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Challenges in detecting volcanic forcing in climate and societal proxies: insights from the 1170/1171 CE eruption

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Abstract
While our current understanding of the impacts of volcanic eruptions on the atmosphere and climate has significantly advanced, uncertainties persist regarding the climate and societal response to major volcanic events of the Common Era, especially during the high medieval period (1000–1300 CE). This study focuses on a sparsely documented medieval eruption from the late 12th century, considered, on the basis of ice-core evidence, to be one of the most prominent volcanic events of the past millennium. In this context, we explore the challenges researchers may encounter when differentiating between volcanic forcing and internal climate variability in climate and societal proxies. We highlight the importance of accurately dating volcanic eruptions for attribution studies and emphasize the need for a thorough examination of historical sources, along with a deep understanding of prevailing socio-economic and political contexts, when seeking to associate famines, pestilence, or social unrest to the climatic effects of explosive volcanism.

Keywords Historical climatology · Paleoclimatology · Volcanism · Ice core · Tree-rings · Historical sources

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1 Introduction

Volcanism is a primary driver of short-term climate variability. Many of the coldest northern hemisphere summers of the last two millennia occurred within a year or two of major volcanic events with very high sulphur yields to the atmosphere (PAGES 2k Consortium 2019; Hegerl et al. 2019). Despite abundant evidence from climate models, observations and proxies for volcanic forcing of climate, attributing observed climatic changes to volcanism remains challenging, as volcanic climate signals often resemble the amplitude of internal variability on interannual timescales (D'Arrigo et al. 2011; Schurer et al. 2019; Predybaylo et al. 2020; Timmreck et al. 2021).

In spite of these challenges, many studies have connected subsistence crises, famines, social unrest, political instability, migrations, and societal collapses with the climatic effects of major volcanic eruptions (Stothers 2000; Fei et al. 2007; Sigl et al. 2015; Büntgen et al. 2016, 2020; Di Cosmo et al. 2017, 2021; Manning et al. 2017; McConnell et al. 2020; Chen et al. 2020; Gao et al. 2021). Some of these studies have highlighted associations between, for example, the repeated collapse of Chinese Dynasties over the last 2000 years, the fall and transformation of the Western Roman Empire in 476 CE, the destruction of the Sasanian Empire in 622 CE, the collapse of the Eastern Türk Empire in 630 CE, the Abbasid Caliphate in 1258 CE, the Anasazi Culture in the 1290s, or the fall of Constantinople in 1453 CE, and the rapid and multiannual summer cooling following large volcanic eruptions.

While such studies present compelling arguments, establishing causal links between climate variability and society is complex, as sociopolitical, economic, and cultural factors also play critical roles (Haldon 2016; Degroot et al. 2021; Stoffel et al. 2022; van Dijk et al. 2023). For instance, regarding the 1257 CE Samalas eruption, Guillet et al. (2017) and Campbell (2017) have demonstrated that the famines documented in Europe and Japan in 1258/59 CE cannot be solely attributed to the climatic consequences of the eruption. One of the first in-depth studies on the role of Tambora's 1815 eruption in the 'last major subsistence crisis in the Western World' from 1816 to 1817 CE (Post 1977) argued that many factors had to be considered beyond the climate impacts of the eruption, including the vulnerability of European society following the Napoleonic wars, poor governance, an economic downturn, and limited grain reserves due to years of requisition and plundering. More recently, Brönnimann and Krämer (2016) and Flückiger et al. (2017) have reinforced this nuanced perspective. Likewise, Gao et al. (2021), while identifying a repeated statistically significant correspondence in timing between Chinese dynastic collapse and explosive volcanism over the past 2,000 years, also noted that some of the largest and most climatically impactful eruptions of the period (including Tambora, 1815 CE, and Samalas, 1257 CE) were not followed by any collapse, whereas comparatively modest eruptions in some cases were. This itself implies the importance of prevailing socioeconomic and political vulnerabilities, varying in time, space, and severity, in mediating the societal efficacy of volcanically induced climatic changes.

As a contribution to further understanding the far-field consequences of volcanism, we focus here on one of the great eruptions of the Common Era, which occurred in circa 1170/71 CE, and which hitherto has received little attention. It is known from sulphur deposition in ice core records, yet the source volcano remains unidentified. Comparable sulphur deposition in Antarctica and Greenland suggests a probable location in the tropics. Following previous nomenclature, we refer to it here as UE2 (unidentified eruption) (Guillet et al.

2023). The concentrations of sulphur in the polar ice indicate an estimated stratospheric sulfur burden of 18 Tg for UE2, roughly double the amounts associated with the eruptions of Krakatau in 1883 CE or Pinatubo in 1991. This ranks it the tenth strongest stratospheric sulphur source in the second millennium CE (Sigl et al. 2015; Toohey and Sigl 2017) (Fig. 1a-c). Ice core records from Greenland (NEEM-2011-S1) and Antarctica (WDC06A) indicate a significant increase in sulfur around the beginning of 1171 CE, peaking at > 80 nssS in Greenland and > 50 nssS in Antarctica in late 1171/early 1172 CE (Fig. 1a-c). This observation led to the estimated date of onset of UE2 being assigned to the year 1171 CE (1st January by default) (Sigl et al. 2015; Toohey and Sigl 2017). Lesser but still elevated sulfate persisted until early late 1172/early 1173 CE (Fig. 1a-c). Guillet et al. (2023), drawing on various independent evidence, including contemporary chronicles and annals, as well as tree-ring records, suggested a time window for the eruption of between summer 1170 and autumn 1171 CE, but with the most likely date between spring and summer 1171 CE. Given this estimate for the eruption timing, our aims here are to locate and evaluate any further evidence for the eruption's consequences on global climate and society. This study also explores the complexities of (i) identifying atmospheric optical phenomena and climate anomalies resulting from volcanic activity within proxy records, (ii) differentiating between the effects of volcanic forcing and internal climate variability, and (iii) drawing conclusions concerning the role of global volcanism on society.

2 Material and methods

2.1 Detecting dust veil records in historical records

Historical reports of atmospheric optical phenomena such as dimming or discolouration of the Sun, reddish or bluish solar haloes and red or purple twilight glows can indicate stratospheric aerosol veils and provide rich input to the record of global volcanism (Stothers and Rampino 1983a, b; Stothers 2002; Sigl et al. 2015). Another proxy for stratospheric turbidity is the brightness and colouration of total lunar eclipses. These observations, often noted by scholars and scribes of the past, provide valuable evidence for refining the chronology of historical volcanic eruptions (Guillet et al. 2023). Dark total lunar eclipses are indicative of high turbidity, whereas a reddish lunar disk suggests a clear stratosphere. The darkest total lunar eclipses since 1600 CE occurred in 1601 CE, 1642 CE, 1816 CE, 1884 CE, 1912 CE, 1983 CE, and 1991 CE, all of which coincided with major stratospheric aerosol veils associated with the eruptions of Huaynaputina in 1600 CE, an unknown eruption circa 1642 CE, Tambora in 1815 CE, Krakatau in 1883 CE, Katmai in 1912 CE, El Chichón in 1983 CE, and Pinatubo in 1991 CE (Link 1961; Keen 1983; Hofmann et al. 2003; Stothers 2004, 2005). Our archival research focused on three key regions: Europe, the Middle East, and East Asia. For Europe, we thoroughly reexamined hundreds of annals and chronicles, written in the twelfth century. These texts, mostly written in Latin, are primarily found in collections of medieval texts, many of which were edited as part of series like the (i) *Monumenta Germaniae Historica*, (ii) *Rerum Britannicarum Medii Ævi*, (iii) *Recueil des historiens des Gaules et de la France*, and the (iv) *Rerum Italicarum scriptores*. They originate from across Europe, including Austria, Czech Republic, England, France, Germany and Italy. For the Middle East, we drew upon the chronicle of Michael the Great (1126–1199

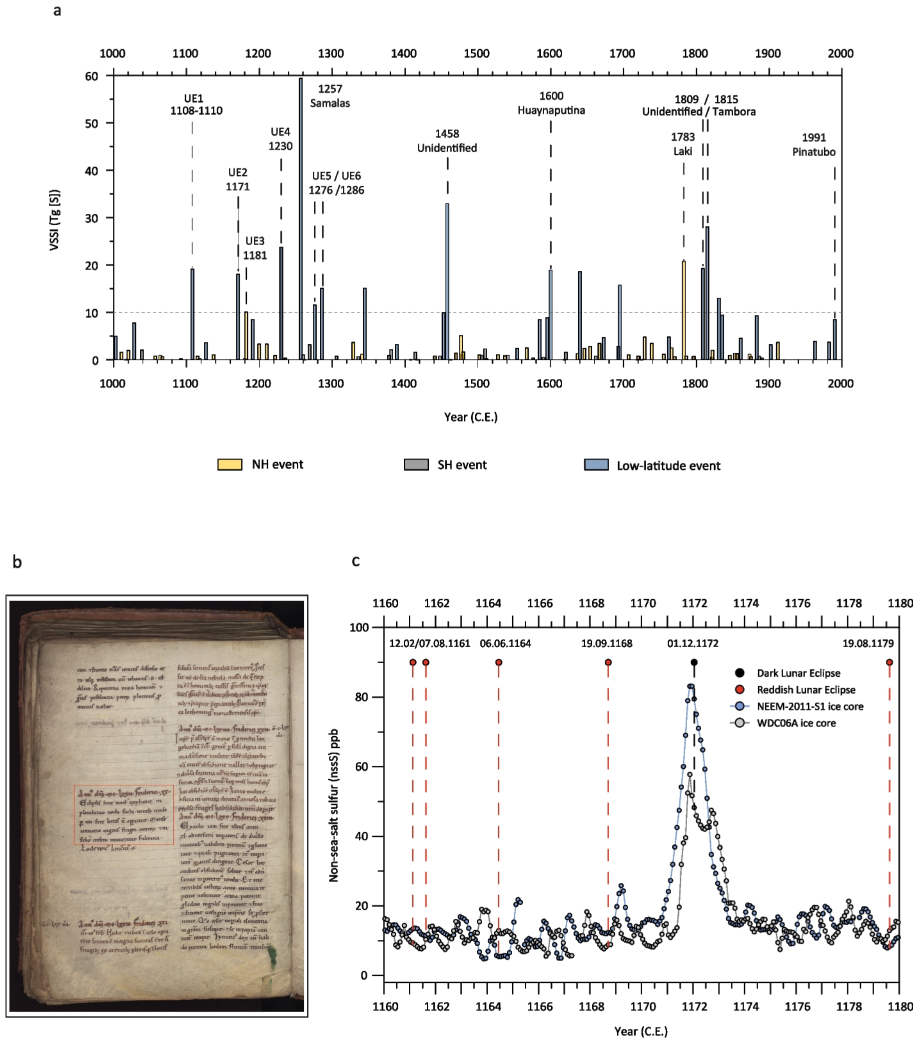

Fig. 1 Dating the UE2 eruption. (**a**) Volcanic stratospheric sulfur injection (VSSI) from the eVolv2k reconstructions (Toohey and Sigl 2017). (**b**) Original manuscript of the Annals of Magdeburg (likely written between 1176 and 1188 CE), Saxon-Anhalt, Germany.
Source: *Annales Magdeburgenses*, Gottfried Wilhelm Leibniz Bibliothek, Niedersächsische Landesbibliothek, Hannover, MS XIX 1105 Bl. 124v. The entry for the year 1172 CE records a dark lunar eclipse occurring on the 12th of January 1172 CE. The text written in Latin reads as follows: *1172. Eclipsis lune in octava epiphaniae in plenilunio noctu factu, inviso modo per quatuor fere horas non apparuit.* This translates to: *There was an eclipse the eighth day after the Epiphany on the night of the full Moon, it was invisible, and did not appear for almost four hours*. (**c**) Monthly-resolved non-sea-salt sulfur records from the NEEM-2011-S1 and the WDC06A ice cores (Sigl et al. 2015) and brightness of the total lunar eclipses observed in Europe for the period 1160–1180 CE. Dark total eclipses of the Moon indicate high atmospheric turbidity, while a reddish disk shown by the eclipsed Moon betrays a clear stratosphere

CE), who served as the Patriarch of the Syriac Orthodox Church from 1166 to 1199 CE. This manuscript, completed around 1195 CE at the Monastery of Mōr-Barṣawmō near Melitene (modern-day Malataya, Turkey), was originally composed in Syriac and is available in English translation (Harrak 2019). For China and Korea, observations of atmospheric optical phenomena and potential indications of dust veils are made in the *Treatise on Astronomy* and *Treatise on the Five Elements* sections of the official dynastic histories. In the context of China, our reexamination encompassed the *Song Shi* (宋史), which serves as the official historical account of the Song dynasty (960 to 1279 CE), and the *Jin Shi* (金史), the official history of the Jin dynasty (1115 to 1234 CE). We also consulted the *Wenxian tongkao* (文獻通考, 'comprehensive examination of existing literature'). In the case of Korea, our investigation focused on the *Goryeosa* (高麗史), chronicle of the Goryeo dynasty (936 to 1392 CE) and the *Goryeosa jeoryo* (高麗史節要), the abridged chronicle of Goryeo, which was completed in 1452 CE, one year after the *Goryeosa*. We omitted Japanese texts, as they are frequently dispersed across a wide range of sources that are not always readily accessible. We evaluated the reliability of dust veil observations through the application of historical source criticism. For lunar eclipses, we used the database of lunar eclipse colouration developed by Guillet et al. (2023). The degree of darkness or brightness exhibited by the Moon was assessed using the established Danjon scale (Danjon 1921; Stothers 2004, 2005). This scale ranges from L=0 (very dark, indicating a high stratospheric turbidity) to L=4 (very bright, copper red or orange, indicating low stratospheric turbidity). A compilation of all identified dust veil reports is available in the following tables: Table S1 for Europe, Table S2 for the Middle East, and Table S3 for East Asia. Lunar eclipse colouration data is available on Zenodo at https://doi.org/10.5281/zenodo.6907654.

2.2 Assessing the climatic and societal impacts of UE2 in historical and tree-ring records

We used the same historical sources to evaluate potential climatic and societal consequences of UE2 in Europe, the Middle East, and Korea. Furthermore, for China, we extended our investigations by making use of the *Compendium of Chinese Meteorological Records of the Last 3000 years (*中国三千年气象记录总集*)* (Zhang 2004).

To investigate Northern Hemisphere (NH) summer temperature variability around the time of UE2, we used the *NVOLCv2* dataset (Guillet et al. 2020), complemented with the *N-TREND2015* (Wilson et al. 2016) and *SCH2015* (Schneider et al. 2015) tree-ring reconstructions. The *NVOLCv2* reconstruction, optimized for assessing volcanic cooling, comprises 25 temperature-sensitive proxy records (13 TRW and 12 MXD chronologies).

To estimate the regional variability of any summer cooling induced by UE2, we used the climate field reconstruction of extratropical NH JJA temperatures spanning the last 1500 years developed by Guillet et al. (2017, 2020). Further details on the methodology can be found in Guillet et al. (2020).

3 Results and discussion

3.1 Identifying contemporary descriptions of dry fogs

3.1.1 Europe

During our examination of European historical sources from 1170–1172 CE, we found no evidence of a volcanic dust veil arising from solar-related observations (e.g., dimming of the Sun, red twilight glows or Bishop's rings). However, a sister study by Guillet et al. (2023) identified numerous records on the brightness of lunar eclipses. These eclipses occurred on 12 February and 7 August 1161, 6 June 1164, 19 September 1168, 13 January 1172, 19 August 1179, 11 December 1182, 18 May 1193, and 5 March 1197 CE. Most were classified as bright (L=2 to L=4), except for the 1172 CE eclipse, rated L=0. Indeed, the *Annales Magdeburgenses* described the 1172 CE eclipse as being "invisible" for almost four hours, using the Latin word "invisus, a, um," rarely employed in eclipse records of the 12th and 13th centuries (Fig. 1b) (Guillet et al. 2023). This unusual phrasing suggests high stratospheric turbidity. Dark lunar eclipses generally occur when the Stratospheric Aerosol Optical Depth (SAOD) exceeds 0.1 (Stothers 2004, 2005). This threshold is generally surpassed between 3 and 20 months after an eruption (Guillet et al. 2023), constraining the most likely time window of UE2 to summer 1170 CE through autumn 1171 CE. This time frame aligns with the dating (1 January 1171 CE) derived from revised chronologies of Greenland (NS1-2011) and Antarctic (WD2014) ice cores (Sigl et al. 2015; Toohey and Sigl 2017) (Fig. 1c).

After 1172 CE, only one report from Kremsmünster Abbey, Austria, in 1173 CE, could potentially hint at volcanic aerosols in the stratosphere. It describes "blood circles surrounding the moon and crosses in the sky" (Table S1). The term "blood circles" may indicate Bishop's rings, a phenomenon named after Reverend Sereno Bishop of Honolulu, who observed a corona or halo displaying a pinkish, lilac, and purple tint encircling the Sun after the 1883 CE eruption of Krakatau (Symons 1888; Sassen et al. 1994). This interpretation aligns with observations of reddish Bishop's rings around the moon in the months and years that followed the 1883 CE Krakatau eruption. For example:

> *On September 15th [1883] the [ship] Carola in 14°8 N., 20°8 W., mentions "a halo visible around the moon, having a deep red outer margin" […]* (Symons 1888, pp. 232-233).

Other interpretations remain possible. The "crosses" mentioned in the text are hard to link to Bishop's rings and could potentially refer to paraselenae (Chetwode and Allman 1847; Lloyd 1847). It is also possible that the "crosses" and "circles" were distinct phenomena occurring on different dates but grouped together in a single report because of their thematic coherence (e.g., as celestial phenomena and potential portents). Ultimately, the brevity of the record and its clear echoes of the Passion of Christ—through the emotive and symbolic use of the terms "blood" and "crosses"—argue for caution in interpretation and prevent any definitive conclusions.

3.1.2 Middle East

Amongst Middle Eastern sources, only one report for 1172/3 CE stands out, that of Michael the Great (Table S2):

[…] the Lord extended his hand once again and the air became covered by darkness to such an extent that the light of the sun looked like the light of the moon.

This description echoes two entries in the same chronicle pertaining to the years 536 and 626 CE, both interpreted as volcanic dust veils (Oppenheimer 2011; Kostick and Ludlow 2015; Sigl et al. 2015). The earlier instance, in which Michael the Great likely copied from John of Ephesus, an ecclesiastical historian of the sixth century, reports:

In the year 848 [536/37 CE] there was a sign in the sun the like of which had never been seen and reported before in the world. If we had not found it recorded in the majority of proved and credible writings and confirmed by trustworthy people, we would not have recorded it; for it is difficult to conceive. So it is said that the sun became dark and its darkness lasted for one and a half years, that is, eighteen months. Each day it shone for about four hours, and still this light was only a feeble shadow. Everyone declared that the sun would never recover its original light.

The next states:

In the year A.D. 626 the light of half the sphere of the sun disappeared, and there was darkness from October to June. As a result people said that the sphere of the sun would never be restored to its original state.

However, unlike these earlier reports, the 1172/3 CE account provides no details on the duration or exact timing of the solar dimming. This lack of precision is problematic, as an annular solar eclipse was visible across the Near East on 12 June 1173 CE, raising the possibility that the report refers to this event rather than stratospheric turbidity. Additionally, it is important to consider the context in which the text was written. In late 1172 CE, the Middle East endured a severe winter and famine leading to political instability and social unrest. In his chronicle, Michael the Great strongly suggests that the disasters were caused by the wrath of God and his reference to the darkened Sun may have been a stylistic device to emphasise divine retribution as the reason for the suffering:

Let us now inform about the calamities that destroyed people, animals and birds. God, O my beloved ones, allowed that the entire universe be more or less dashed at this time. This was done justly, because our unsubmissive attitude surpassed the chastisement. After the crops were damaged in Ilul [September] and Tisrin [October], astrologers interpreted the blow as an omen, but pretended that these things would not happen again at this time. Therefore the Lord extended his hand once again and the air became covered by darkness to such an extent that the light of the sun looked like the light of the moon. Intensive snow fell down in the likeness of waterfalls, covering mountains and plains. (see Table S2).

In conclusion, one should therefore be cautious of interpreting the solar dimming of 1172/73 CE too literally. This case illustrates the challenges of attributing recorded solar phenomena to volcanic dust veils.

3.1.3 East Asia

In both China and Korea, the *Treatise on Astronomy* and the *Treatise on the Five Elements* found within the official dynastic histories, offer abundant insights into atmospheric optical phenomena. These include occurrences like "rainbows", "vapors", "haloes" of diverse colors encircling the moon and sun, "red" and "blue suns", as well as instances of "haze" and "fog" that attenuate the sun's luminance. While the term "vapor" likely often refers to auroras (Keimatsu 1969a, b; Saitō and Ozawa 1992; Hayakawa et al. 2015), recent research suggests that red and blue suns, along with some haloes, could be used as indicators of volcanic aerosols present in the stratosphere. The documented observations of a blood-red Sun in Europe in both 939 CE and 1783 CE have for instance been interpreted as potential manifestations of volcanic haze and have been associated with the 939 CE Eldgjá and 1783 CE Laki eruptions in Iceland (Thordarson and Self 2003; Oppenheimer et al. 2018). In China, the sighting of a pale blue Sun in 43 BCE (Scuderi 1990) has been connected with an eruption recently identified as the 43 BCE Okmok eruption in Alaska (McConnell et al. 2020). However, linking and definitively attributing the optical atmospheric phenomena documented in Chinese and Korean records to volcanic aerosol veiling can be challenging since other phenomena can result in similar optical effects. For instance, large parts of China and Korea are highly susceptible to dust storms due to the presence of Pleistocene loess deposits within the arid interiors of Mongolia and China (Sun et al. 2003; Deng and Jiang 2005; Chun et al. 2008). These dust storms make for hazy skies and reduced solar intensity, and can result in blue or red suns and colorful haloes (Sullivan and Standaert 2021). Smoke from fires can also result in blue and red suns and Bishop's rings (Simons 2020; Wullenweber et al. 2021). Furthermore, Chinese and Korean celestial observations were often seen as omens or portents of forthcoming events. The colours of atmospheric optical phenomena also frequently held specific connotations or predictive value. This could promote the alteration and manipulation (e.g., re-dating) of observations for political motives (Hayakawa et al. 2015).

In the case of UE2, we have identified, over the period 1165–1179 CE, three reports of atmospheric optical phenomena that potentially serve as evidence of a volcanic stratospheric dust veil:

(i) The red sun and yellow halo of August 2, 1168 CE:

六月丁巳, 日赤黃暈周匝。Translation : *On day Dingsi, in the sixth month, a reddish-yellow halo encircled the sun.* (See Table S3)
Accepting this as evidence, however, would imply that UE2 was misdated by four years in the revised ice core chronologies for Greenland (NS1-2011) and Antarctica (WD2014). Furthermore, the observation of a red lunar eclipse in Europe in September 1168 CE argues for low stratospheric turbidity in that period. We conclude that this observation most likely does not pertain to volcanism.

(ii) The blue sun of July–August 1170 CE:

六月, 日青無光。Translation: In the sixth month, the sun was pale blue and had no brightness. (See Table S3)

This observation falls within the early end of the time window estimated for UE2 and could potentially allude to stratospheric volcanic aerosol loading from this eruption. However, the entry is brief and lacks details on its duration, making it difficult to confidently attribute it to UE2.

(iii) The solar dimming of May 2nd 1178 CE:

四月丁丑, 塵霾晝晦, 日無光。Translation: *On day Dingchou, in the fourth month, there was dust and haze and [the sky] was dim during the daytime. The sun had no brightness.* (See Table S3)
This 1178 CE account is too late to associate with UE2. The presence of haze and dust might suggest fallout from a dust storm (Chun et al. 2008).

3.2 Detecting volcano-induced impacts in proxy records

3.2.1 NH summer of 1171 CE

Given the estimated magnitude of the stratospheric sulphur yield from UE2 and its inferred tropical location, pronounced NH summer cooling could be expected. This is not clearly evident in the *NVOLCv2* reconstruction for summer 1171 CE (–0.27 °C). This value falls above the 10th percentile of the temperature distribution of the last ~ 1500 years and ranks as 438th coldest year. In the *NVOLCv2_filt* reconstruction, more sensitive to high-frequency variability, the JJA temperature anomaly is similar (–0.24 °C) but ranks as the 309th coldest year (Fig. 2a and b). These findings are consistent with the *N-TREND2015* and *SCH2015* reconstructions, which both indicate a JJA cooling of -0.22 °C (200th coldest year) and -0.24 °C (171st coldest year), respectively (Fig. 2b).

The JJA gridded reconstruction (composed of 3065 1° × 1° grid points with a CE > 0.1) does not reveal homogeneous and widespread NH summer cooling in 1171 CE. Quebec, Scandinavia, Siberia and Central Asia experienced cooler than average conditions during spring and summer 1171 CE, but other regions including Alaska, British Columbia and the Pacific Northwest were warmer. The muted cooling evident across Western Europe (Fig. 2c) is consistent with historical sources that suggest a warm and dry summer (Fig. 3). In Austria, the annals of Klosterneuburg report dry weather, as well as good harvest in 1171 CE (Table S1):

> *For two years, there was such a severe drought that almost all the regions of Austria, apart from those along the Danube, were dried up. Yet there was such an abundance of food that both people and livestock were well sustained.*

The Annals of Brescia (Italy) provide a more succinct description, simply reporting *magna siccitas*, which can be translated as *great drought* (Table S1) (Fig. 3).

Detecting the impact of UE2 on the climate of East Asia also poses difficulties. Spring, summer and autumn of 1171 CE brought a severe drought in China, with the most pronounced impact being felt in the middle-lower areas of the Yangtze River basin, especially the present-day provinces of Hunan and Jiangxi, with a lesser impact in Anhui, Jiangsu, and Zhejiang (Fig. 4a and Table S3). This response appears consistent with studies suggesting

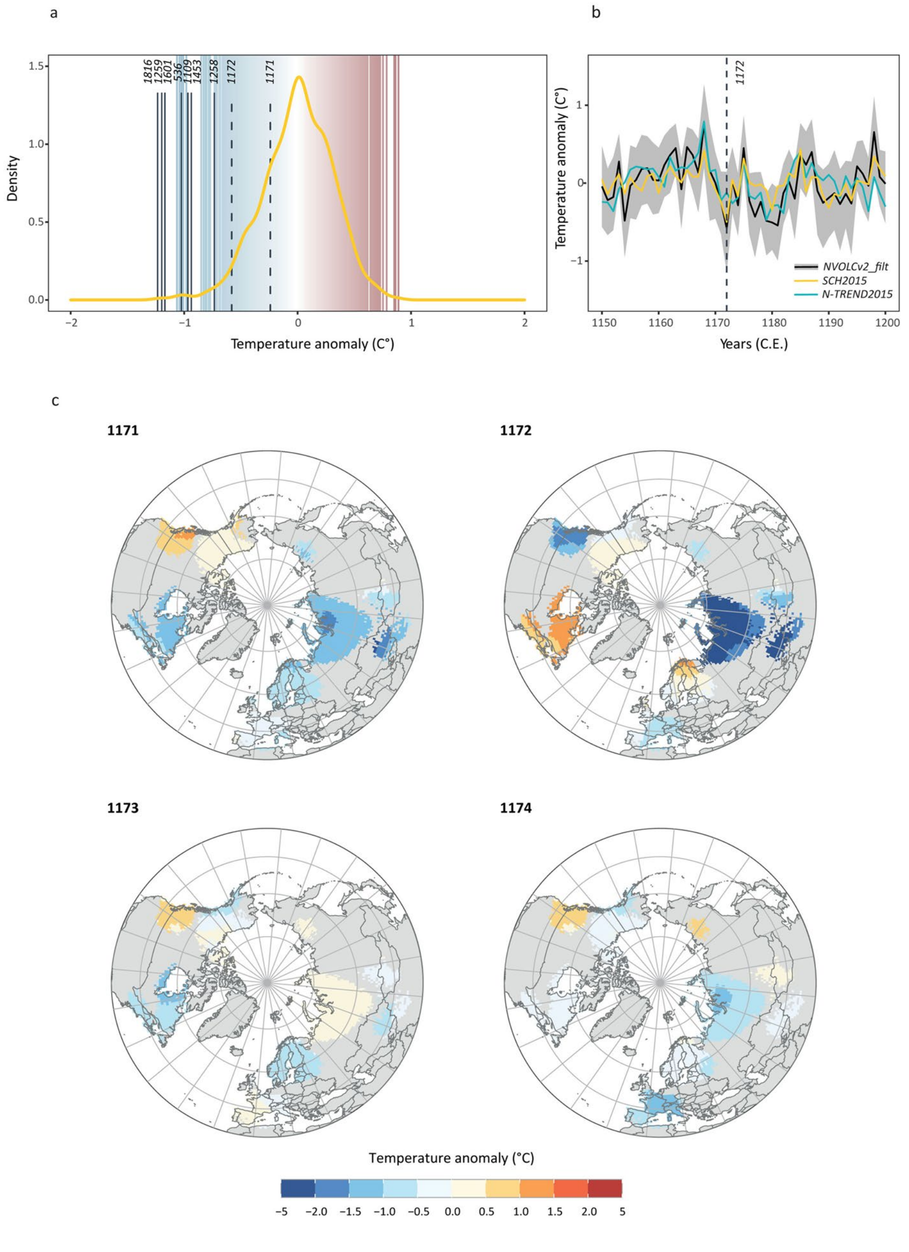

Fig. 2 Tree-ring reconstructions (*NVOLCv2*) of NH extra-tropical land (40–90°N) summer temperature anomalies following UE2. Panel (**a**) shows the distribution of June-July-August (JJA) temperature from the *NVOLCv2_filt* reconstruction for the period 500–2000 CE, with the yellow curve representing the probability density function. The black lines indicate the position of the years following the largest known volcanic eruptions of the last 1500 years in the distribution. The dashed black lines mark the position of the years 1171 and 1172 CE in the distribution. Panel (**b**) compares the *NVOLCv2_filt* reconstruction with two published summer temperature reconstructions, *N-TREND2015* (Wilson et al. 2016) and *SCH2015* (Schneider et al. 2015), for the period 1150–1200 CE. The grey shading represents the 95% bootstrap confidence interval of *NVOLCv2_filt* reconstruction (Guillet et al. 2020). Panel (**c**) illustrates the spatial extent of the JJA temperature anomalies in the aftermath of UE2 in the Northern Hemisphere.

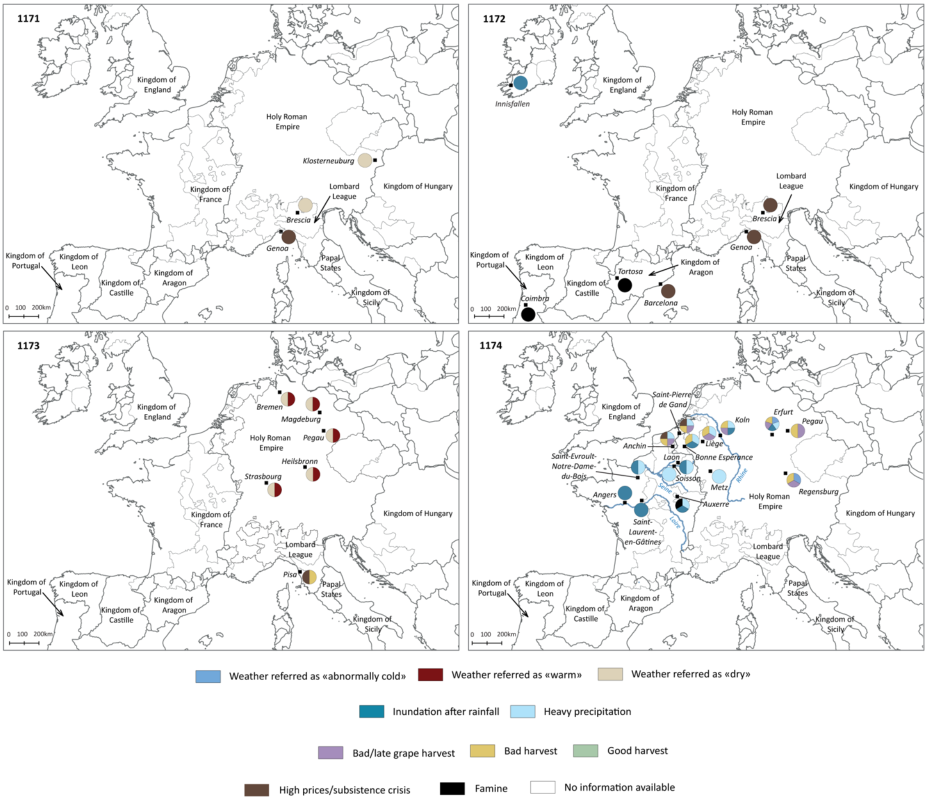

Fig. 3 Climatic anomalies and societal impacts reported in European historical sources during the summers of 1171, 1172, 1173 and 1174 CE. The delineation of political boundaries is based on the *Nüssly Historical Atlas of Europe* (Nüssly and Nüssly 2010). Delimiting political borders with precision towards the end of the 12th century comes with uncertainties. Therefore, these maps only intend to offer a broad perspective on the geopolitical context around the year 1200 CE

that volcanic forcing may suppress the East Asian Summer Monsoon (EASM) (Fan et al. 2009; Schneider et al. 2009; Wegmann et al. 2014; Man et al. 2014), and with documented droughts repeatedly coinciding with eruption years during the Western Han era (206 BCE-8 CE) (Yang and Ludlow 2024), as well as in later periods of Chinese history (Zhuo et al. 2014; Gao et al. 2017). However, more recent proxy and modeling analyses point to a more complex response (Tejedor et al. 2021; Liu et al. 2022). These recent studies suggest that significant volcanic eruptions might, when followed by El-Niño, lead to an intensification of the EASM (Liu et al. 2022). Hence, whilst plausible, it is not possible to be fully confident in ascribing these drought conditions to UE2.

Historical records provide no information regarding weather conditions in the Korean peninsula (Fig. 4a).

In summary, the limited cooling observed during summer in the Northern Hemisphere, the lack of dust veil reports, the relatively warm and dry summer in Europe, and the dry spring and summer in China, collectively make it challenging to firmly attribute the spring-summer weather anomalies of 1171 CE to UE2.

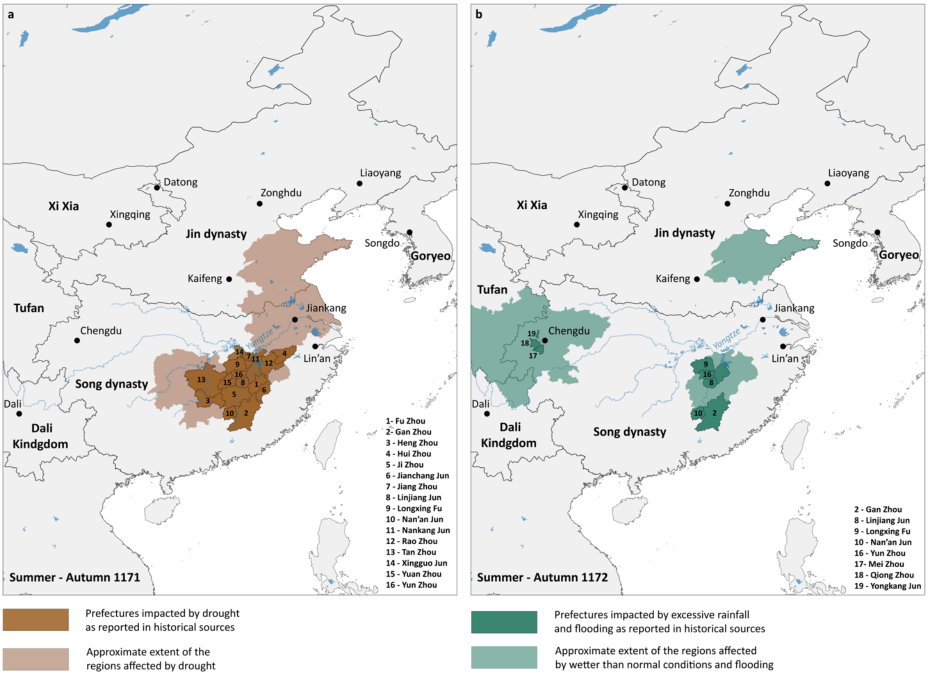

Fig. 4 Approximate spatial extent of drought and rainfall events in China during the summer and autumn of 1171 (**a**) and 1172 CE (**b**). The delineation of political and administrative boundaries is based on *Hartwell China Historical GIS version 5* (Hartwell 2015). Accurately reconstructing the precise borders of ancient China and its neighbouring political entities poses significant challenges. Thus, this map is intended only to offer readers a general overview of the geographical boundaries during the Jin and Song dynasties, around 1200 CE

3.2.2 NH winter of 1171/1172 CE

Historical reports referring to weather conditions during winter 1171–72 CE are scarce but three contemporary accounts from Belgium, the Netherlands and Wales attest to exceptionally mild conditions (Table S1). Whereas in Tournai (Belgium), the chronicler rather tersely note a mild, windy, stormy and rainy winter, the chronicler of Egmond (Egmond aan den Hoef, Netherlands) provides more detail (Table S1):

> *The winter was very mild to such point that frost barely lasted more than two days. Trees were already leafing and young birds were hatching in early February.*

These mild winter conditions are supported further by *Brut y Tywysogion* (Wales) reporting *"an extraordinary season of fine weather in winter"* (see Table S1). NH winter warming, over Northern Eurasia and parts of North America, has been considered a typical response of the atmosphere to stratospheric aerosol veils from large eruptions, apparent in both observations and models (Robock and Mao 1992; Shindell 2004; Zambri and Robock 2016; Banerjee et al. 2021; Azoulay et al. 2021; Coupe and Robock 2021). In the case of our historical evidence, this association would be consistent with a spring or summer 1171 CE timing of UE2. However, we note that some recent modelling studies have failed to reproduce a NH winter warming (Polvani et al. 2019; Polvani and Camargo 2020; Marshall et al. 2022).

3.2.3 NH summer of 1172 CE

Summer temperatures in 1172 CE show stronger cooling in the NH reconstruction. The unfiltered *NVOLCv2* reconstruction indicates a JJA cooling of –0.61 °C in 1172 CE. This cooling (rank 122) is below the 10th percentile of the summer temperature distribution for the last ~ 1500 years. In the *NVOLC_filt* reconstruction the JJA temperature anomaly is comparable (–0.58 °C) but ranks as the 52th coldest year. While falling below the 10th percentile of the temperature distribution, this summer cooling is modest compared with that following other major second millennium eruptions, e.g., in 1816 (–1.23 °C), 1601 (–1.17 °C), 1258/59 (–0.73 °C,–1.2 °C), 536, (-1.02 °C), 1109 (–0.96 °C) and 1453 (–1 °C) or– to a lesser extent– in 1641 CE (–0.68 °C). We also note that some large-scale reconstructions, such as *N-TREND2015* (Wilson et al. 2016), do not show pronounced cooling in 1172 CE, which, again, highlights the challenge of confidently identifying volcanic climatic signals in proxy reconstructions.

The JJA gridded reconstruction shows a spatially heterogeneous response in 1172 CE, with the strongest cooling over Siberia (<–2 °C), Central Asia (<–2 °C) and Yakutia (<–0.8 °C). The severe cold conditions registered in Siberia and Central Asia are also evident in occurrences of frost- and light-rings in the tree-ring chronologies of Yamal and the Polar Urals (Hantemirov et al. 2004, 2023). According to the reconstruction, above-average temperature (> 1 °C) prevailed over Quebec and Northern Scandinavia.

Over Western Europe, we observe limited cooling of around–0.2 to–0.4 °C, consistent with the general absence of weather observations for the year in the contemporary accounts. Only the Annals of Innisfallen (Ireland) reports for 1172 CE, *"very bad weather this year, which killed the greater part of the cattle of Ireland"* (Table S1).

Relevant information is scarce in East Asian sources, particularly regarding the Korean Peninsula. However, in China, some areas within the provinces of Sichuan, Jiangxi and Shandong witnessed increased precipitation and flooding in the spring and summer of 1172 CE (Fig. 4b, Table S3). This observation may support an emerging hypothesis suggesting an enhancement of the East Asian Summer Monsoon (EASM) following significant volcanic eruptions (Liu et al. 2022).

If we distill all the information to hand—the combination of warm and dry conditions in Europe during summer 1171 CE, the dust veil evident from the dark lunar eclipse observation in January 1172 CE, the NH winter warming in 1171/72 CE, the signal of NH summer cooling in 1172 CE—it points to UE2 happening around spring 1171 CE. In this scenario, the cool conditions during summer 1171 CE may be attributed to internal variability. However, further confirmation or refutation of this hypothesis would require additional high-resolution proxies covering the Northern Hemisphere.

3.2.4 NH winter of 1172/1173 CE

The chronicler Michael the Great describes exceptional cold and heavy snowfall over the whole Middle East from September 1172 until April 1173 CE (Figure S1):

> *In the same year 1483 [1172 CE], in Hal [September], cold, rain, and snow suddenly took place and ruined grapevines, olive trees, cotton and sesame plants which turned dark and black as if they were burnt by fire. This chastisement happened not only in Assyria, Bet-nahrin* [i.e., the land "between the rivers", Tigris and Euphrates], *and Syria, but also in the lands of Persia, Armenia, Palestine and Egypt. The entire universe looked like rubbish consumed by fire and turned into ash and dust, a terrible scene for onlookers. […] Strongmen not only could cross with much difficulty from one village to another, but also from one house to another. Streets of cities and of village were filled with snow and frost, and people were kept in houses as if inside graves. The frost solidified rivers, springs and every source of water to such an extent that people, animals and birds succumbed to thirst, as well as to hunger.* (see Table S2)

The observations of severe conditions in the winter of 1172/73 CE, including snowfall in Jerusalem, echo patterns observed in winter 1991/1992 CE following the Pinatubo eruption of June 1991 CE. During that time, the Middle East witnessed uncharacteristically cold weather, with a rare snowstorm experienced in Jerusalem. Colder-than-normal conditions even led to widespread coral bleaching in the Red Sea (Robock 2003; Osipov and Stenchikov 2017). In contrast, North America, Western Europe, and Siberia experienced above average tropospheric temperatures in the first winter after Pinatubo's eruption (Robock 2003). The climatology of the second winter after the eruption was similar (Robock 2003). Yet at this stage, confidently attributing the cold spell of 1172/1173 CE to volcanic forcing is challenging. Indeed, Michael the Great does not report significant cooling in the first winter following the eruption in 1171/1172 CE, thereby limiting the parallel to the Pinatubo case. Unless the author misdated the cold year by a year, caution must be exercised in relating these observations to UE2 (as opposed to internal climate variability).

Annals from France, the Netherlands and Austria also attest to cold conditions over Western and Central Europe in winter 1172/73 CE. In Austria, the Danube River remained frozen for nearly two months and spring ice melting caused disastrous floods (Table S1). Several other regions in Western Europe experienced relatively cool spring weather, with reports of snowfall in Central Germany (Annals of Pöhlde) in April and May 1173 CE (Table S1).

3.2.5 NH summer of 1173 CE

For the summer of 1173 CE, the Annals of Strasbourg in France, as well as the Annals of Magdeburg and Pegau in Germany, record warm and dry conditions over Central and Western Europe (Fig. 3 and Table S1). This is consistent with available tree-ring chronologies from the region, which indicate above-average temperatures (Fig. 2c) and near-average NH summer temperature in the *NVOLCv2_filt* reconstruction (Fig. 2b). The absence of Northern Hemisphere summer cooling suggests that any lingering radiative forcing due to remaining UE2 atmospheric aerosol was by then negligible.

In East Asia, particularly in Korea, historical sources from the summer of 1173 CE report a severe drought caused by a prolonged lack of rain since January. This drought was sufficiently severe that the emperor and officials organised ceremonies to pray for rain (Table S3). However, the evidence is too scarce to confidently attribute this drought to UE2.

3.2.6 NH summer of 1174 CE

While contemporary European chroniclers and annalists do not specifically mention the summers of 1171, 1172, and 1173 CE as notably cold, we have more detailed information regarding the summer and autumn of 1174 CE. These seasons are described as unseasonably cold and wet in regions of France, Belgium, the Netherlands, and Germany (Fig. 3 and Table S1). The *Annales Ratisponenses*, for instance, report that frost and freezing temperatures caused severe damage to crops, including vineyards, in Bavaria, Germany at the end of May 1174 CE:

> *In the year 1174 of the Lord's incarnation, six days before the calends of June (May 27), winter* [i.e., frost] *consumed all the grain and grapes in the Regensburg area*. (Table S1)

Similarly, an anonymous chronicler from St Peter of Erfurt in Thuringia, Germany, states that heat was lacking all summer, while incessant rain in autumn caused flooding and led to poor harvest in various regions (Fig. 3 and Table S1). The independent reconstruction by Pfister and Wanner (2021) of summer temperature corroborates our findings and marks the summer of 1174 CE as one of the coldest of the twelfth century. The *NVOLCv2* gridded reconstruction also suggests colder-than-average temperatures for the summer of 1174 CE (Fig. 2c).

Unless we consider the possibility that ice cores may have been misdated by 2 years and discount the dark total lunar eclipse of 1172 CE as evidence for a dust veil, it appears improbable that the adverse conditions observed over Western and Central Europe can be attributed to the UE2. It is, therefore, more likely that the cold summer of 1174 CE resulted from natural variability. This case emphasizes that cold summers can occur independently of volcanic eruptions and underscores the importance of accurately dating volcanic events to correctly identify and link climate anomalies to them.

3.3 Identifying the potential impacts of the UE2 eruptions on medieval societies

3.3.1 Europe

Several contemporary sources do describe subsistence crises and famines between 1171 and 1173 CE, primarily in Northern Italy (Lombardy, Liguria), Catalonia (Spain), and Northern Portugal (Fig. 3 and Table S1). However, confidently attributing these circumstances to UE2 is complex. Except for the *Annales Ianuenses* (Annals of Genoa, Italy), which succinctly notes that "the time was excessively unfavorable," available historical sources do not explicitly link the famines to meteorological conditions. Even in the case of Genoa, understanding the famine requires considering the political and socio-economic context. Since 1167 CE, several Northern Italian cities had been in conflict with the Holy Roman Emperor Frederic I Barbarossa (1122–1190 CE). These cities formed an alliance with Pope Alexander III (1105–1181 CE), known as the Lombard League, to resist the emperor's attempts to reduce their liberties. In Genoa, the subsistence crisis reported in the *Annales Ianuenses* in 1171 CE directly resulted from a conflict with cities that were part of the Lombard League. The League decided to halt grain trade with Genoa after the Archbishop of Mainz, Christian I (ca. 1130–1183 CE), an emissary of the emperor, was received there with honor. This action was seen as a provocation, leading to the grain embargo:

> […] *Christian, the Archbishop of Mainz and chancellor and legate of all Italy, was sent by lord Frederick, the German emperor, into Lombardy, against the will of the Lombards, who at that time were in rebellion and at war with the same emperor; and he crossed the river Tanaro, not by bridge or on foot, but by riding horses at fast speed, near the city of Alessandria. And coming to our city, he was received, out of respect for the emperor, with the highest honors, and was accorded such respect as far as Luna* [i.e, today La Spezia, Liguria, Italy]. *Therefore, the leaders of Lombardy* [i.e, the leaders of the Lombard League]*, outraged and in a way angry against Genoa, moved some of their cities to prohibit the grain to be brought to our city; however, some was still brought in, but not as much. But because the time was excessively unfavorable and provisions were lacking in nearby places, the price of a mina of grain rose to ten solidi or less, and this scourge persisted for a period of a year and a half.* (See Table S1)

Historical sources from Austria, England, France, and Germany make no mention of subsistence crises at that time (Fig. 3). A possible exception comes from the Annals of Inisfallen (Ireland), which hint at subsistence stress for 1172 CE when reporting mass cattle mortality arising from “very bad weather” (a description unfortunately ambiguous as to the exact meteorological variables and seasons involved) in a society heavily dependent upon cattle and dairying (Table S1) (Campbell and Ludlow 2020).

By contrast, multiple historical sources report a widespread pestilence in early winter 1173/1174 CE affecting the British Isles, the Holy Roman Empire, the Kingdom of France, and Italian Peninsula. According to descriptions, infected individuals suffered from coughing with often fatal consequences. The annalist of the cathedral of Cologne (North Rhine-Westphalia, Germany) provides a good example of the situation:

> *This year, on December 1, 1173, an unbearable cough of unprecedented magnitude spread throughout the German Empire and Gaul, the old as well as the younger men and children were weakened, they were struck down by death in great numbers. Even the bishop of Münster Louis* [i.e., Louis I of Wippra] *died of the plague and was replaced by Hermann, Count of Katzenelnbogen by decision of the emperor*. (See Table S1)

Medieval chroniclers’ descriptions of these symptoms align with influenza (Hirsch 1883; Potter 2001). Interestingly, the *Annales Magdeburgenses* (Annals of Magdeburg) in Germany ascribed this disease to a noxious “bad air”:

> *It also fell dust coming from a dense/thick cloud, from which was conceived a cough excessively painful/hard to bear for men, this epidemic was of great strength, a very large number succumbed to it and in particular pregnant women. Louis, abbot of our monastery died from it*. (Table S1)

The falling 'dust' in the description should not be assumed to have a volcanic origin. Instead, it likely refers to the miasma theory, popular in the Middle Ages, and holding that diseases were caused by poisonous vapor or emanations in the air. This idea has its roots in Greek and Roman medicine and particularly Hippocrates' treatise on *Air, Water and Places*.

Climatic change has been associated with transmission of infectious disease throughout history and given that volcanic forcing is a key driver of climatic variability it is plausible to consider it among the factors influencing disease outbreaks. Perhaps the most striking coincidence between climate-forcing eruptions and disease is the Justinian Plague, which emerged just a few years after major volcanic eruptions in 536 and 540 CE (Stothers 1999). Post (1977) also documents outbreaks of typhus in Ireland following the 1815 CE eruption of Tambora, implicating both the sociopolitical circumstances in the aftermath of the Napoleonic Wars and the volcano's climatic consequences for agricultural productivity. However, as Luterbacher et al. (2020) note, establishing clear causal connections between climate events and epidemics is challenging, especially for ancient cases where high resolution data is scarce. In the case of the apparent respiratory disease epidemic in the winter of 1173/74 CE, there is presently no conclusive evidence linking it to any indirect effects of UE2.

3.3.2 Middle East

The Middle East faced a severe famine during the harsh winter of 1172/1173 CE, a crisis extensively documented by Michael the Great. The famine had far-reaching consequences, extending its grip as far as Sijistan, a region covering parts of present-day Iran, Pakistan, and Afghanistan (Classen 2010) (Figure S1). Michael the Great attributed the famine to multiple factors, primarily exceptional cold, which damaged crops, reducing harvests. Livestock, having difficulty finding food and reaching liquid (i.e., unfrozen) water sources (Table S2), also perished in great numbers. Snow accumulation hindered travel between regions, disrupting transport of foodstuffs that might have alleviated the crisis. In certain areas, the situation was intensified by hoarding. For example, the chronicler recounts the fate of the Cappadocian governor who perished in the city of Sebastea (Figure S1) during the winter of 1172/1173 CE due to his refusal to distribute grain to alleviate the suffering population:

> *Pressured by famine, they contrived to kill him [i.e., the governor of Cappadocia], so that they may feed themselves and their children with his wheat. When they agreed with each other and took oath, they attacked him and killed him and his wife - the sister of the sultan– and five hundred of his household, and cast them on the snow, not considering them worthy of burial.* (Table S2)

Michael the Great's chronicle notes that the famine's repercussions persisted in several regions for at least four years, partly due to further poor harvests in 1174 and 1175 CE. Given the inconclusive association between volcanic forcing and the harsh winter of 1172/1173 CE, the available evidence is insufficient to confidently ascribe a role for UE2 in this food crisis.

3.3.3 East Asia

Similar conclusions can be drawn for East Asia. The drought experienced in China in 1171 CE (Fig. 4a), along with the destruction of crops that followed with the summer floods of the year 1172 CE (Fig. 4b) led to subsistence crises and famines, especially in Jiangxi and Shandong, despite the efforts of the imperial and local administration to relieve the population:

> *During the autumn of the seventh year of the Qiandao reign period [1171], over ten counties in Jiangdong and Jiangxi suffered from famine, with Jiangzhou, Yunzhou, and Longxingfu Prefecture being particularly severely affected. People resorted to wild grasses and fruits to alleviate hunger and fled to the Huai River region. An edict was issued to allocate money from the imperial treasury to adopt the abandoned children.* (See Table S3)

Food crises were experienced also the following year:

> *There was no wheat harvest in Jiangxi area this year. Famines in Longxingfu (prefecture) were frequent. In Nanchang and Xinjian districts, over 28,000 people affected by famines had to rely on government support*. (See Table S3)

In Korea, the severe drought that took place in 1173 CE also led to a severe famine which is vividly reported in the *Goryeosa jeoryo*:

> *Summer, Fourth month. The King personally prayed at the Founder's shrine and gave out pardons. There were prayers for rain. From January there had been no rain so springs and fields were all drying, trees and others drying up, sickness also has risen. People are increasingly dying of starvation. Even raw human flesh is sold on the market*. (See Table S3)

However, presently, given our limited understanding of UE2's impact on East Asian climate and ongoing uncertainties regarding its role in the 1171 or 1173 CE droughts and 1172 CE floods, caution is needed when attempting to directly link these events to subsistence crises, famines, and to UE2. We can, at best, note the close timing of the droughts and floods with the eruption.

4 Conclusions

In this paper, we combine a systematic analysis of medieval European, Middle Eastern and East Asian historical sources, tree-ring and ice-core records to date and document the possible climatic and societal impacts of UE2, credited with the tenth largest sulphur injection of the last millennium. Information from ice cores and astronomical observations point to an eruption occurring between summer 1170 and autumn 1171 CE, with the most likely date falling between spring and summer 1171 CE (Toohey and Sigl 2017; Guillet et al. 2023). These findings are consistent with contemporary historical sources that describe exceptionally warm conditions in Central and Western Europe in the NH winter 1171/72 CE– a pattern observed following other large volcanic eruptions– and by relatively cool NH summers reconstructed from NH tree-ring network in 1172 CE. In addition, a severe cold spell was reported in the Middle East from 1172 to 1173 CE. The period from 1171 to 1173 CE was a troubled time marked by subsistence crises and famines in regions such as the Mediterranean, the Near East, China, and Korea, with some subsistence stress implied for Ireland in 1172 CE. A widespread European epidemic, likely influenza, was also reported in the winter of 1173/1174 CE. Yet, quantifying the exact extent to which UE2 contributed to these events remains difficult. While arguments can be made to link both the reported weather anomalies and societal stresses to volcanic forcing, unforced climate variability and other societal and political circumstances may have been sufficient alone. We conclude that disambiguating the influences that have led to climatic variation and societal change remains complex, all the more so for remote periods when data are sparse. At a time when the literature on the impacts of large volcanic eruptions on climate and society seems to be burgeoning, this contribution sounds a note of caution. A promising avenue of research to further understand the climatic impacts of UE2, and dissociate coincidence from causality, would be the application of climate simulations and event attribution methods, similar to the approach taken by Schurer et al. (2019) in their study of the 1815 Tambora eruption. A complementary statistical approach is the examination of the frequency and timing of climatic and societal events relative to the dates of multiple explosive eruptions over long time periods to determine whether there are consistent patterns of response occurring in particular post-eruption years (e.g., Zhuo et al. 2014; Manning et al. 2017; Yang and Ludlow 2024).

As climate extremes can occur in the absence of large volcanic eruptions, precisely dating their past occurrence is essential for detecting their potential impacts on climate and societies. This case study highlights the valuable contributions of multi-proxy approaches, utilizing ice-core, tree-ring and historical archives to constrain the dating of past volcanic events. Historical reports of dust veils have frequently been used in the past to identify the presence of volcanic aerosols in the stratosphere. Among these, we advocate for the use of accounts detailing the coloration and brightness of total lunar eclipses, whenever such records are available. Records of total lunar eclipses offer the advantage of precise dating, frequent observations, and documentation by contemporary observers. Furthermore, their interpretation is less ambiguous than descriptions of solar dimming or Bishop's rings, which can be confused with parhelia, haloes, or solar eclipses.

The climate response of UE2 does not appear in the proxy reconstructions to be as dramatic as would be expected of a stratospheric sulfur burden of order 18 Tg. UE2 thus reminds us that volcanic forcing responses are superimposed upon natural climate variability and regional influences that will moderate or exacerbate impacts of a given event (Brönnimann and Krämer 2016; Schurer et al. 2019). A similar consideration pertains to societal impacts which, even when the existence of extreme climatic conditions is confirmed, will still be mediated by pre-existing socioeconomic and political contexts. Lastly, when considering reports of blue/red sun, blood circles or unusual solar dimming as evidence of dust veils, or when reading contemporary accounts that attribute apparent atmospheric anomalies (dust and dense clouds) with the onset of a probable influenza outbreak in 1173 CE, it is essential to critically analyse such material with knowledge of their contemporary contexts to disentangle scientific from religious interpretations. For that reason, a profound understanding of the mindset of Medieval societies as well as their religious beliefs is yet another prerequisite for the credible analysis and interpretation of volcanic impacts on climate and past societies.

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Data availability The historical data underlying this study can be found in Supplementary Dataset S1, S2, and S3. Lunar eclipse colouration data is available on Zenodo at https://doi.org/10.5281/zenodo.6907654. The tree-ring-based reconstructions can be downloaded at https://doi.org/10.5281/zenodo.3724674. Ice-core data can be retrieved from the following link and repository: https://doi.org/10.1038/nature14565 and https://doi.org/10.1594/WDCC/eVolv2k_v2.

Declarations

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