documents can then allow any climatic and societal impacts to be identified and understood (Yun et al., 2023; Oppenheimer, 2011).

Although China's well-documented climate history provides a solid starting point to investigate volcanic-climatic-societal impacts, few scholars have attempted this systematically. Exceptions are Gao et al. (2021), who identify a persistent interactive role for short-term climatic shocks (inferred from ice-core-based dates of explosive volcanism) and pre-existing societal stress (inferred from warfare frequencies) in dynastic collapse during the Common Era. ~~Specific s~~Studies of specific cases of post-eruption climatic perturbation ~~cooling~~ and its impacts include the circa 626 CE event (Fei et al., 2007), the Icelandic Eldgjá eruption in circa 939 CE (Fei et al., 2003), and the 1600 CE Huaynaputina eruption in Peru (Fei et al., 2016). The 1815 Tambora (Indonesia) eruption is most studied regarding the impact of sudden volcanic cooling, regional crop failure, famine and economic crisis in China (e.g., Yang et al., 2005; Zhang et al., 1992; Fei, 2018). Associations between drought and explosive volcanism (Shen et al., 2007), and solar phenomena and eruptions (Zhang, 2007), have also been examined. Furthermore, recent studies have increasingly referenced climatic and atmospheric optical records in Chinese sources as a complement to natural archives, for instance, research on the 43 BCE Okmok (Alaska) eruption (McConnell et al., 2020; Wang et al., 2024), the 852/3 CE Mount Churchill (Alaska) eruption (Mackay et al., 2022), and other medieval-era eruptions (Guillet et al., 2023). However, the comparatively abundant historical climate records of China hold much further potential for this purpose.

The Han Dynasty (206 BCE- 220 CE) is known for frequent natural disasters and it's ~~ever~~ evolving "ominous politics", with these two elements together profoundly shaping the society. Much research has thus been dedicated to understanding the contemporary interpretation of climate anomalies as "portents" endowed with cultural and political agency (e.g., Bielenstein,1950; Eberhard, 1933; Cai, 2015). Our paper concentrates on the Western Han Dynasty (206 BCE – 8 CE) as it experienced multiple volcanic eruptions, with two periods particularly notable in having sharply increased polar sulfate deposition around ~~4~~43BCE and 168 BCE (Sigl et al., 2015; Toohey and Sigl, 2017; McConnell et al., 2020). Tree-ring growth anomalies and reconstructed summer temperature corroborate the ice-cores in suggesting the 160s BCE and 40s BCE were extremely cold (Sigl et al., 2015). Because sulfate deposition was identified in both poles, the 168 BCE eruption is considered tropical in location. This was followed by three smaller but notable ~~extratropical NH~~ eruptions in, respectively, 164 BCE, 161 BCE and 158 BCE (deemed to be extratropical NH in location ~~such~~ because their sulphate was confined to Greenland (Sigl et al., 2015)), with potentially corresponding records from Babylon (Iraq) of dim suns in 164 BCE and 161 BCE (Sachs and Hunger,1996; McGovern, 2024), and hydroclimatic anomalies and unrest in Ptolemaic Egypt (Ludlow and Manning, 2021; Singh et al., 2023). Chinese records of a discoloured sun and cold temperatures around 43 BCE have already been noticed and linked to a documented 44 BCE eruption of Etna (Sicily) (e.g., Bicknell, 1993~~,~~;Fei et al., 2016). A more recent reassessment has convincingly associated these phenomena (and the relevant Greenland sulfate) with a massive 43 BCE eruption of Okmok (Alaska), closely following a notable extratropical NH eruption in 46 BCE (McConnell et al., 2020).

Scholars often structure their analyses of Han history according to each emperors' reign; this includes climatic history, given the political importance of disasters, materially and as omens. The 160s BCE fell under the rule of Emperor Wen (the fifth Emperor of the Western Han Dynasty, reigning from 180 BCE - 157 BCE), while the 40s BCE were in Emperor Yuan's reign (the eleventh Emperor of the Western Han Dynasty, reigning from 48 BCE - 33 BCE), ~~which~~ and encountered the most disasters, especially water-related disasters, earthquakes, snowfall and famines, of all the Western Han dynasty (Jiao et al., 2009). These events leave a considerable imprint on the dynasty's record and we aim to identify the climatic stresses, atmospheric optical anomalies and societal impacts and responses that appear statistically associated with eruptions during the dynasty's duration. This is facilitated by applying Superposed Epoch Analyses to time series of variables including warfare and vagrancy derived from the historical sources. A qualitative comparison will then focus on two three-decade periods comprising the years before, during and after the volcanic episodes of 168-158 BCE and the 40s BCE to allow a closer examination of attempts to restore political, economic and societal stability following multiple potentially volcanically induced climatic and societal impacts.

2 Material and Methods

2.1 Survey and categorization of documented climate anomalies and impacts

To create a comprehensive chronological dataset of climatic records for the period, historical sources are re-surveyed and their content integrated with established datasets that include *A Compendium of Meteorological Records of China in the Last 3000 Years* by Zhang et al. (2004), *The General History of Natural Disasters in China-the Volume of Qin and Han* by Jiao et al. (2009), and the *Table of Natural and Human Disasters in Chinese Dynasties* by Chen et al. (1933), as well as two studies on Han climate that provide lists of relevant records (Chen, 2016; Chen, 2001). These all slightly differ regarding the events included. Of primary sources, dynastic histories are closely surveyed, especially *Shiji* (史記, *Records of the Grand Historian*, by Sima Qian, completed 91 BC) and *Hanshu* (漢書， *Book of Han*, by Ban Gu, completed 82 CE). Within *Hanshu*¸ climatic and atmospheric optical phenomena are mainly found in the *Annals*, *Treatise on the Five Elements* and *Treatise on Astronomy*, but are also scattered in some of its constituent biographies. Thus, it was deemed necessary to survey all volumes of *Hanshu*, together with *Shiji* and other relevant sources. These include *Zizhi Tongjian* (資治通鑑, *Comprehensive* ~~*mirror*~~ *Mirror to* ~~*aid*~~ *Aid in* ~~*government*~~*Government*, by Sima Guang, a chronicle recording Chinese history from 403 BC to 959 CE) and *Wenxian Tongkao* (文獻通考, a comprehensive examination of literature from earlier periods, compiled by Ma Duanlin in 1307 CE).

In deriving our counts of climate disasters, if the same event is documented in more than one sources, we counted it only once to avoid artificially inflating event frequencies. Thus, in terms of research method, our counting is consistent throughout the whole period under study — the Western Han Dynasty — including the case study years 180-150 BCE and 60-30 BCE. In addition, we compared our counts with all the existing datasets mentioned above. In rare cases, where there are slight differences, we re-examined the historical contexts and details of the relevant records to confirm our decision about whether the event in question should be counted. This approach has also been detailed in the notes of Table S1 and the additional "Notes for the Tables" document in the supplementary materials. In total, eighteen types or categories of climate and climate-related records are identifiable, and in Figure 1 we list each type and their frequency counts. Notably, the number of records does not always equal the number of events, because, in our annual chronologies, when multiple records refer to the same events (based on context, timing, locations, etc.), they are counted only once. The categorization of each record is also provided in column D "Summary" in supplementary table S1.

Climate and Related Record Types	Number of Records
cold	9
drought	44
earthquake	27
famine	27
flood	37
frost	3
hail	9
landslide	7
locust	18
plague	13
poor harvest	20
rain	11
river dried	1
river overflow	16
river flows backward	2
snow	14
thunder	3
wind	11

Figure 1 Types of climate and climate-related records extracted from the historical documents.

Similarly, new chronological datasets for harvest conditions, warfare (including rebellions), population changes (including that arising from vagrancy, the movement of garrisons and planned migration) and amnesties (pardons to the convicted on special occasions, sometimes including awards to the common people) have been derived as potential proxies for societal stress and mechanisms of response. The new warfare dataset builds upon the *Tabulation of Wars in Ancient China* (Editing Committee of China's Military History, 1985), complemented by a thorough reading and lexical search of *Hanshu*. The dataset of amnesties builds on Wu's (2003) study of the Han dynasty's amnesty system. ~~No~~ Few pre-existing compilations of Han harvest conditions or population change exist, although Ge's (2014) study of Western Han population and geography offers a solid foundation for the later theme. Valuable studies by Yin et al. (2015), Su et al. (2014) and Fang et al. (2015) analyze the association between climate change and grain harvests over extended time periods. However, a new annual dataset reflecting harvest conditions is needed to facilitate the Superposed Epoch Analysis (SEA) approach taken in the present study. ~~Hence, t~~The records in these two datasets (i.e., harvest condition and population change, see ~~supplementary material~~Table S4 and S5) are extracted from hundreds of annals, accounts, tables, treatises and biographies of *Hanshu* and *Shiji*. Only direct and credible attestations to harvest conditions (i.e., without inferring additional poor harvests from reported flooding or insect outbreaks) and population changes are included. All the datasets mentioned above are provided in the Supplementary material accompanying ~~of~~ this paper.

2.2 Time-series and quantification of climatic and societal impacts

The reliability of each record in our datasets is assessed by applying general principles of historical and textual criticism (e.g., McNeil, 2000) adapted to the context of the Han era. Within each dataset, records are categorized (see earlier) to construct annual count or frequency series for ~~meteorological and related extremes~~climate and climate-related disaster events. When documented disasters are ambiguous regarding location or extent, these are taken as applying to the northern and central part of the empire, where the major population and the major agricultural areas were located. Decadal frequency ~~time series~~counts of ~~all variables~~each series are also provided for a perspective on broader trends. However, these frequencies cannot capture all relevant information in the available records. Thus, we also present an “impact index”, building upon Chen (2016), and capitalizing on three common features of our climate records that state (or imply) different dimensions of the scale of events:

phrasing, duration and affected area. Each feature is assigned a score from 1-3 (for wording, from mild to serious, then extreme; for duration, from days to months and then years; for affected area, from local to regional, then empire-wide). Multiplying these scores produces an impact index, with higher scores equating to greater impact. These are provided for the most serious climate disaster of each given year. For more nuance, we also create individual time-series of events plausibly representing impacts arising (at least in part) from (or occurring in response to) climate ~~ic~~ and climate-related disasters shocks that are documented in sufficient abundance to attempt statistical analysis. These (as per the preceding section) include years of bad harvests, annual famine and plague incidence, annual warfare and rebellion frequencies, years experiencing vagrancy and annual planned migration incidence.

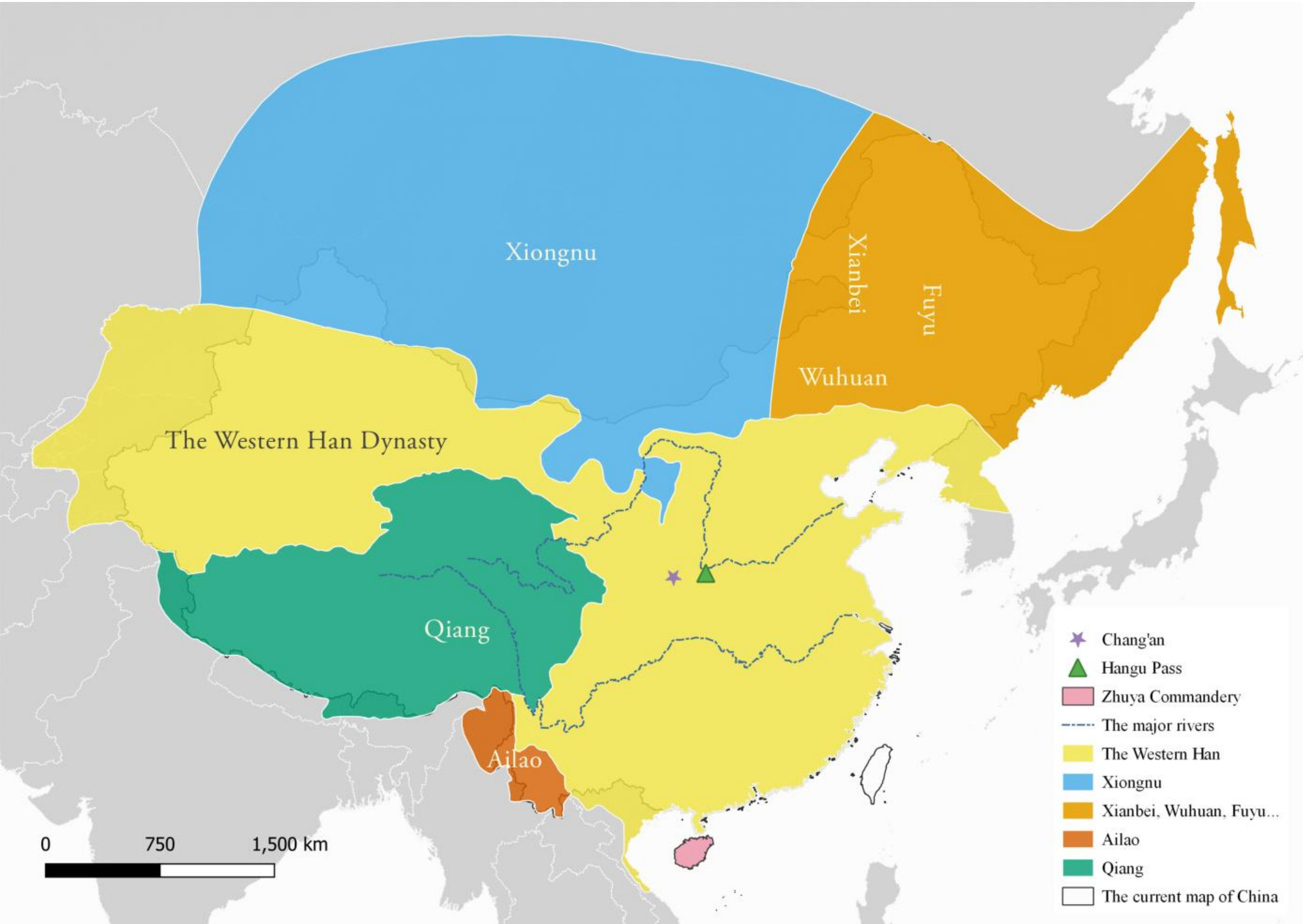

Figure 2 Map of the later period of the Western Han Dynasty and the major relevant areas and locations during this time, based on the *Historical Atlas of China* (Tan, 1982). The star mark is Chang'an, the capital of the empire. The Guandong area (as referenced in the main text) refers to the region east of the Hangu Pass. As noted by Tan (1982), the distribution of the various ethnic groups (i.e., Qiang, Xianbei, Fuyu, Wuhuan and Ailao) is only indicative due to limited historical records. The area labelled "Xiongnu" outlines the general region where these groups of people were active. This map also displays the Yellow River (upper) and the Yangtze River (lower) as they appear today. Notably, the Yellow River changed course multiple times and its depiction here is therefore only indicative for the study period.

2.3 Superposed epoch analysis

Superposed epoch analysis (SEA) is widely employed to overlay and average (i.e., composite or superpose) multiple temporal sections of a given time-series (e.g., of a potentially dependent phenomenon) around a series of specifically dated focal events known or hypothesized to have a direct (or indirect) causal influence on (or correlative association with) the potentially dependent phenomenon (e.g., Manning et al., 2017; Rao et al., 2019; Campbell and Ludlow, 2020; Gao et al., ~~2020~~2021). This allows an assessment of whether consistent responses register in the potentially dependent phenomenon, during or following the focal event years. SEA has been widely used to assess hydroclimatic responses to volcanic eruptions (e.g., Rao et al., 2019) and has been increasingly adapted to examine potential post-volcanic responses in societal variables (e.g., political revolts in Ptolemaic Egypt (Manning et al., 2017) or Chinese dynastic collapses (Gao et al., ~~2020~~2021)~~)~~, and violence and societal stressors such as famine in the Ancient Near East (Ludlow et al., 2023). Our focal events are years when ice-core sulphate deposition data (Sigl et al., 2015) imply explosive eruptions, whilst the new climatic and societal variables (described above) are the dependent or response timeseries. Only tropical and ~~northern~~ Northern ~~h~~Hemisphere extratropical eruptions are considered, in being most likely induce adverse climate in the Western Han empire. Fourteen such eruption years are identified from 206 BCE to 8 CE, comprising 190, 180, 168, 164, 161, 158, 147, 141, 123, 105, 85, 46, 43 and 35 BCE. For context, the volume of sulphate deposition associated with each eruption in the NEEM Greenland ice-core is shown in Figure 3 as one indication of their relative climate forcing potential (Sigl et al., 2015), alongside negative growth anomalies from the "N-Tree" temperature sensitive Northern Hemisphere tree-ring chronology (Sigl et al., 2015) and a new tree-ring-based precipitation reconstruction for Jingyuan and Gansu, China (Qin et al., 2025).

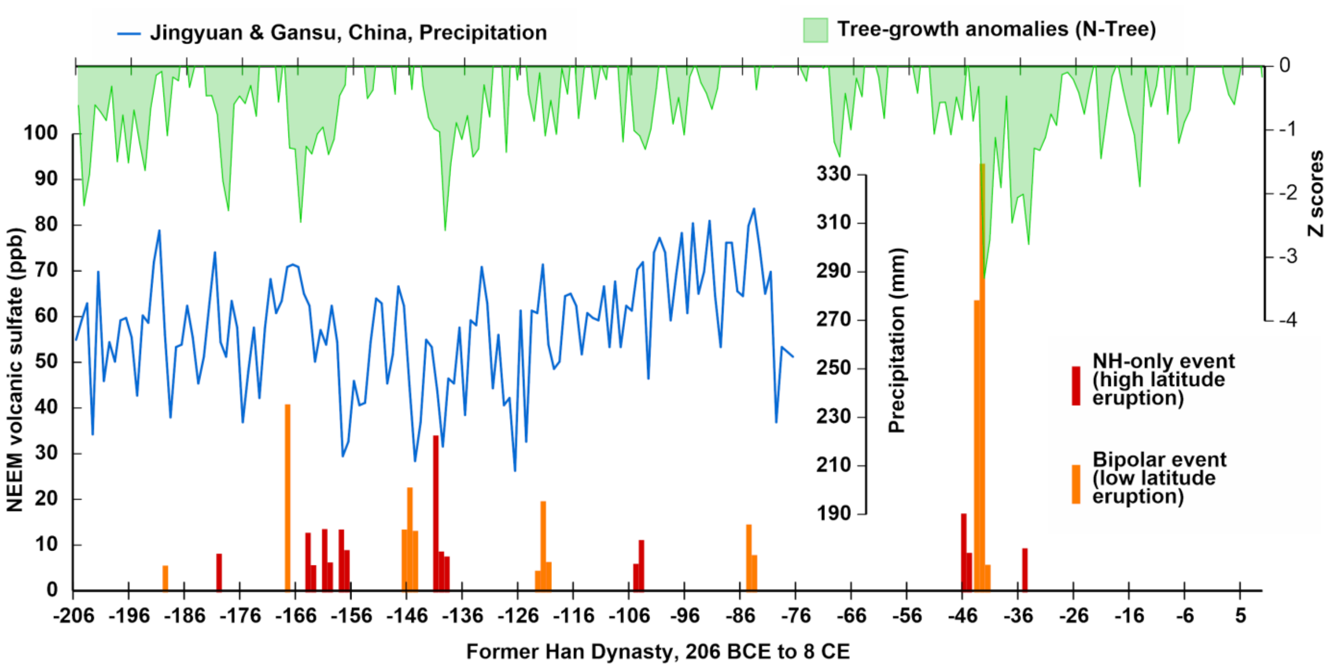

Figure 3. Indicative climate forcing potential as represented by the (non-sea-salt) volcanic sulphate volume measured in parts per billion (ppb) in the annual layers of the NEEM Greenland ice-core for the fourteen inferred tropical and NH extratropical eruptions identified during the Western Han period (Sigl et al., 2015). Higher volumes imply greater climate forcing potential. These deposition volumes can be converted into time-integrated global radiative forcing estimates of the reduction in solar energy received at the Earth's surface in watts per square meter arising from the atmospheric loading of volcanic sulphate aerosols. For each eruption, these are 190 BCE (1.69 w/m^{-2} reduction), 180 (0.64), 168 (7.90) 164 (1.31), 161 (1.46), 158 (1.51), 147 (7.50), 141 (3.29), 123 (6.56), 105 (1.27), 85 (4.15), 46 (2.07), 43 (23.21) and 35 BCE (0.74). For context, the temperature sensitive NH N-Tree tree ring chronology is also shown (plotting negative growth anomalies relative to the 1000-1099 CE mean; Sigl et al., 2015), as is the Qin et al. (2025) tree-ring-based precipitation reconstruction for Jinqyuan and Gansu, China.

2.4 Comparative case studies

The Western Han's 214-year span enables a closer comparative analysis of two episodes of explosive volcanism already recognized in Ptolemaic Egypt and the Ancient Near East for inducing climatic-societal impacts, namely, the 168-158 BCE "volcanic quartet" and the 40s BCE (McConnell et al., 2020; Ludlow and Manning, 2021; Kostick et al., 2023; Singh et al., 2023). Our qualitative case studies of the historical periods 180–150 BCE and 60–30 BCE complement the SEA approach by allowing consideration of records less suitable for quantitative analysis, particularly regarding societal responses to climatic stress evolving on different timescales. The case study approach allows us to ask, moreover, whether responses changed between episodes. The 40s BCE certainly inherited a political legacy from the 168–158 BCE period, but significant changes had also occurred in state-governance, disaster perception, and more. In each case study, responses are also contextualised by reference to climatic and societal conditions in the decade immediately preceding and following the eruptions, and attention paid to whether responses were effective in impact mitigation.

3. Results and Discussion

3.1 Quantitative Analysis

3.1.1 Climatic impacts and atmospheric optical anomalies

Figure ~~1~~ 4 (top panel) shows the diversity of documented climate-induced (flood, drought, cold) and potentially related (famine, plague, locusts) disasters and other societal stressors (warfare and conflict) in decadal totals. The figure also presents combined counts of disasters across categories (with and without famine and plague) plus decadal impact index scores. It is well known that famine and plague can be triggered by climatically induced shocks to agriculture and food supply (e.g., harvest failures and animal mortality promoting subsistence crises that can compromise human immune systems). Mass movement of people in search of subsistence under such circumstance can also facilitate the spread of disease. However, in both cases, the underlying societal context is critical, and both famine and plague can occur in the absence of any meaningful climatic input. For example, conflict can impact food supply through scorched earth warfare (targeting crops and animals), by removing agricultural labour supply (when diverted to military service), or indirectly impact food availability by increasing market prices when food is requisitioned for military supplies or trade routes are disrupted. This diminishment of food supply and access can again impact human immune systems, while mass movements of peoples as part of military service or to escape conflict can similarly facilitate disease spread (these mechanisms are listed in Gao et al. (2021)). Hence, the above-mentioned distinction between counts that include and exclude famine and plague is maintained when conducting our SEAs to examine the potential volcanic role in climate and climate-related disasters, allowing us to explore whether the apparent link between documented disasters and volcanic eruptions persisted both with and without the inclusion of famine and plague-related disasters, given that these latter disasters can also have non-climatic origins.

Annual disaster frequencies are shown in the bottom panel of Figure 4, with years experiencing one or more disasters being common. Coherent trends of genuine climatic origin playing out on multi-decadal scales are difficult to confidently identify, however; particularly given the many potential non-climatic influences on disaster incidence and their recording (e.g., Ludlow, 2012). Nonetheless, some years and decades apparently suffered notably more frequent and impactful disasters. The impact index for our case studies reveals the 40s and 30s to be particularly impacted, whereas the 160s and 150s BCE exhibit more moderate (if certainly not low) scores. The high scores for the 40s and 30s BCE result from increased counts across all disaster categories (excepting locusts), a marked contrast to the lows of the 50s BCE. The annual frequency data shows that disasters in 163 and 158 BCE are the main contributors to the elevated decadal values of the 160s and 150s BCE, whereas those in 48 and 43 BCE make the most substantial contribution to that decade. It may be notable that of these individual years, 158 and 43 BCE coincide with ice-core-based dates of major eruptions, whereas 163 BCE follows by just one year (Figure 3). The possibility cannot be excluded, however, that such close timings are coincidental. We thus employ an SEA approach (Figure 5) to assess (1) whether eruption dates more broadly co-occurred with (or were closely followed by) increased disasters during the Western Han era ~~more broadly~~ and (2) ~~whether~~ the probability that any observed increase arose by chance.

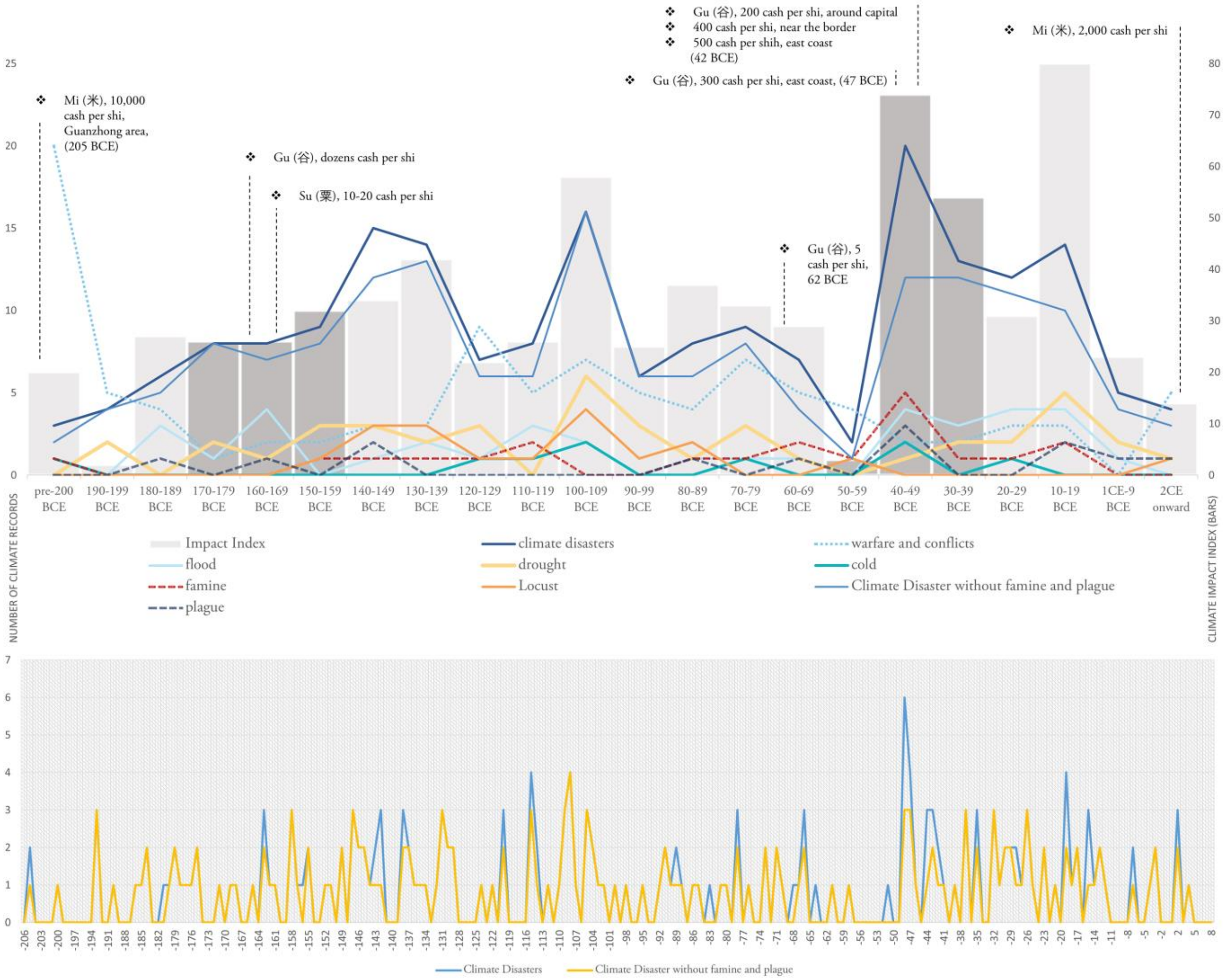

Figure ~~1~~4. The top panel shows the time-series of various proxies of climatic and societal stresses in the Western Han dynasty at a decadal resolution. The bottom panel presents the time-series of the number of climate disasters, both including and excluding instances of famine and plague, at an annual resolution. *Shi* (top panel) is a unit of measurement, and it is approximately 30 kg today. Gu (谷) here refers to grain in general. Mi (米) is understood as rice or hulled millet, and Su (粟) refers to spiked millet (Dubs, 1938; Swann, 2013; Hsu, 1980).

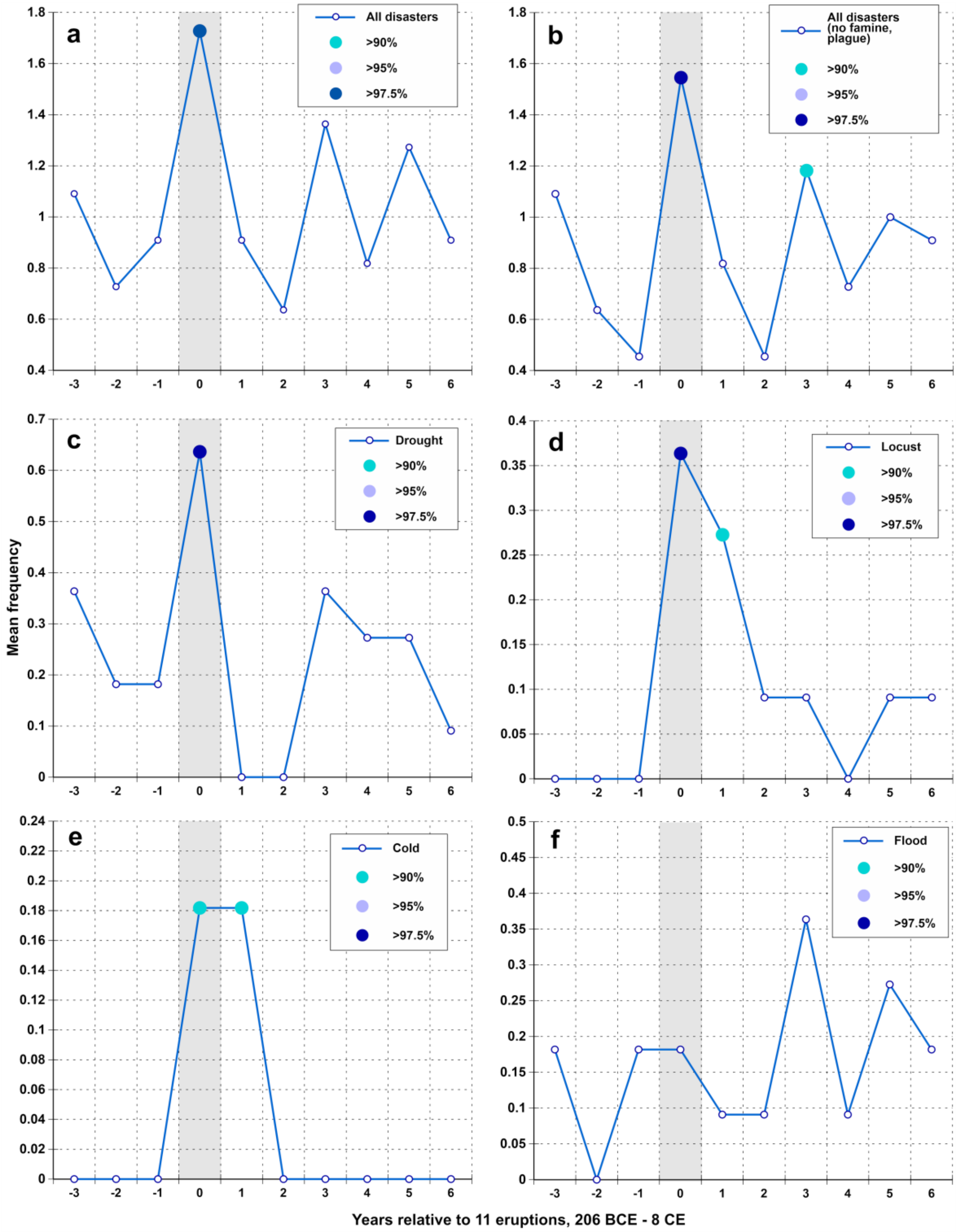

Figure ~~2~~5. Superposed Epoch Analysis (SEA) results of the time series of climate and climate-related disasters relative in timing to 11 presumed-tropical and Northern Hemisphere (NH) extratropical volcanic eruptions (identified based on ice-core evidence (Sigl et al., 2015)) as focal event years (represented at year zero on the horizontal axes). Colour coded cots identify years deemed statistically significantly elevated at (at least) 90% confidence.

Figure ~~2~~ 5 thus visualizes multiple SEA outcomes in which our disaster time-series are superposed relative in time to the presumed tropical and extratropical NH eruption dates taken from Sigl et al. (2015) but adjusting the Okmok eruption date from 44 to 43 BCE, following McConnell et al. (2020). Our analyses employ ten-year superposition windows that show (as a reference baseline) the mean frequencies for our disaster categories in each of the three years preceding eruptions (Superposed Years -3 to -1, horizontal axes, Fig. ~~2a~~5a-f), the mean frequency in the eruption years themselves (Superposed Year 0), and the mean in each of the six years following (to identify any potential multi-year or lagged post-eruption impacts (Superposed Years 1 to 6)). We note that three of the 14 eruption dates are omitted because their inclusion introduces a “double counting” artefact that can occur in the SEA approach when focal event dates recur closely in time and are comparatively small in number (Manning et al., 2017). In addressing this issue (which manifests in our analyses as an artificial secondary peak in Superposed Year 3) we identify eruption dates that occur within three years of each other and exclude the smaller of these events (based on the Greenland sulfate deposition volumes of Sigl et al. (2015), Figure 3) as being less likely to elicit a climatic and societal response. We thus omit (1) 164 BCE, which follows the larger eruption of 168 BCE, (2) 161 BCE, which precedes the larger eruption of 158 BCE, and (3) 46 BCE, which precedes the larger eruption of 43 BCE.

Taking Fig. ~~2a~~5a, which considers the combined climate and related disaster time-series (comprising 198 events, distributed across 113 years of the 214-year Western Han era, and ranging from zero to a maximum of six in any given year), we observe the highest peak in mean disaster frequency during eruption years. While this suggests a volcanic influence, we must also assess the likelihood that it has arisen randomly. To do this, we follow the approach of Campbell and Ludlow (2020) and Gao et al. (2021) in randomly re-ordering the combined climate and related disaster time-series 10,000 times~~,~~. ~~on~~ On each randomisation we ~~calculating~~ calculate the mean frequency of the randomly re-ordered disasters that fall in each of the years (-3 through 0 to plus 6) relative to our 11 set eruption dates. This produces a randomised reference distribution against which to compare the mean values observed relative to our eruption dates when using the actual (original) time series of climate and related disasters. The outcome is shown in Fig. ~~2a~~5a, where any actually observed superposed means (blue line, Fig. 2a) that fall within the top 10%, 5%, or 2.5% of means in our random reference distribution are colour-coded and taken, respectively, as having a less than 10%, 5%, or 2.5% likelihood of occurring purely by chance (i.e., they are considered statistically significant at > 90%, >95%, or >97.5% confidence). Ultimately, the mean disaster frequency in Year 0 (the eruption years themselves) is the only value deemed statistically significantly elevated (at 98.4% confidence), supporting the identification of a recurrent role for explosive volcanism in triggering climate and climate-related disasters during the Western Han era.

While our records leave little doubt that famine and plague were often associated by contemporaries with adverse climate conditions, it is known that they may also have multiple non-climatic origins (e.g., population movement, conflict) (Gao et al., 2016), as discussed earlier. We thus repeat the above SEAs but remove disasters solely involving these events from the combined time-series (leaving 164 events across 107 years, ranging from zero to four in any given year). The highest peak nonetheless persists in Year 0 (Fig. ~~2b~~5b) and remains statistically significant (now at 99.4% confidence). A smaller secondary peak in Year 3 now also registers as marginally significant (at 90.8%).

It is also instructive to examine the association between volcanic dates and disaster categories individually. Figure ~~2c~~ 5c thus shows that mean drought frequencies (43 events across 39 years, ranging from zero to two in any given year) peak suddenly in Year 0 (at 99.6% confidence and represent the only statistically significantly elevated year~~)~~, while locust disasters (18 events across 16 years, ranging from zero to two in any given year) shown in Fig. ~~2d~~ 5d peak in Years 0 and 1 (at 98.7% and 93.3% confidence, respectively). No other years approach significance in either category. Cold disasters (Fig. ~~2e~~5e) show equivalent peaks in Years 0 and 1 (each significant at 90.6% confidence), suggesting a multi-year temperature impact consistent with expectations (e.g., Gao et al., 2017). Even so, the lower significance of cold disasters may be surprising given that cold is totemic of volcanic climatic impacts (at least for summer, as some NH continental landmass regions may experience transient winter warming (Robock and Mao, 1992; Robock, 2000; Zambri et al., 2017)). We note, however, that only nine cold disasters are recorded for the Western Han dynasty (distributed across eight years, with seven years registering one such disaster and only one year experiencing two), with the small sample size likely bearing upon these results. Of all disaster categories, flooding (36 events across 33 years, ranging from zero to two in any given year) alone fails to exhibit any notably elevated frequencies (Fig. ~~2f~~5f). This is not unexpected given our contrasting finding of increased drought frequency in the same broad area from which most of our records come (~~,~~ northern and central China), which accords with findings of increased drought in

China in other periods following tropical and NH extratropical eruptions (e.g., Zhuo et al., 2014; Gao et al., 2017). Other high-resolution climate proxies, where available for the period, can add further nuance. Important here is the Qin et al. (2025) tree-ring-based precipitation reconstruction for northern China that runs from 270 to 77 BCE (Figure 3). Visual inspection of this reconstruction suggests that multiple eruptions in the Western Han period were indeed closely followed by growing season precipitation reductions in the spatial domain for which these trees capture a climatic signal. These include the eruptions in 158 (presumed extratropical NH), 147 (presumed tropical), 141 (presumed extratropical NH) and 105 BCE (presumed extratropical NH)). Yet, this response is not wholly consistent, with the presumed tropical eruption in 168 BCE followed by notable elevated precipitation.

3.1.2 Societal Impacts

To assess whether societal stressors exhibit any notable volcanic association, we begin by superposing our annual impact index values (Section 2.2) on our 11 volcanic focal dates (Fig. ~~3a~~6a). Index values of between one and 27 are assigned across 114 years, with all other years assigned a value of zero. We see the mean index value peak in Year 0 (statistically significant at 98.2% confidence), before falling below the 90% threshold, but remaining elevated relative to pre-eruption values. This is unsurprising given the elevated mean disaster frequencies seen in Section 3.1.1. For individual stressors, we start with bad harvests, of which 26 such years are identified. Their mean superposed frequency indeed also peaks in Year 0 (Fig. 6~~3~~b), but (at 87.4%) does not meet the minimum 90% confidence threshold. This may be partly explicable given that we consider these events less consistently reported in the sources. In addition, the variance captured in the time-series itself is limited to presence-absence (0,1) format. We cannot, therefore, at present identify whether the poor harvests associated with eruptions were particularly widespread or severe.

For famine and plague, we are more confident that the sources capture most events of any notable scale. However, the respective frequencies remain small, with 21 famines across 21 years (thus ranging between zero and one in any given year) and 13 plagues across 11 years (mainly ranging between zero and one in any given year, with just one year experiencing two plagues). In Fig. ~~3c~~6c, we observe a moderately elevated mean famine incidence in Years -1, 0, 2 and 3, though none reach the 90% confidence. In Fig. ~~3d~~6d, the only statistically significant peak in mean plague frequencies is observed for Year -1 (96.6% confidence), with no plague documented in any of our 11 eruption years. A one year offset could be plausibly attributed to small uncertainties in ice-core layer counting and/or small delays between eruption dates and the deposition of sulphate in the ice (Sigl et al., 2015; Gao et al., 2016). Under this interpretation, the plague peak in Year -1 might be associated with our volcanic eruptions. However, this is inconsistent with the recurrent peaks in climate disasters that do occur in Year 0 (Fig. ~~2~~4) as well as the impact index peak in Year 0 (Fig. ~~3a~~5a). While our randomisation testing is intended to mitigate some drawbacks of small number statistics, they cannot be entirely circumvented. It is thus notable that the peak in Year -1 depends entirely on one plague reported in 44 BCE (one year before the 43 BCE Okmok eruption) and one in 142 BCE (one year before the unknown 141 BCE eruption). Future work may address these limitations (e.g., by creating harvest, famine and plague indexes that derive greater information from the available evidence concerning spatial extent or severity that may be particularly associated with volcanically triggered cases).

For cases of vagrancy, which refers to historical records where the word “vagrant” (流民) is directly used or where historical accounts clearly describe groups of people abandoning their homes or land~~in which many people are documented as abandoning their homes or land~~, often in search of food, we identify 33 years experiencing this phenomenon and our time-series is presence-absence (0,1) in format. Figure ~~3e~~ 6e reveals elevated mean frequencies in Years 2 and 3 (statistically significant at 93.2% and 92.9%, respectively), suggesting a somewhat delayed onset of this behaviour in response to adverse conditions wrought by eruptions. Planned migrations, by contrast, refer to records of events in which large numbers of people were relocated long-term (for years or more) following edicts, administrative orders, or similar. The state may have undertaken such relocations for many potential reasons, such as labour needed for large-scale construction projects, or to garrison new territories, but also plausibly to increase food security by returning abandoned land to productivity or facilitate expansion into uncultivated territories (precedents for which exist elsewhere in the ancient world (see Ludlow et al., 2023)). We identify 44 years experiencing such migrations (again presence-absence in format) and see that their mean frequency increases suggestively in the three years following our eruptions (Fig. 6f), though never reaching statistical significance (Year 3 comes closest at 83.9%). We note that escaping, fleeing, and surrender events during (or due to) war are not counted, because, based on a detailed examination of these records, their scale appears relatively small, and their impacts are temporary, unless sources clearly mention that the surrendering populations were to be resettled in specific areas (e.g., the over 50,000 people led by Chanyu that surrendered to the Han government in 55 BCE). The movement of populations for temporary labour needs is also not counted, as these populations were characteristically dismissed from their duties after short periods of time.~~In cases of planned migrations, the state deliberately relocated large numbers of people for many potential reasons, such as temporary labour needed for construction, or to create garrisons, but also plausibly to increase food security by returning abandoned land to productivity or facilitate expansion into uncultivated territories (precedents for which exist elsewhere in the ancient world (see Ludlow et al., 2023)). We identify 44 years experiencing such migrations (again presence-absence in format) and see that their mean frequency increases suggestively in the three years following our eruptions (Fig. 3f), though never reaching statistical significance (Year 3 comes closest at 83.9%).~~

Finally, we examine the potential influence of volcanically induced climatic shock on violence and conflict, starting with annual warfare and rebellion frequencies (139 events across 90 years, ranging from zero to 11 in any given year). The scholarly literature on climate-conflict linkages is undecided on whether such events may increase or decrease following climatic stress (and can depend upon the precise conflict typology in question; see Section 3.2.2), and we thus test for the statistical significance of ~~movements in both directions~~changes toward either higher or lower frequencies. Notable in Fig. ~~3g~~6g, therefore, is an unusually low mean frequency in Year 1 (reaching statistical significance, at 98.8% confidence) that follows from another low in Year 0 (though not itself significant, at 88.3% confidence). Figure ~~3h~~ 6h repeats the test, but considers warfare only (~~i.e.,~~ comprising101 events across 71 years, after omitting internal rebellions, and ranging from zero to eight in any given year). Much the same pattern is observed here, with Year 1 being the sole value to reach statistical significance (at 98.9%). When considering rebellion only (comprising 66 events across 50 years, ranging from zero to four in any given year), ~~there are apparently~~ modestly low frequencies are apparent in Years 0 and 1, but these do not emerge as statistically significantly ~~high or~~ low. These results are further discussed in Section 3.2.2.

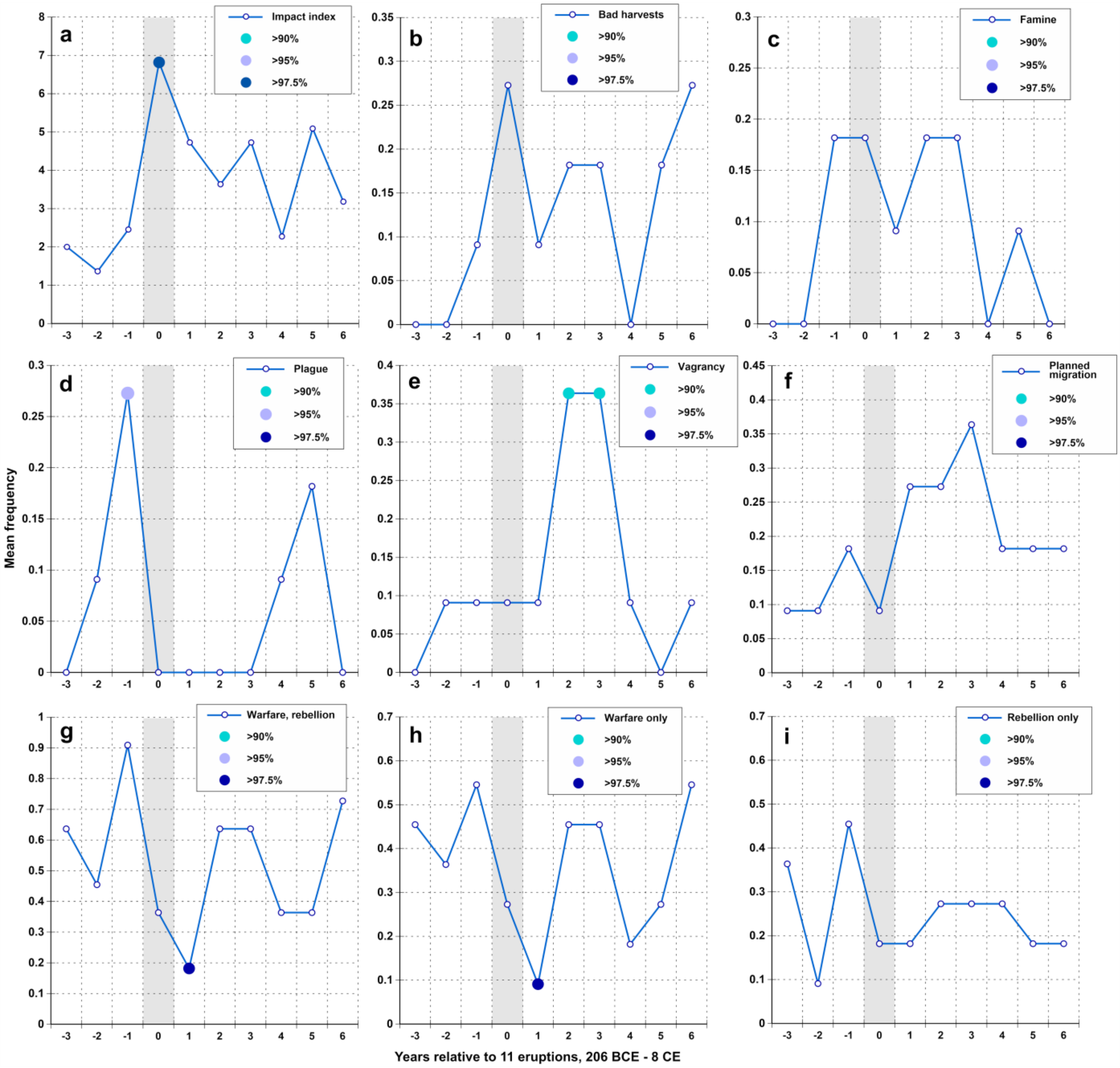

Figure ~~3~~6. Superposed Epoch Analysis (SEA) results showing the compositing of each~~the~~ time series of societal stress proxies relative in time to the dates of 11 presumed-tropical and ~~Northern Hemisphere~~extratropical ~~(~~NH~~)~~ volcanic eruptions (identified based on ice-core evidence (Sigl et al., 2015)) that are taken as focal event years and represented at point 0 on the horizontal axes. Colour coded cots identify years deemed statistically significant at (at least) 90% confidence (one-tailed).

3.2 Comparative Case Study

3.2.1 Climatic impacts and atmospheric optical anomalies

Climate records of the Western Han dynasty (Table S1 in the Supplement) suggest that the 170s BCE, which did not experience any known major explosive eruptions (Sigl et al., 2015), suffered only occasional short-term local or regional flooding, snowfall and windiness. Two state-wide droughts in autumn 177 BCE and spring 171 BCE may, however, have contributed to some mounting climatic stress before the “volcanic quartet” of four sequential eruptions in 168, 164, 161 and 158 BCE that are thought to have been both hydro-climatically and societally impactful in other major civilizations of the period, such as Ptolemaic Egypt (Singh et al., 2023). ~~.~~ In the 160s BCE, the Yellow River first overflowed in the winter of 168 BCE in today’s Henan province, then flooded again in 165 BCE, importantly highlighting that post-volcanic hydroclimatic conditions can depart from expectations (e.g., of eruptions associated with drought, as per Section 3.1.1), especially over large spatial scales as represented by Han China. We may infer that these challenging circumstances continued, with an imperial edict in 163 BCE noting that:

> "Recently for many years there have continually been no good harvests. Moreover, there have been visitations of floods, droughts, sickness, and epidemics…" (*Hanshu, Annals of Emperor Wen*; Dubs, 1938). ［詔曰："間者數年比不登，又有水旱疾疫之災……"　《漢書・文帝紀》］

In autumn 161 BCE, continuous rain is reported to have caused severe floods that submerged thousands of houses and killed hundreds of people. By contrast, the 150s BCE was a decade of serious drought, more consistent with post-volcanic expectations, even if a causal link cannot be drawn conclusively between any specific single eruptions and droughts. A drought from spring 158 BCE lasted into summer and led to a locust plague, with drought visiting again in 155 BCE, afflicting the central and northwest of the empire.

Of our later second case study period, most years in the 50s BCE experienced almost no documented climate or related ~~natural~~ disasters (Table S1). Only one local locust outbreak is recorded from 60-49 BCE. This situation reversed dramatically in the 40s BCE, however. Even before the eruptions of 46 and 43 BCE, large-scale severe flooding in 48 BCE contributed to famines, epidemics and even cannibalism in Guandong (east of Hangu Pass, see Figure 2), where the Western Han dynasty ~~most~~ population and farmlands were concentrated. The situation further deteriorated through the decade and the evidence of 43 BCE clearly implies a volcanic contribution. The annals, treatises, and multiple biographies in *Hanshu* (Table S1) thus document a pale-blue sun, with the *Treatise on the Five Elements* providing the most detailed description:

> "In the 4th month (May 7-June 5), the sun was pale blue (blue-white) in colour and cast no shadows. Right in the middle (of the Sun) frequently there were shadows and no brightness. That summer was cold until the 9th month, the Sun then regained its brightness…" (*Hanshu, Treatise on the Five Elements*; Yau and Stephenson,1988) ［元帝永光元年四月，日色青白，亡景，正中時有景亡光。是夏寒，至九月，日乃有光。《漢書・五行志》］

The pale-blue sun was accompanied by extreme summer cold, marked by frosts in the 3rd (April 8- May 6) and 9th (approximately October) months. While the former damaged wheat and mulberries, the latter effectively killed the year's harvest and famine swept the whole empire in 42 BCE, possibly triggering societal unrest (Section 3.2.2). In the 30s BCE, after an initial cross-regional flood and overflow of the Yellow River (in 39 BCE), disasters occurred less frequently and severely. The incidence and timing of the pale-blue sun as well as the extremity of conditions that same year (and that immediately following) can be credibly associated with the heavy atmospheric aerosol loading and consequent radiative cooling expected from a massive eruption like Okmok in 43 BCE (McConnell et al., 2020).

3.2.2 Societal Impacts

Our first case study period (180-150 BCE) witnessed one plague and famine. The plague occurred in 163 BCE, notably just one year after the 164 BCE eruption, but can also be considered a combined outcome of the multiple disasters from previous years (Section 3.2.1). The famine occurred in 156 BCE, just two years after the 158 BCE eruption and a potentially associated drought and locust plague (discussed above), and was certainly serious:

> … an imperial edict said, "Recently, for successive years there have not been good harvests, so that many people are lacking food; early death is cutting short their natural [span of] years…" (*Hanshu, Annals of Emperor Jing*; Dubs, 1938) [詔曰：“間者歲比不登，民多乏食，夭絕天年……”《漢書・景帝紀》]

In comparison, the 40s BCE suffered almost continuous famine. The empire-wide famine from October 43 BCE ~~caused~~ was associated with rocketing grain prices to rocket, as documented in 42 BCE:

> "At the time, bad harvests had lasted for years. Each *Shi* (a measurement unit, approximately 30 kg today) of grains cost more than 200 cash in the capital, but about 400 per *shi* around the remote areas, and about 500 per ~~*Shi*~~ *shi* in Guandong. There were famines everywhere, and the imperial court was very concerned about the situation, and it also encountered mutinies of the Qiang people (an ethnic group)." *Hanshu, the Biography of Feng Fengshi* [是時，歲比不登，京師谷石二百餘，邊郡四百，關東五百，四方饑饉，朝廷方以爲憂，而遭羌變。《漢書・馮奉世傳》]

For context, Han grain prices during 180-150 BCE varied within a more constrained range of dozens to 100 cash per shi (Huang, 2002; Tan, 1994), though we have no prices explicitly recorded for any of the volcanic quartet years in order to assess any short-term departures from this price range. After a period of commodity price increase due to the prevalence of counterfeit coins around 120 BCE (Ban and Swann 2013), grain prices restabilized during a period of good harvests, reaching a low of 5 cash per shi in 62 BCE *(Hanshu, Annals of Emperor Xuan)*. Prices were thus dramatically higher across multiple regions in 42 BCE, with those in the Guandong area in particular outstripping the already high price of 300 per shi in 47 BCE~~Prices were thus dramatically higher in 42 BCE, outstripping the already high price of 300 per shi in 47 BCE~~ *(Hanshu, Treatise on Food and Money)*. Unfortunately, ~~there is no~~we are not aware of any price information regarding the 30s BCE. These price changes should be considered in tandem with evidence of the harvest situation (Table S4 in the Supplement). The first bad harvest during 180-150 BCE is recorded for 163 BCE, representing the first of an apparent run of poor harvests that lasted at least into 156 BCE. The timing of these ongoing harvest failures is almost parallel with the three volcanic eruptions of 164, 161 and 158 BCE, yet the years after 168 BCE (with its large presumed-tropical eruption) have documented bumper harvests, thereby exemplifying the regional complexity of volcanic climatic impacts. Additionally, whereas the bad harvests of the 40s BCE are reflected by marked grain price fluctuation, the poor yields of the 160s and 150s BCE might not~~did~~ affect prices enough as to merit their inclusion in the surviving records.

Disasters are often linked to large-scale internal population movements (e.g., Chumky et al., 2022), and population movements can be inferred for our first case study period from records of vagrancy ~~for our first case study period~~ in 178, 174 and 156 BCE, with planned migrations (mostly for apparent administrative and agricultural reasons) in 178, 177, 170, 169, 165 and 152 BCE (Table S5 in the Supplement). The latter thus do not align well with the dates of the volcanic quartet eruptions (unless the migration in 165 BCE is considered as a potential part outcome of the 168 BCE eruption). The available records do, however, document that vagrancy in 156 BCE was indeed a consequence of bad harvest and famine (see ~~this record in~~ table S5). This may be plausibly connected to the 158 BCE eruption, with some additional possible role for cumulative impacts of earlier quartet eruptions. Planned migrations also occurred in our 60-30 BCE case study period, with those in the years 59, 57, 55 and 48 BCE all pre-dating known eruptions, and only the planned migration of 42 BCE plausibly associated (chronologically) with explosive volcanism (the 43 BCE Okmok eruption). The sources suggest that these initiatives were undertaken mainly for military purposes (e.g., garrisoning and settling surrenderers). Vagrancy was certainly frequent, occurring in 48, 47, 43, 42 and 32 BCE, and often in explicit association with the ongoing disasters of the 40s BCE (with a plausible volcanic role for events in 43 and 42 BCE).

Assessing any role for climate in warfare and rebellion is challenging given the multiple "pathways" that might act either synergistically or antagonistically to promote or suppress violence and conflict, with the net outcome in any instance mediated by cultural, political, and environmental contexts and the specific violence and conflict typologies considered (Ludlow et al., 2023). A commonly cited pathway by which violence and conflict might rise after climate and related disasters involves competition for reduced resources (e.g., food after harvest failure) (Homer-Dixon, 1999). The operation of such a pathway can be plausibly linked to known challenges in our period such as vagrancy. This might compound food supply issues (e.g., if agricultural land is abandoned), reduce social stability (e.g., via tensions between incumbent and newly mobile groups seeking subsistence, potentially through theft), and place the dynasty under financial strain with lost revenues from land abandonment at a time when expenditure needs rise to support the population. We might also posit an increased need for military intervention to deter or suppress rival state activity aimed at exploiting Western Han difficulties, or external mobile non-state actors (e.g., pastoralists) opportunistically (or by necessity) raiding into Western Han territories, or internal but distinct groups hoping to cede from Western Han control. Such pathways are indeed consistent with existing work that has found associations between adverse climatic conditions and an increased incidence of nomadic-agriculturalist conflict in China (Su et al., 2016; Pei et al., 2019).

Despite the above, the net general outcome for warfare and rebellion frequencies in the Western Han period appears as a reduction one-year post-eruption (Fig. ~~3~~6). This suggests that ~~F~~for organised warfare and large-scale rebellion (if not specifically nomad-agriculturalist conflict) at least, the difficulties of conducting or sustaining military operations during adverse conditions (Winters et al., 1998) or of resourcing troops when harvests had deteriorated and societal needs and potential internal instability was higher (e.g., Manning et al.~~,~~ (2017) in the case of Ptolemaic Egypt) may have won out (on net, if not in every instance) over pathways promoting increased warfare, ~~or~~ large-scale rebellion or specific conflict typologies such as nomadic-agriculturalist (or pastoralist-sedentary) conflict. This finding is also consistent with that of Gao et al. (2021), who did not find any persistent causal role for explosive volcanism as a trigger for large-scale warfare and rebellion frequencies during the Common Era. Detailed examination reveals that most wars of ~~the~~ our study period were between Han and ethnic groups, or ~~they~~ were revolts led by vassal kings, marquises or tribes. Their overt causes appear political rather than climate or disaster driven. This is broadly consistent with most rebellions of the period occurring in the pre-eruption decade of our 180-150 BCE case study, with none occurring during or within three years post-eruption~~s~~, except a relatively small-scale rebellion plotted by Xiny~~Y~~uan P~~p~~ing (新垣平, a Fangshi, occultist) in 164 BCE. However, while the net general outcome of volcanically induced climatic disasters may have been to suppress warfare and rebellion, in specific individual cases the opposing pathways (outlined above) may still have prevailed~~,~~. ~~and i~~It is notable, therefore, that warfare between the Han government and the Xiongnu, a confederation of nomadic tribes, was recorded in 166, 162 and 158 BCE, close to or in eruption years, a result more consistent with expectations from Su et al. (2016) and Pei et al. (2019), which also suggests that reconciling our findings with these authors will require further careful attention to the exact typologies and geographies of the conflicts in question. ~~Whether these events can be solidly linked to climatic conditions merits further study.~~

In our 60-30 BCE period, repeated rebellions occurred in the Zhuya ~~Commanderies~~ Commandery (current Hainan, see Figure 2) until its abolition in 46 BCE, during a time when the government faced repeated climate and related disasters. Instructive of competing state imperatives (and the ~~antagonistic~~ competing pathways mentioned above, variously suppressing or promoting conflict) is Jia Juanzhi's (賈捐之, an official) attempt to convince Emperor Yuan to withdraw rather than suppressing the insurgents and instead focus more on disaster relief in Guandong *(Hanshu, Biography of Jia Juanzhi)*. Similarly, the rebellion of the Qiang tribe in autumn 42 BCE occurred when sources suggest that the whole empire suffered bad harvests, extreme grain prices and famine. When General Feng Fengshi (馮奉世, a general) requested 40,000 soldiers to address the Qiang revolt, other officials opposed his suggestion, citing that there was no extra manpower available since people were busy with the autumn harvest. Feng argued:

> "…the whole state is suffering from famine. The soldiers and horses are emaciated, and they have been greatly consumed. The equipment for defence and combat has been disused for a long time. The barbarians all show contempt for our officials at the border. That is why the Qiang people revolt …" (*Hanshu, Biography of Feng Fengshi*) [天下被饑饉，士馬羸秏，守戰之備久廢不簡，夷狄皆有輕邊吏之心，而羌首難。《漢書・馮奉世傳》]

Ultimately, he received only 12,000 soldiers and eventually the emperor had to send larger forces (over 60,000 soldiers) to restore order. Thus, climatic and societal impacts potentially induced by the 43 BCE Okmok eruption may in this case have played important roles in initiating conflict and then influencing (e.g., constraining) state strategies taken in response. It is also worth noting that warfare was not the only form of violence and conflict reported in the sources. Increasing robbery and brigandage are reported in an edict in 42 BCE:

> "…But the Yin and Yang [a Chinese philosophical concept regarding balance and harmony between opposites] have not yet accorded [with each other], the three luminaries have been veiled and indistinct, the great multitude have suffered greatly, have wandered, and have been scattered on the highways and paths. Robbers and brigands have arisen simultaneously…" (*Hanshu, Annals of Emperor Yuan*; Dubs 1938) [……然而陰陽未調，三光晻昧。元元大困，流散道路，盜賊並興。《漢書・元帝紀》]

In 41 BCE, a similar record is found, blaming an earthquake, rain and fog in mid-winter (Table S1). The possible statistical association between crime and volcanic climatic impacts merits further research.

3.2.3 Societal Responses

The immediate responses taken by the Western Han government in our case study periods share similarities but also significant differences due mainly to changes in agricultural policies, disaster perception, and socio-economic conditions. A summary of these policy changes is shown in ~~sees~~ Fig. ~~4~~7.

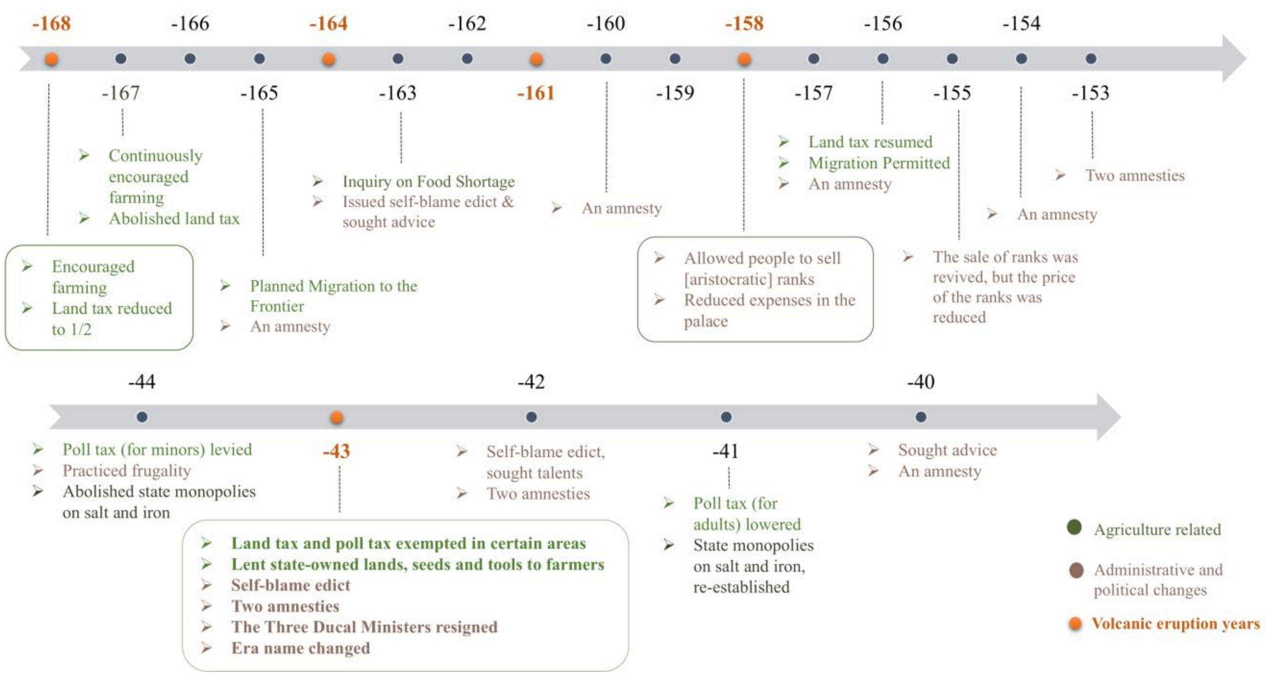

Figure 47. Summary of important policy changes related to the case study period

From 180-169 BCE, actions to address climate and climate-related natural disaster impacts are barely documented, excepting a self-blame edict (a proclamation in which the emperor takes responsibility for disasters) in 178 BCE following a solar eclipse. This may imply that disaster relief was not too demanding in human and monetary terms in these years. For the Yellow River flooding of 168 BCE, however, extensive labour was assembled to repair the embankment *(Hanshu, vol.29)*. After further flooding of the river in 165 BCE there is no specific infrastructure damage recorded but the event was treated as an "omen" for which the emperor issued orders to build a temple and offer sacrifices *(Shiji, Vol.28).* The situation became more serious in the years leading up to 163 BCE, as the state suffered the combined consequence of crop failures, floods, droughts and diseases. A classic self-blame edict (the full text of the edicts in our two case study periods is given in tables S2 and S3) was issued by the emperor with a request to seek suggestions from officials, especially for the causes of food shortage. A further flood occurred in autumn 161 BCE, but responses are absent from the records. By contrast, five approaches were documented when spring drought in 158 BCE lasted into summer and triggered locusts:

> [The emperor] ordered that the nobles should not pay tribute. He opened [to the common people] the mountains and marshes, reduced the [imperial] robes and the imperial officers, diminished the [regular] number of Gentlemen and officials, and opened the granaries in order to succour the people. The people were allowed to sell [aristocratic] ranks. (*Hanshu, Annals of Emperor Wen*; Dubs, 1938) [令諸侯無入貢，弛山澤，減諸服御，損郎吏員，發倉庾以振民，民得賣爵。《漢書・文帝紀》]

These five approaches comprise tribute reduction, opening access to state-owned natural resources, practicing frugality, opening granaries and selling ranks. While the first four were common strategies during climate disasters, the sale of noble ranks was recorded more rarely as a measure to address disasters, for instance, the permission to sell ranks was reissued with reduced price in 155 BCE *(Shiji vol.30)* to address drought in the same year. Ranks in the Han period could be sold for cash or used as ransom for reducing punishment (Hsu, 1980). The Han government began the practice of trading ranks for grain with the intention of solving supply issues for armies stationed at borders while elevating the status of farmers, but it developed into a strategy to secure food during disasters in the reign of Emperor Wen and Jing (180 BC-141 BC). However, this measure increased social differentiation (Li, 2006), as the rich could also buy ranks that entitled them to corvée exemption and immunity for past and even future crimes (Hsu, 1980). Migration was also permitted in 156 BCE to address food shortages, as the emperor recognized the challenges arising from an uneven distribution of population and agricultural sources and hoped to encourage farming in underdeveloped areas.

In our 60-30 BCE period, with climatic stresses accumulating rapidly from 48 BCE onward, all common relief measures were implemented (sending officials to investigate circumstances, seeking talents (i.e., to enlist the help of talented persons) and suggestions, tax and loan reductions or exemptions, opening access to state-owned resources, granaries and more). An edict in the 3rd month, likely before the first frost in 43 BCE documented in *Hanshu*, already granted an amnesty to allow the newly pardoned to *"improve their personalities, renew themselves, and each pay attention to cultivating his acres"* (*Hanshu*; Dubs, 1938). The amnesty also included loaning fields, seeds and food to the amnestied and poor, and awarding ranks and other items like wine and silk to a variety of officials and people. However, actions more symbolic than practical appear to have been taken to address the continued summer cold and ominous pale-blue sun, namely, the resignation of the Three Ducal Ministers' (thereby attributing them some blame for the prevailing circumstances) and the change of era name from Chuyuan (初元) to Yongguang (永光), which implies eternal brightness. For the frost in the ninth month of 43 BCE and the great famine that followed, no measure is documented until the next spring. As part of a self-blame edict (in the second month), an amnesty was granted accompanied by the giving of noble ranks and items to common people, gold to the nobles and silk to the virtuous especially the diligent cultivators of fields (*Hanshu, vol.9*). A month later, a solar eclipse precipitated another edict, blaming the increasingly violent and cruel behaviour of the people as the source of the sun's diminished light, and again the emperor sought good and capable talents (*Hanshu vol.9*). The ongoing bad harvest led to a third edict (in the sixth month) in 42 BCE, together with the fourth amnesty since 43 BCE. Yet another edict and amnesty were issued that exempted the poor from loans and debts in 40 BCE, partly intended to address unrest. This makes self-blame edicts and amnesties the most documented state measures in this case, used more frequently than at other times in the Western Han.

Comparing self-blame edicts from our two case study periods reveals the differences arising from changing perceptions of climate anomalies. Han philosopher Dong Zhongshu (董仲舒), the founder of Han Confucianism, conceptualized natural disasters as "warnings from heaven", which were initially used to constrain the ruler's power. However, his theory was taken further and became more influential later, especially during Emperor Yuan's reign, as he revered Confucianism. When Emperor Wen and Jing's edicts emphasized inquiry about causes of disasters and sought to tackle problems, Emperor Yuan encouraged officials to discuss moral issues and government policies by interpreting portents. However, the self-blame edicts do not necessarily imply the emperor's willingness to take responsibility. In 43 BCE, Emperor Yuan, being criticized for his inability to trust the virtuous and eliminate the evil (Huang 2016), preferred to blame the Three Ducal Ministers, who were believed to be responsible for harmonizing Yin and Yang *(Hanshi Waizhuan; Hanshu)*. Eventually, Yu Dingguo (于定國), the Lieutenant Chancellor, Shi Gao (史高), the Commander-in-chief and Xue Guangde (薛廣德), the Grandee Secretary, all resigned. This was the first time in Western Han history that the three Ducal Ministers openly and proactively took responsibility for their "strict liability" (Jiao et al 2009). Furthermore, the interpretation of meteorological anomalies was often contested and manipulated by rival elites as tools for partisan struggle. Indeed, the dimmed sun in 43 BCE was exploited by the powerful eunuchs Shi Xian (石顯) and Hong Gong (弘恭) to suggest the demotion of Zhou Kan (周堪) and Zhang Meng (張猛), their political antagonists. Interestingly, in 40 BCE, Zhou and Zhang came back to the court when the emperor interpreted a solar eclipse that year as a sign that he made a mistake in precipitating these resignations (*Hanshu, vol.36*). Thus, in practical terms, "moral cosmology" (Cai, 2015) as a concept parted ways from its original intention to constrain power or promote Confucius' ethical ideals. Furthermore, the political struggles (including over the interpretation of omens) that occurred during disasters arguably mad disaster relief less effective.

Similarly, amnesties usually involved freeing prisoners and could be permitted for various reasons, including as a celebration of the enthronement of a new emperor, celebrating auspicious meteorological signs, and more. In the case of climate anomalies, the granting of amnesties was also a way to cultivate a virtuous society and thereby ward off future disasters (Jiao et al., 2009). Thus, most amnesties were granted to comfort the public rather than have substantial effects on disaster relief, and the accompanying awards such as cattle, wine, silk and noble ranks might serve the same purpose. Such measures could initially ease the tensions between different classes because many convicts were common people who struggled to survive when the privileged class's benefits were barely affected by natural disasters. Loaning fields and seeds to the amnestied people and turning them ~~into~~ towards agricultural labour could also contribute to societal stability during disasters, but consecutive amnesties may have been of reduced effectiveness. As reported by an official in 42 BCE, those who had been pardoned repeatedly ~~committed~~ continued to commit crimes and social behaviour was not improved *(Hanshu Vol.81)*. This may imply that the burden on the common people's livelihood was not effectively relieved during disasters.

From an economic perspective, the gap between rich and poor became increasingly significant during the Western Han era. The bigger this gap ~~is~~, the more vulnerable the society may have become~~s~~ to climate and climate-related disasters~~extremes~~. Contemporary documents, such as Jia Yi's (賈誼, 200-168 BCE, a politician and essayist) memorial, stated *"Licentious and luxurious customs increase day by day",* while there were those who attempted to sell their children *(Hanshu vol.24, Swann 2013).* Chao Cuo's (晁錯, a politician and official) memorial (in 178 BCE), mentioned that independent farmers could not *"make both ends meet even in a year of normal crops"* and had to borrow at high-interest rates to pay exorbitant taxes (*Hanshu vol.24*, Hsu 1980). In the 40 BCEs, the contrast became more obvious. In Gong Yu's (貢禹, 124-44 BCE, a high official) memorial (44 BCE), he compared the expenses in Emperor Wen and Jing's court to inform Emperor Yuan of the excessive extravagance enjoyed by the privileged class and some government departments, while farmers continuously suffered from:

> "…having paid a [regular] tax in kind of grain, and also having paid the hay tax, the private demands solicited by authorities of the district and the village become too heavy a burden to bear" (*Hanshu vol.72*; Hsu, 1980) [已奉谷租，又出稿稅，鄉部私求，不可勝供。《漢書・食貨志》]

To address social and economic inequalities, one common state strategy during disasters was practicing frugality, which was undertaken in 158 BCE by reducing the number of imperial officers and four times in the 40s BCE by cutting imperial expenses in banquets, entertainment and horses (in 48 (twice), 47, and 44 BCE), reducing palace officers (in 46 BCE) and abolishing offices (in 44 BCE). For the overtaxed poor, with the intention to encourage farming, land tax was reduced by half to 1/30 of the annual produce in 168 BCE and was completely abolished for 12 years until it resumed ~~to~~ at 1/30 in 156 BCE *(Hanshu)*. The state also charged poll tax. While suanfu (算賦, poll tax on adults) was reduced three times to 40 cash during Emperor Wen's (179-157 BCE) rule, with a gap in its documentation, it was next known to be 90 cash in 52 BCE and decreased to 80 cash in 41 BCE (Hsu 1980). As for kouqian (口錢, poll tax on minors), there are no records concerning this during our earlier case study period, but sources show that its first taxable age was raised from three to seven in 44 BCE. This move was suggested by Gong Yu, considering the difficulties of the people's livelihood (*Hanshu vol.72*). However, whether other changes in taxes were related to disasters is not documented. There were indeed tribute exemptions (in 158 BCE) and land tax exemptions in affected areas (in 48 and~~,~~ 47 BCE) to offer immediate relief after disasters. Other economic changes during these two periods include the "Ever-normal granary (常平倉)", established in 54 BCE as a state instrument for the leveraging of grain prices to benefit farmers but this was abolished in 44 BCE, after several years of climatic disasters, when officials pointed out that it should not *"strive* [i.e., compete] *with the people for profits" (Hanshu, vol. 24)*. The state monopoly on salt and iron production was disestablished in the same year but resumed in the winter of 41 BCE as the government had insufficient income due to too much tax exemption *(Hanshu, vol.9)*. The association between these economic changes and possible volcanic-induced climate stress requires further exploration, but the repeated disasters of the 40s BCE drained the empire's wealth, further affecting the government's ability to implement disaster relief measures later.

As discussed, many policy changes in Han time before, during and after recurrent climate disasters aimed to encourage agricultural activities (Fig. 4, table S2, S3 in the Supplement). However, during times when the harvest was doomed to be damaged by extreme weather, such measures were hardly helpful. In Emperor Wen's time, agriculture was generally underdeveloped therefore production was low and grain storage was insufficient (Hsu, 1980), regardless of good harvests. Under this circumstance, it was intuitive that officials and the emperor prioritized the development of agriculture, even in disaster prevention and relief. Nevertheless, as pointed out by Hsu (1980), one big problem of Han agriculture was that the heavy burden of non-agricultural expenses and taxes exhausted farming resources, and eventually independent farmers lost their lands and became tenants that were constantly exploited. The government neglected this aspect and blamed people for overly pursuing commercially profitable activities therefore causing food shortages (e.g., the edict in 163 BCE, table S2), indicating the ruler's misunderstanding of agricultural development. Hence, chronic food shortages went unresolved while businesses were at times needlessly suppressed.

4 Conclusion and Discussion

This paper has employed a mixed-method approach to explore associations between explosive volcanism and climatic stresses, societal impacts and potential responses in Western Han sources. Statistically, the mean frequency of combined climate and climate-related disasters (plus individual categories such as drought, cold and locusts) exhibited statistically significant increases in association with volcanic eruption dates. A detailed qualitative examination of climate records from 180-150 BCE reveals that the 170s BCE was relatively quiescent regarding natural disasters, while the 160s BCE experienced recurrent floods, with plague and poor harvests in 163 BCE potentially associated with explosive volcanism in 164 BCE, and large-scale extreme droughts in the 150s BCE potentially associated with explosive volcanism in 158 BCE. In our second case study period, the years 60-49 BCE barely experienced disaster, but the climatic stresses suddenly mounted in 48 BCE and continued over the following years of the decade. Although we cannot conclusively attribute all these events to volcanism, the hydroclimatic extremes during and shortly after the volcanic quartet years of 168 to 158 BCE, and the sudden extremes of cold and atmospheric optical anomalies in 43 BCE are consistent with expectations of the atmospheric and climatic consequences of major explosive eruptions.

Of societal impacts, our impact index and individual metrics such as vagrancy demonstrate statistically significant associations with volcanic eruptions, whilst other metrics ~~should~~ such as the incidence of bad harvests and famine are suggestive in their association, if not formally statistically significant. From a qualitative perspective, there were poor harvests from 163 BCE to the mid-150s BCE and again in the 40s BCE that can be plausibly associated with eruptions, and the latter caused rapid grain price increase. For conflict, we observed that warfare frequencies statistically significantly decreased after volcanic eruptions, with our case studies showing that the parties involved in warfare could experience pressure to refrain and direct their resources to relief efforts during disasters. However, this finding may not apply to all conflict typologies, such as nomad-agriculturalist conflicts (Su et al., 2016; Pei et al., 2019), and a more refined examination of the role of climatic pressures is warranted.

Our results show that Western Han society and government experienced ongoing vulnerability to periodic disasters, but also demonstrated considerable resilience in persisting in the face of these events. Nonetheless, gaps between awareness and knowledge, as well as shortcomings in the perception and understanding of the environment and human-nature relationships, restricted the development of its disaster prevention and mitigation system. As an agrarian society, it relied heavily on the reliability of weather. However, the "warnings from heaven" theory, conceived as a constraint to power, was instrumentalized for political struggles among the bureaucrats, who abused their posts to gain wealth, while the lower classes suffered. In addition, the Han government realized the importance of food storage for disaster prevention, as mentioned in Jia's memorial, *"…increases the stores of grains in order to fill government granaries and roofed depots, in preparedness against floods and droughts…"* (*Hanshu vol.24*; Ban and Swann, 2013) ［"……廣畜積，以實倉廩，備水旱……"《漢書・食貨志》］, but strategies employed to achieve this goal could be ineffective or counterproductive. For instance, the sale of ranks for the government to collect food later aggravated social differentiation and inequality; the "ever-normal granary" for leveraging grain prices was abolished as it competed with the people for profits and possibly because the government could not afford its high-maintenance during ongoing disasters. Similarly, in disaster relief, tax reduction or exemption might initially offer assistance, but later drain the state's wealth and hinder further disaster relief. All of these, together with strategies to encourage farming by restraining the development of business, resulted in a less diverse (and thereby potentially more fragile) economy. These developments decreased society's resilience to natural disasters and may be considered examples of maladaptation, comprising intentional adaptation measures that eventually increase society's vulnerability (Juhola et al., 2016).

In general, the reigns of Emperor Wen and Jing (180-141 BCE) are known for their steady economic and societal development, while Emperor Yuan (48-33 BCE) is associated with Western Han decay. However, we cannot conclude that the earlier period had more effective systems and measures to address disasters. Firstly, the severity and frequency of climatic anomalies varied in these two periods. The latter suffered more devastating consecutive disasters, which left the society limited recovery time. Secondly, changing perceptions linked to "ominous politics" might affect the documentation of climatic anomalies. There could be more records during the less peaceful time, especially with a ruler like Emperor Yuan who highly praised Confucius classics and encouraged criticism (Huang 2016). Thus, we can only examine what history has left to us, and compare it with other evidence, and that requires more innovative exploration with both quantitative and qualitative methods. The other limitation is the relatively short period we study. This makes possible a comprehensive reading of the available historical sources but may affect the statistical power of SEA approaches by limiting sample sizes. Thus, extending the period under study (e.g., including the period from the Qin to Eastern Han dynasties (221 BCE - 220 CE)) offers one way forward. Finally, applying contemporary theories and frameworks to evaluate the effectiveness of disaster relief measures may not be suitable for such an early dynasty. However, one important criterion is always the individuals' livelihood, which calls for the lens of micro-history. With the gradually uncovered but still limited historical materials and archaeological evidence of the Han era, literary works, such as the poem quoted at the opening of our study ~~in the beginning~~ provide a glance into this aspect and offer new research opportunities.

Data availability

The chronological dataset of climatic records is provided in Table S1. Major policy changes and their relevant translations are listed in Table S2 (180–150 BCE) and Table S3 (60–30 BCE). The chronological datasets of harvest conditions and population changes in the Western Han Dynasty are presented in Table S4 and Table S5, respectively. All tables are provided as supplementary material for this paper. Volcanic eruption events identified through ice-core data can be found in Supplementary Data 5 of https://doi.org/10.1038/nature14565 (Sigl et al., 2015).

Author contributions

ZY and FL conceptualized and designed this paper. ZY conducted the research, analyzed historical records, and constructed the datasets. ZY and FL performed the superposed epoch analysis (SEA), and FL produced the graphs that visualized the SEA results. ZY prepared the original draft of the paper, and FL was involved in the editing process.

Competing Interests

The authors declare that they have no conflict of interest.

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References

Ban, G. and Dubs, H. H.: The history of the former Han dynasty, Waverly Press, 1938.

Ban, G. and Swann, N. L.: Food and Money in Ancient China: The Earliest Economic History of China to A. D. 25 [Han Shu 24], Martino Publishing, 2013.

Bicknell, P.: Blue suns, the son of heaven, and the chronology of the volcanic veil of the 40s BC, The Ancient History Bulletin, 7, 2-11, 1993.

Bielenstein, H.: An Interpretation of the Portents in the Tsien-Han-shu, 22, Museum of Far Eastern Antiquities, 1950.

Butzer, K. W.: Collapse, environment, and society, Proceedings of the national Academy of Sciences, 109, 3632-3639, 2012.

Cai, L.: The hermeneutics of omens: The bankruptcy of moral cosmology in Western Han China (206 BCE–8 CE), Journal of the Royal Asiatic Society, 25, 439-459, 2015.

Campbell, B. M. and Ludlow, F.: Climate, disease and society in late-medieval Ireland, Proceedings of the Royal Irish Academy: Archaeology, Culture, History, Literature, 120, 159-252, 2020.

Chen, G.: Table of Natural and Human Disasters in Chinese Dynasties (中国历代天灾人祸表), Beijing Tushuguan Chubanshe, Beijing1933.

Chen, Y.-l.: (Disaster Peaks of the Han Dynasty: A Political-Economic Analysis) 兩漢災害高峰期−天災，人禍與治亂盛衰的關聯性分析, Historical Inquiry (臺大歷史學報), 47-116, 2016.

Chen, Y.: A Study of Natural Disaster and the Societies of Han Dynasties (灾害与两汉社会研究), Central China Normal University, Wuhan, 2001.

Chumky, T., Basu, M., Onitsuka, K., Parvin, G. A., and Hoshino, S.: Disaster-induced migration types and patterns, drivers, and impact: A union-level study in Bangladesh, World Development Sustainability, 1, 100013, 2022.

Deirmendjian, D.: On volcanic and other particulate turbidlty anomalies, in: Advances in Geophysics, Elsevier, 267-296, 1973.

deMenocal, P.: Cultural responses to climate change during the Late Holocene. Science 292, 667e673, 2001.

Donovan, A. and Oppenheimer, C.: Extreme volcanism: disaster risk and societal implications, Extreme natural hazards: Disaster risks and societal implications, 29-46, 2014.

Eberhard, W.: Beitrage zur kosmologischen spekulation der Chinesen der Han-zeit, Berlin, 1933.

Fang, X., Su, Y., Yin, J., and Teng, J.: Transmission of climate change impacts from temperature change to grain harvests, famines and peasant uprisings in the historical China, Science China Earth Sciences, 58, 1427-1439, 2015.

Fasullo, J. T., Otto-Bliesner, B. L., and Stevenson, S.: The influence of volcanic aerosol meridional structure on monsoon responses over the last millennium, Geophysical Research Letters, 46, 12350-12359, 2019.

Fei, J.: Meteorological history and historical climate of China, in: Oxford Research Encyclopedia of Climate Science, 2018.

Fei, J. and Zhou, J.: The drought and locust plague of 942–944 AD in the Yellow River Basin, China, Quaternary international, 394, 115-122, 2016.

Fei, J., Zhang, D. D., and Lee, H. F.: 1600 AD Huaynaputina eruption (Peru), abrupt cooling, and epidemics in China and Korea, Advances in Meteorology, 2016, 3217038, 2016.

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.

Fei, J., Zhou, J., Hou, Y., and An, Z.: Chinese historical records of the climatic impact of~ 934 AD Eldgjá eruption in Iceland, Global Geol, 22, 214-225, 2003.

Floret, N., Viel, J.-F., Mauny, F., Hoen, B., and Piarroux, R.: Negligible risk for epidemics after geophysical disasters, Emerging infectious diseases, 12, 543, 2006.

Gao, C., Gao, Y., Zhang, Q., and Shi, C.: Climatic aftermath of the 1815 Tambora eruption in China, Journal of Meteorological Research, 31, 28-38, 2017.

Gao, C., Ludlow, F., Amir, O., and Kostick, C.: Reconciling multiple ice-core volcanic histories: The potential of tree-ring and documentary evidence, 670–730 CE, Quaternary international, 394, 180-193, 2016.

Gao, C., Ludlow, F., Matthews, J. A., Stine, A. R., Robock, A., Pan, Y., Breen, R., Nolan, B., and Sigl, M.: Volcanic climate impacts can act as ultimate and proximate causes of Chinese dynastic collapse, Communications earth & environment, 2, 234, 2021.

Ge, J.: The population and geography of Western Han (西汉人口地理), Commercial Press, Shanghai2014.

Guillet, S., Corona, C., Ludlow, F., Oppenheimer, C., and Stoffel, M.: Climatic and societal impacts of a “forgotten” cluster of volcanic eruptions in 1108-1110 CE, Scientific reports, 10, 1-10, 2020.

Guillet, S., Corona, C., Oppenheimer, C., Lavigne, F., Khodri, M., Ludlow, F., Sigl, M., Toohey, M., Atkins, P. S., and Yang, Z.: Lunar eclipses illuminate timing and climate impact of medieval volcanism, Nature, 616, 90-95, 2023.

Haldon, J., Chase, A. F., Eastwood, W., Medina-Elizalde, M., Izdebski, A., Ludlow, F., Middleton, G., Mordechai, L., Nesbitt, J., and Turner, B.: Demystifying collapse: climate, environment, and social agency in pre-modern societies, Millennium, 17, 1-33, 2020.

History, E. C. o. C. s. M.: Tabulation of Wars in Ancient China Liberation Army Press, Beijing1985.

Homer-Dixon, T. F.: Environment, scarcity, and violence, Princeton University Press2010.

Hsu, C.-y.: Han Agriculture: The Formation of Early Chinese Agrarian Economy, 206 BC-AD 220, University of Washington Press1980.

Huang, C.-S.: A Study on the Controversies over Confucian Classics in the Former Han Dynasty: Exemplified by the Development of Anomalies Theories in the Periods of Emperors Xuan, Yuan, and Cheng (西漢經學的另類戰場：從宣元成三朝災異說之發展為例), Historical Inquiry 臺大中文學報, 043-094, 2016.

Huang, M.-t.: A Comprehensive Survey of Grain Price in Chinese History (中国历代粮食价格问题通考), Journal of Chinese Humanities (文史哲), 33-48, 2002.

Iles, C. E., Hegerl, G. C., Schurer, A. P., and Zhang, X.: The effect of volcanic eruptions on global precipitation, Journal of Geophysical Research: Atmospheres, 118, 8770-8786, 2013.

Jiao, P., Liu, C., and He, Y.: The General History of Natural Disasters in China-the Volume of Qin and Han (中国灾害通史・秦汉卷), Beijing Book co.INC, Beijing, 2009.

Kostick, C., Hill, A., McGovern, R., Medenieks, S., Yang, Z., and Ludlow, F.: Vulkaanuitbarstingen in de Oudheid: Reacties op Plotselinge Klimaatschommelingen in de Eerste Acht Eeuwen voor Christus [Volcanic Eruptions in Antiquity: Responses to Sudden Climatic Variability in the First Eight Centuries BCE], Phoenix, 69, 2023.

Li, J.: 中国古代经济史稿, Wuhan University Publishing House, Wuhan2006.

Ludlow, F.: Assessing non-climatic influences on the record of extreme weather events in the Irish Annals, At the Anvil: Essays in Honour of William J. Smyth. Dublin: Geography Publications, 93-133, 2012.

Ludlow, F. and Manning, J.: Volcanic eruptions, veiled suns, and Nile failure in Egyptian history: Integrating hydroclimate into understandings of historical change, in: Climate Change and Ancient Societies in Europe and the Near East: Diversity in Collapse and Resilience, Springer, 301-320, 2021.

Ludlow, F., Kostick, C., and Morris, C.: Climate, violence and ethnic conflict in the Ancient World, The Cambridge world history of genocide, 1, 2023.

Mackay, H., Plunkett, G., Jensen, B. J., Aubry, T. J., Corona, C., Kim, W. M., Toohey, M., Sigl, M., Stoffel, M., and Anchukaitis, K. J.: The 852/3 CE Mount Churchill eruption: examining the potential climatic and societal impacts and the timing of the Medieval Climate Anomaly in the North Atlantic region, Climate of the Past, 18, 1475-1508, 2022.

Mass, C. F. and Portman, D. A.: Major volcanic eruptions and climate: A critical evaluation, Journal of Climate, 2, 566-593, 1989.

McConnell, J. R., Sigl, M., Plunkett, G., Burke, A., Kim, W. M., Raible, C. C., Wilson, A. I., Manning, J. G., Ludlow, F., and Chellman, N. J.: 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, 15443-15449, 2020.

McGovern, R.: Cuneiform to Computer: Meteorological Data from Ancient Babylon, Department of History, Trinity College Dublin, Unpublished PhD Thesis, 2024.

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 Press2011.

Owen, S.: An Anthology of Chinese Literature: Beginnings to 1911 W. W. Norton & Company, New York1996.

Pei Q, Lee H F, Zhang D D, et al. Climate change, state capacity and nomad–agriculturalist conflicts in Chinese history. Quaternary International, 508: 36-42, 2019.

C. Qin, B. Yang, A. Bräuning, F. Charpentier Ljungqvist, T. J. Osborn, V. Shishov, M. He, S. Kang, L. Schneider, J. Esper, U. Büntgen, J. Grießinger, D. Huang, P. Zhang, S. Talento, E. Xoplaki, J. Luterbacher, and N. C. Stenseth: Persistent humid climate favored the Qin and Western Han Dynasties in China around 2,200 y ago, Proceedings of the National Academy of Sciences, 122 (1) e2415294121, 2025.

Rao, M. P., Cook, E. R., Cook, B. I., Anchukaitis, K. J., D’Arrigo, R. D., Krusic, P. J., and LeGrande, A. N.: A double bootstrap approach to Superposed Epoch Analysis to evaluate response uncertainty, Dendrochronologia, 55, 119-124, 2019.

Robock, A.: Volcanic eruptions and climate, Reviews of geophysics, 38, 191-219, 2000.

Robock, A. and Mao, J.: Winter warming from large volcanic eruptions, Geophysical Research Letters, 19, 2405-2408, 1992.

Sachs, A. J. and Hunger, H.: Astronomical diaries and related texts from Babylonia, Verlag der österreichischen Akademie der Wissenschaften Vienna1988.

Scuderi, L. A.: Oriental sunspot observations and volcanism, Quarterly Journal of the Royal Astronomical Society, Vol. 31, NO. 1/MAR, P. 109, 1990, 31, 109, 1990.

Sear, C., Kelly, P., Jones, P., and Goodess, C.: Global surface-temperature responses to major volcanic eruptions, Nature, 330, 365-367, 1987.

Shen, C., Wang, W.-C., Hao, Z., and Gong, W.: Exceptional drought events over eastern China during the last five centuries, Climatic Change, 85, 453-471, 2007.

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

Sima, Q. and Watson, B.: Records of the Grand Historian, Columbia University Press New York1993.

Singh, R., Tsigaridis, K., LeGrande, A. N., Ludlow, F., and Manning, J. G.: Investigating hydroclimatic impacts of the 168–158 BCE volcanic quartet and their relevance to the Nile River basin and Egyptian history, Climate of the Past Discussions, 2022, 1-56, 2022.

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

Su, Y., Fang, X., and Yin, J.: Impact of climate change on fluctuations of grain harvests in China from the Western Han Dynasty to the Five Dynasties (206 BC–960 AD), Science China Earth Sciences, 57, 1701-1712, 2014.Su Y, Liu L, Fang X Q, et al. The relationship between climate change and wars waged between nomadic and farming groups from the Western Han Dynasty to the Tang Dynasty period[J]. Climate of the Past, 2016, 12(1): 137-150

Tan, Q.: Historical Atlas of China, Cartographic Publishing House, Beijing, 1982.

Tan, W.: 中国物价史 (The history of commodity price in China), Hubei People's Press, Wuhan1994.

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., 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.

Twitchett, D., Fairbank, J. K., Loewe, M., Chaffee, J. W., Franke, H., Smith, P. J., Mote, F. W., Feuerwerker, A., MacFarquhar, R., and Peterson, W. J.: The Cambridge History of China: Volume 1, The Ch'in and Han Empires, 221 BC-AD 220, Cambridge University Press1978.

Wang, P. K., Lin, E. K.-H., Lin, Y.-S., Lee, C.-R., Lin, H.-J., Chen, C.-W., and Pai, P.-L.: Possible impact of the 43 BCE Okmok volcanic eruption in Alaska on the climate of China as revealed in historical documents, Climate of the Past, 20, 1513-1520, 2024.

Weiss, H. and Bradley, R. S.: What drives societal collapse?, Science, 291, 609-610, 2001.

White, S. and Pei, Q.: Attribution of historical societal impacts and adaptations to climate and extreme events: integrating quantitative and qualitative perspectives, Mag, 28, 44-45, 2020.

Wittmann, A. D. and Xu, Z.: A catalogue of sunspot observations from 165 BC to AD 1684, Astronomy and Astrophysics Supplement Series (ISSN 0365-0138), vol. 70, no. 1, July 1987, p. 83-94., 70, 83-94, 1987.

Wu, W.: A Study of the System of Amnesties in Han Dynasties (汉代赦免制度研究), Graduate School of Chinese Academy of Social Sciences, 2003.

Yang, Y., Man, Z., and Zheng, J.: A serious famine in Yunnan (1815-1817) and the eruption of Tambora Volcano (in Chinese), Fudan Journal (Social Sciences), 1, 79-86, 2005.

Yau, K. and Stephenson, F.: A revised catalogue of Far Eastern observations of sunspots (165 BC to AD 1918), Quarterly Journal of the Royal Astronomical Society, 29, 175-197, 1988.

Yin, J., Su, Y., and Fang, X.: Relationships between temperature change and grain harvest fluctuations in China from 210 BC to 1910 AD, Quaternary International, 355, 153-163, 2015.

Yun, S.-H., Lee, J., Chang, C., and Oppenheimer, C.: A re-assessment of historical records pertaining to the activity of Mt. Baekdu (Paektu, Tianchi) volcano, Geoscience Letters, 10, 30, 2023.

Zambri, B., LeGrande, A. N., Robock, A., and Slawinska, J.: Northern Hemisphere winter warming and summer monsoon reduction after volcanic eruptions over the last millennium, Journal of Geophysical Research: Atmospheres, 122, 7971-7989, 2017.

Zhang, D.: A compendium of Chinese meteorological records of the last 3,000 years, Jiangsu Education Publishing House, Nanjing, 2004.

Zhang, D. e.: Abnormal atmospheric optic phenomena recorded in Chinese historical literature in relation to global volcanic activities, Quaternary Sciences, 27, 305-310, 2007.

Zhang, P.-Y., Wang, W. C., and Hameed, S.: Evidence for anomalous cold weather in China 1815-1817, The year without a summer, 436-447, 1992.

Zhuo, Z., Gao, C., and Pan, Y.: Proxy evidence for China's monsoon precipitation response to volcanic aerosols over the past seven centuries, Journal of Geophysical Research: Atmospheres, 119, 6638-6652, 2014.