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Possible impact of the 43 BCE Okmok volcanic eruption in Alaska on the climate of China as revealed in historical documents

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Abstract. The Okmok volcanic eruption in Alaska has recently been discovered and is precisely dated to have occurred in 43 BCE. Some Chinese climate records of 43–33 BCE have been found in historical documents that provide descriptions of observed environmental abnormities that appear to be consistent with the anticipated changes due to volcanic climate forcing. In this paper, we provide a full translation with discussions of the Chinese climate records that may be related to the Okmok eruption. We have converted ancient Chinese calendar dates to modern Gregorian dates and provided the latitudes and longitudes of the geographical locations mentioned in the records. Relevant climate information in similar areas of China in the decades after the 1783 Laki eruption is also briefly summarized for comparison. We believe the detailed information contained in these records will be useful for further research on the climate impact of volcanic eruptions.

1 Introduction

It has been known for some time that volcanic eruptions represent an important forcing that shapes the global climate (Bradley, 2015; Gao et al., 2008), and some recent events, such as the eruption of Mount Pinatubo in 1991 that caused discernable climate cooling, have been studied and reported (e.g., McCormick et al., 1995; Sukhodolov et al., 2018). Since climate change is a globally urgent issue facing human society and predictions of future climate change rely mainly on climate models which at present still produce results with large uncertainties (IPCC, 2023), it is of great importance to improve and validate these models. One common practice is to run these models to back-predict the past climate during a certain period with known forcing terms and compare the model results with observations. An example of such activities is the Paleoclimate Model Intercomparison Project (PMIP; see, e.g., Jungclaus et al., 2017), but they require high-quality past climate data and evidence of events that might indicate important climate forcing. Given the high impact of volcanic forcing on climate change, obtaining accurate volcanic eruption records is evidently highly important.

Large, explosive volcanic eruptions exert short-term cooling on the global climate, which counteracts greenhouse-gas-induced warming and, by doing so, may alter climate conditions of certain regions. For example, it has been suggested that this cooling reduces land–sea thermal contrast and suppresses summer precipitation, especially in low-latitude monsoon regions (Gao and Gao, 2018; Iles and Hegerl, 2014; Schneider et al., 2009; Robock et al., 2008). Changes in monsoon rainfall have great repercussions on the food production and human societies in these areas. Thus, it is important to understand these large eruptions and their impacts on climate.

A recent study revealed a previously unreported volcanic eruption that occurred on Mount Okmok in Alaska with an unprecedentedly accurate dating technique and pinpointed that the eruption occurred in early 43 BCE (McConnell et al., 2020). Such accurate dating is very important, as it can link unambiguously with other records describing climate-related phenomena observed at the same time to form a complete cause-and-effect chain, which is valuable data for climate–model validation: only those models that include the right causes at the right moment through the right physical sequence and produce the accurate effect as observed can be regarded as validated for this forcing. The records discussed here reveal such a cause-and-effect chain.

In interpreting climate change, we also need to keep in mind that climate is governed by the complex interactions among various external forcing and internal modes, and volcanic responses can invoke but also be easily overridden by internal modes such as ENSO. This is certainly also true in East Asia. Sometimes the climate signals of these factors overlap and render the determination of the causes difficult. In addition, the reconstructed climate change may look different when interpreted by different sets of proxy data. For example, Gao et al. (2017) demonstrated that a discrepancy exists between the reconstruction by Anchukaitis et al. (2010) based on the tree-ring-derived Monsoon Asia Drought Atlas (MADA; see Cook et al., 2010) and that by Chinese historical documents when analyzing the climatic responses in China after the 1815 Tambora eruption. Later, Feng et al. (2013) used a multiproxy-based reconstruction that supported the document-based reconstruction (Gao and Gao, 2018). This underlines the importance of accurate data sets for climate studies.

2 Okmok eruption in 43 BCE and contemporary Chinese climate records in 43–33 BCE

Chinese historical documents contain many records with information about the climate conditions of the time. Many of these have been utilized for the reconstruction of past climate in China (see, e.g., Wang, 1979, 1980; Wang and Zhang, 1988, 1992, 1994; Zhang and Wang, 1994). We have recently digitized the climate records in China from the past 3000 years listed in Zhang (2013) by designing an extensive dictionary to convert these records into digital form and build a climate database called REACHES (Wang et al, 2018, 2023) so that researchers can utilize these records even if they are not familiar with the Chinese language (Wang et al., 2018; Lin et al., 2020).

Among these ancient records, one that caught our attention a long time ago is the “cold summer” record dated to 43 BCE, as it is the first such report with precise timing in an official national chronicle, *Han Shu* (the history of the Han dynasty), about which more will be said later. This and other sequel records at that time are, in our opinion, of importance for understanding the impact of volcanic eruptions on the global climate. They were briefly mentioned in McConnell et al. (2020) but without much detail. It is felt that, by providing the full contents of these Chinese records, climate researchers can profit by digging deeper into this event and scrutinizing the meaning of the descriptions of the records. This will lead to a better understanding of the volcanic impact on climate both qualitatively and quantitatively.

In the following sections, we will provide full translations of these records that we deem relevant to the Okmok eruption along with our observations and interpretations that we believe would be useful.

We used the online utility (Shouxing Tianwenli, 2024) to convert the Chinese calendar to the Gregorian calendar. The approximate latitudes and longitudes of the locations mentioned in these records were determined using the historical GIS developed at Academia Sinica (Liao and Fan, 2012). If a record contains no specific location name, then it was usually an event observed in the national capital at the time, i.e., Chang’an (長安; 34.03899° N, 108.9311° E). All events discussed below occurred during the reign of Emperor Yuan of the Han dynasty (漢元帝) who ruled China in the period 48–33 BCE. Starting in 140 BCE, it became a tradition of Chinese imperial systems to give a special name, called the era name, to the years of a certain period during the reign of an emperor. There might be several such eras during the reign of an emperor if deemed necessary. Even though Emperor Yuan only reigned 16 years, he had four such eras: Chu Yuan (初元; 48–44 BCE), Yong Guang (永光; 43–38 BCE), Jian Zhao (建昭; 38–33 BCE), and Jing Ning (竟寧; 33 BCE).

All records discussed below were derived from the following five original Chinese historical documents and from Zhang (2013):

1. Annals of Emperor Yuan, *Han Shu* (漢書 元帝紀)
2. Records of Five Elements, *Han Shu* (漢書 五行志)
3. Biography of Feng Fengshi, *Han Shu* (漢書 馮奉世傳)
4. *Lord Fu’s Notes of Ancient and Contemporary Affairs* (伏侯古今注)
5. *Comprehensive Reflections to Aid in Governance* (資治通鑑)

The first three documents are all from *Han Shu* authored by Ban Gu (AD 32–92) who was the pioneer of Chinese chronological history. The second document (#2) contains a large number of observed abnormal environmental phenomena. The fourth document (#4) was written by Fu Wuji (circa AD 130). Both Ban Gu and Fu Wuji lived in the Han dynasty. The fifth document (#5) is a comprehensive reference

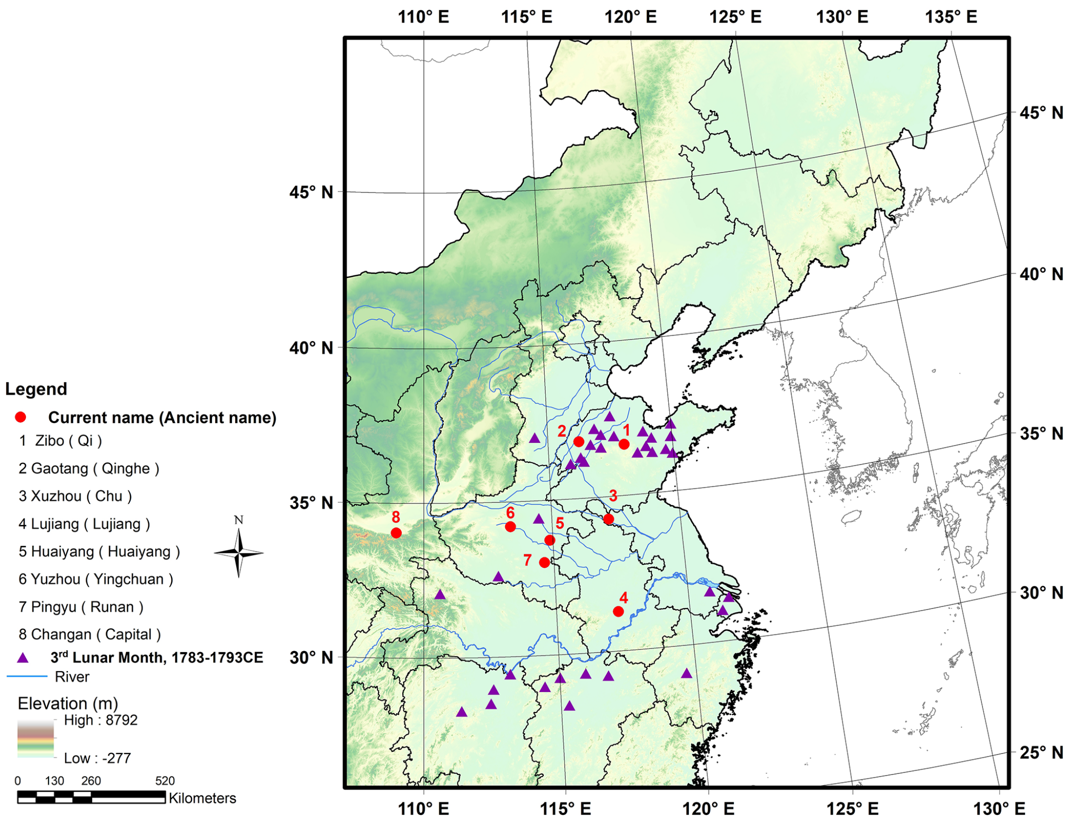

Figure 1. A map showing the locations mentioned in the text. Red dots are those associated with the Han dynasty records (location names in the legend). Purple triangles are those associated with the cold records in the general area of central China in the period of 1783–1793.

compiled in the Song dynasty led by Sima Guang (AD 1019–1086) based on imperial historical documents. We use numerical indices to indicate the source of the records (at the end in parenthesis) in the following sections. The records are listed in chronological order.

Figure 1 shows a map of the locations mentioned below.

(a) 43 BCE (Yong Guang first year)

i. "In the third month (8 April–6 May), snowfall. Frost damaged wheat crops. No harvest in the fall." (#1)

ii. "In the third month, frost damaged mulberry." (#2)

iii. "In the fourth month (7 May–5 June), the sun was bluish-white in color and cast no shadow. When the sun reached its zenith, it did cast shadow but had no glare. The summer was cold. The glare of the sun recovered in the ninth month (2–31 October)." (#2)

iv. "On the second day of the ninth month, frost damaged crops. Severe famine occurred in the whole country." (#2)

Of the above four records, number (iii) is the most directly relevant to the volcanic eruption; hence we will discuss it first. Coloration of the sky and of the celestial objects in it can be an important indication of the presence and the altitude level of volcanic dust. For example, Guillet et al. (2023) utilized the coloration of the moon during total moon eclipses to determine the stratospheric turbidity so as to infer the occurrence of climate-forcing volcanic eruptions. In this record, the original Chinese characters describing the color of the sun in this record were 青白 (qing bai), which can be translated as "greenish-white" or "bluish-white" due to the somewhat ambiguous meaning of "qing" in the ancient Chinese language, as it could mean either "bluish" or "greenish", but we shall use bluish-white for our discussion here. The description of the sun color here already indicated that it was unusual, and the most likely cause, in light of the discovery of the Okmok eruption, was that the sun was veiled by a thin layer of volcanic dust in the sky. Such blue sun (and moon) phenomena caused by volcanic ash have been observed repeatedly and lasted for hours at a time during the 1883 Krakatoa eruption (Minnaert, 1993).

The second important indication of the presence of volcanic ash is that the sun cast no shadow except when it was at its zenith. Again, this was likely due to the presence of volcanic dust that scattered sunlight, rendering the sky light a diffuse light source which therefore cast no shadow (Minnaert, 1993). This effect is more pronounced when the sun angle is low in the morning or in the late afternoon, as the sun's rays have to go through a thick layer of the atmosphere. When the sun is at its zenith, its rays go through a much thinner layer of the atmosphere; therefore it suffers less scattering and is capable of casting a shadow. However, the scattering was obviously substantial enough to reduce the glare of the sun as described by the record.

The record indicates that the summer was cold. The use of "cold" (寒) to describe summer conditions was rather unusual in Chinese historical records and must indicate a rather severe departure from the norm. A few cold days in a summer may not be so unusual, but a whole cold summer must be extremely rare. Thus, we feel that the estimate of 2 °C colder than the normal mean given in Tan et al. (2003) is reasonable. A cooling of such magnitude was possible under the strong volcanic radiative forcing associated with the Okmok eruption.

The record then says that the sun glare recovered in the ninth month, roughly 5 months after the sighting of the unusual sun color. This should indicate how long the volcanic dust hovered over northern China in 43 BCE. This information should be of importance to researchers trying to model the cooling and those interested in modeling the transport of volcanic dust to China from Okmok.

Now we can go back to examine records (i) and (ii), which both indicate cold conditions in the third month. Even though these events occurred before the sighting of volcanic dust, it is still possible that the cold climate was caused by the volcanic forcing, as the spring weather of northern China is usually strongly influenced by the movements of polar air masses. Okmok is located much further north than China, and the cold air mass originating in the Alaskan polar region can certainly influence the spring weather in northern China. The volcanic forcing could have caused air masses that were colder than normal, resulting in the frosty third month in China when they moved south.

Record (iv) can be interpreted in a similar way. Even if the volcanic dust had disappeared, it is still possible that the forcing effect lasted longer; hence the frost and famine could still be attributed to the volcanic event.

(b) After 43 BCE

It is known that the impact of volcanic eruption on climate can last many years if the dust reaches stratospheric levels, such as in the case of the Pinatubo eruption in June 1991 (McCormick et al., 1995). Hence it is also useful to list relevant climate records a few years after an eruption event. In the next section, we list those records within 10 years after the 43 BCE Okmok eruption.

i. 42 BCE (Yong Guang second year)

   – In the sixth month (24 July–22 August), the imperial decree declared, "Recently, there are years of poor harvest, and all areas are in serious condition. People worked hard on tilling but received no produce. They are suffering from famine, and there is no relief." (#1)
   – "At this time, there were many crop failures … All areas are suffering famine." (#3)

These two records are essentially saying the same thing, namely, poor crop yield led to famine which could be attributed to the cold climate. However, the term "years" could mean two or more years; therefore the climate that resulted in famine might or might not be related to the Okmok eruption.

ii. 41–40 BCE (Yong Guang third year)

   – In the 11th month (7 December 41–5 January 40 BCE), the imperial decree declared, "[It] rained in mid-winter, and heavy fog [occurred]." (#1)

The words in brackets were added by us to render the sentence easier to understand in English. Rain in mid-winter is extremely rare in northern China, both now and then, where the capital of the Han dynasty, Chang'an, is located, and this statement must indicate a severe anomaly. The rain that occurred in mid-winter was presumably because of the unusually warm weather at this time. This was obviously not directly due to the negative radiative forcing of the volcanic dust, but could it be a climatic repercussion of the severe coldness of the previous year? Similarly, the fog must have been extraordinarily heavy to deserve a mention in the decree. In addition, fog consists of liquid droplets (since the statement did not say ice fog); therefore this also indicated an abnormally warm climate that winter. It is not known whether fog can be directly related to a volcanic event, but it could also be a result of repercussion. Both require further study in the future.

iii. 39 BCE (Yong Guang fifth year)

   – In the fall (7 August–6 November), Yingchuan (潁川; 34.19589° N, 113.3792° E) flooded and killed people (#1).
   – Heavy floods in summer (5 May–6 August) and fall. Rain in Yingchuan, Runan (汝南; 32.99044° N, 114.6317° E), Huaiyang (淮陽; – 33.70539° N, 114.8841° E), and Lujiang (盧江; –31.26964° N, 117.3212° E) damaged houses in rural areas, causing floods that killed people (#2).
   – In this year, the Yellow River flooded at the Lingmingdu mouth 靈鳴犢口 in Qinghe (清河; 36.83046° N, 116.2479° E), but the Tunshi river (屯溪; a tributary of the Yellow River) dried out (Vol. 21, History of Han, #5).

All of these records mentioned floods, and the second entry seems to indicate that the flood was caused by heavy rain. Again, they were not directly related to the volcanic eruption, but they might be its climatic repercussion.

iv. 38 BCE (Jian Zhao first year)

– In the eighth month (7 September–6 October), a large swarm of flying white moths shrouded the sun (#1).

This is also not directly linked to the volcanic event, but it is also possible that the unusual biospheric phenomena might have been caused by the abnormal climate conditions due to the repercussion.

v. 37–36 BCE (Jian Zhao second year)

– In the 11th month (23 December 37–20 January 36 BCE), an earthquake occurred in Qi and Chu. A big blizzard broke trees and damaged houses (#1).

The earthquake should not be related to the Okmok eruption, but it could have resulted in the cold climate that led to the strong blizzard.

– In the 11th month, a big blizzard occurred in the Qi (齊; 36.64394° N, 118.0556° E) and Chu (楚; 34.27161° N, 117.2056° E) areas and was 5 chi 尺 deep (#2).

The information in this record is essentially the same as the one above, but it gave additional information on the snowfall amount: 5 chi. Chi is a Chinese length unit whose length varied from time to time historically. Han rulers were unearthed, and it was determined that 1 chi in the Han dynasty is roughly 23.1–23.3 cm (Hsu, 2009). 5 chi is therefore roughly 116 cm or 46.4 in., certainly an unusually heavy blizzard in these locations that could have caused the disasters reported in the previous record.

– Jing Fang (77–37 BCE) from Dong Jun spoke to Emperor Yuan about the disasters and abnormities. "Ever since Your Majesty ascended the throne, the sun and the moon have lost their glares, stars orbited reversely, mountains collapsed and springs gushed out from underground, the earth quaked and rocks fell, frost appeared in summer and thunders were heard in winter, plants withered in spring and flowered in fall, frost was unable to kill plants, and flood/drought and locust outbreaks occurred. People suffer from famine and plagues, bandits cannot be suppressed, and prisoners are everywhere. All the disasters and abnormities mentioned in *Chun Chiu* (a chronicle of the Lu dukedom edited by Confucius) have happened." (Vol. 21, History of Han, #5)

According to traditional Chinese belief, abnormal natural phenomena, whether astronomical or on earth, occurred because they reflected the state of health of the political system. When auspicious phenomena (such as colorful clouds or a large gathering of cranes) occurred, they indicated that the system was running well and that the emperor was regarded as virtuous and fit to rule. If ominous signs (such as what was mentioned in these records) occurred, then there must have been something wrong in the system, and ideally a faithful government official should not have been afraid to tell the truth to the emperor. These uncomplimentary comments from Jing Fang, a procurator and scholar known for his studies in divination, must have been very unpleasant to the royal ears, as he attributed all these disasters and abnormities to the incompetent rule of Emperor Yuan. It took great courage for a low-level official to take such action, but this also indicates that what he said about the abnormal climate events must have occurred, otherwise it would have been purely suicidal to make such statements.

Unfortunately, Jing Fang was framed by the head eunuch, Shi Xian, who was the real target of Jing Fang's attribution, and eventually died in jail. Attributing these climate abnormities to political incompetence is obviously unscientific, but there is no way Jing Fang could have known that the real culprit was a volcano some 6000 km from his country.

vi. 35 BCE (Jian Zhao fourth year)

– Dust fall (#4)

Unfortunately, there is no precise month given in this record, and it was unclear whether this had a connection with the volcanic eruption or not.

There is another record listed under this year stating that "in the third month, snowfall occurred and many swallows died". However, this is possibly an error, as the event should belong to one in 29 BCE and the month should be the fourth month (Shi, 1994). This is beyond the 10-year period of interest here and will not be discussed.

vii. 33 BCE (Jing Ning first year)

– Heavy fog. All trees turned white. (#4)

Like the previous record, this record does not contain the month information, and we do not know to which season it belonged. It is also unknown why trees turned white. However, one possibility of trees turning white is that this was a freezing fog event such that fog droplets stuck on trees and turned into ice. If so, this record can possibly be interpreted as indicating conditions that were colder than usual, especially if the fog did not happen in winter.

3 A brief comparison with the possible responses in China in the post-Laki period

As mentioned before, the climate is governed by the complex interaction of many factors; therefore, what is described in the previous section should be taken as a possible, but not definite, climate response to the Okmok eruption in China. Nevertheless, we believe the possibility is high, as we observe a similar climate fluctuation pattern in central China after another large eruption in 1783–1784, the Laki eruption in Iceland. Like the Okmok case, the Laki eruption was a

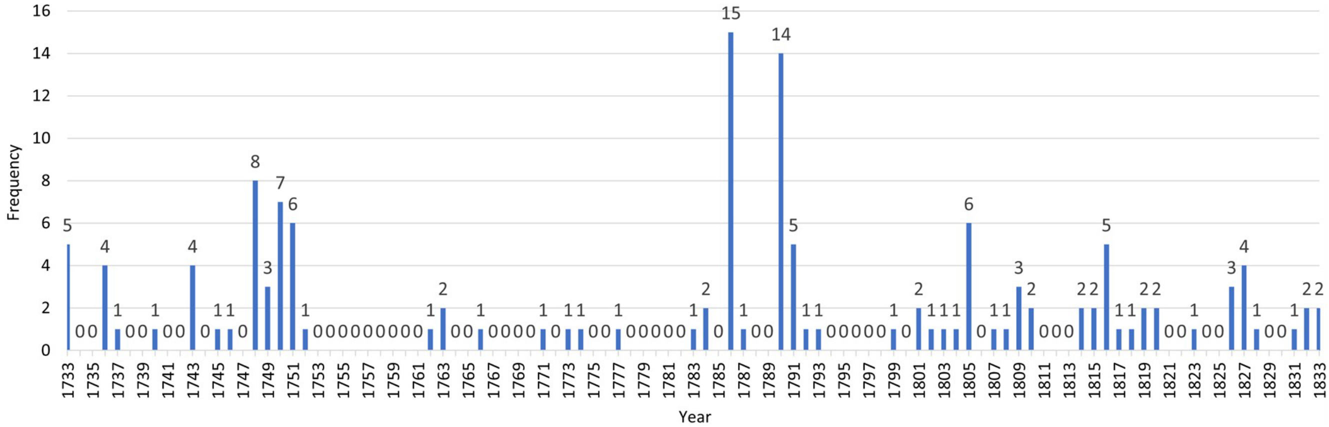

Figure 2. Annual number of cold-condition records in northern and central China in the period of 1733–1833 derived from the REACHES database.

high-latitude event and a strong one with a volcanic explosivity index (VEI) of 4; therefore we would expect that it had an impact on the climate fluctuation in China at that period. Since the winter season is normally cold in central and northern China, it would be more difficult to attribute cold winters to the influence of a volcanic eruption. Instead, we show the evidence of cold climate in the third month, which corresponds to late spring in the Chinese lunar calendar. This season was generally regarded as warm and a time for flowers to blossom. Frost or snow in this season should then indicate conditions that are colder than normal. Figure 2 shows the frequency of frost and/or snow records in the third month of the period 1733–1833 in northern and central China as mentioned in the last section. The exact locations of the records associated with the post-Laki decade (1783–1793) are shown in Fig. 1 as purple triangles. We can see that they generally overlap with those locations mentioned in Sect. 2.

Figure 2 shows that the annual number of cold records in northern and central China was high in 1748–1751, which, if due to volcanic factors, could be associated with the Oshima–Ōshima eruption in Japan in 1741–1742 (Smithsonian Institute, 2013), but the impact would occur many years later. The cold conditions then subsided considerably for the next 35 years. Then, two very high peaks in 1786 and 1790 and a moderate peak in 1791 occurred, several years after the Laki eruption. After that, a series of peaks occurred in 1805, 1816, and 1827, a roughly 11-year periodicity. The timing of the 1786–1791 peaks suggests that they could be due to the volcanic radiative forcing of the Laki eruption, as the impact can occur a few years after an eruption. On the other hand, it is less certain what was responsible for the cold peaks in the 19th century.

4 Conclusions

In the above, we translated several climatic records kept in Chinese historical chronicles for the 10-year period (43–33 BCE) following the Okmok eruption, which was recently identified to be in 43 BCE (McConnell et al., 2020). These records clearly portray a generally cold and harsh climate period that was commensurate with the negative radiative forcing expected for a volcanic eruption. Descriptions of the observed optical abnormities of the sun and moon also match the expected consequences due to the veiling of high-altitude volcanic dust, which might have lasted as long as 6 months. Such a long veiling period at such a long distance away from the source should indicate that the eruption must have been of extraordinary magnitude, as suggested in McConnell et al. (2020).

The precise dating of volcanic eruptions, such as the studies in Gao et al. (2008) and McConnell et al. (2020), is obviously very important for identifying the cause or forcing responsible for certain past climate conditions, such as the cold summer of 43 BCE, recorded in Chinese history which otherwise would always remain a mystery. Conversely, there are many other similar climate records listed in Chinese historical documents that can be used for reconstructing past climates and their environmental impact, and, when combined with new technologies such as in Gao et al. (2008), they can significantly advance our knowledge about the science of climate change (Wang et al., 2018; Lin et al., 2020).

Data availability. The climate database based on historical documents from China (REACHES data set) is available at https://doi.org/10.1038/sdata.2018.288 (Wang et al, 2018). The reconstructed temperature index is published as https://www.ncei.noaa.gov/access/paleo-search/study/37720 (Wang et al, 2023). Data not presented in the paper can be made available upon reasonable request.

Author contributions. PKW primary conceptualized and supervised the work. EHL identified additional materials and added a new direction. YL and CW performed historical data curation. KHL, YL, CL, HL, and PP collected resources and made the initial analysis. All authors contributed to the drafts and gave final approval for publication.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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