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

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Abstract. A massive eruption of Okmok ~~volcano~~ volcanic eruption in Alaska has been recently discovered and precisely dated to have occurred in 43 BCE. Some Chinese climate records of 43 - 33 BCE in historical documents have been found that provide descriptions of observed environmental abnormities that appear to be consistent with the anticipated changes due to volcanic climate forcing. We provide full translation with discussions of the Chinese climate records that may be related to the Okmok eruption in this paper. 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. Some information about the few decades of post-Laki 1783 eruption climate condition in similar areas of China are 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.

Summary

We provide detailed translation of some abnormal meteorological conditions in 43-33 BCE described in Chinese historical documents possibly related to the Okmok volcanic eruption in Alaska in early 43 BCE. The cold summer record and the abnormal color and low brightness of

the sun point to the clear link to the volcanic impact. The reported duration for the visual condition of the sun to return normal should be useful for researchers modeling the volcanic impact on climate.

1. Introduction

It has been known for some time that volcanic eruptions are an important forcing in shaping the global climate (Bradley, 2015; Gao et al., 2008) and some recent events, such as the eruption of 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 the human society and that predictions of future climate change rely mainly on climate models which, at present generation, 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 PMIP which stands for Paleoclimate Model Intercomparison Project (see, e.g., Jungclaus et al., 2017). But this requires high quality past climate data and evidence of events that might indicate important climate forcing. Given 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 the greenhouse gas-induced warming and, by doing so, may alter climate conditions of certain regions. For example, this cooling has been suggested to reduce land-sea thermal contrast and suppress summer precipitation, especially in low-latitude monsoon regions (Gao and Gao, 2018; Iles & 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 obviously important to understand these large eruptions and their impacts on climate.

A recent study revealed a previously unreported volcanic eruption occurred in Mount Okmok in Alaska with an unprecedented accurate dating technique and pinpointed that the eruption occurred in early 43 BCE (McConnell et al., 2020). Such accurate dating is very important in that it can link unambiguously with other records describing climate-related phenomena observed at the same time to form a complete cause-and-effect chain, and such a chain becomes a 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 considered as validated for this forcing. The records discussed here reveal such a cause-and-effect chain.

In interpreting the climate change, we also need to keep in mind that the climate is governed by the complex interactions among various external forcing and internal modes, and volcanic responses can invoke but also easily overwritten by internal modes such as ENSO. This is certainly true in East Asia also. 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 supports 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 that contain information about the climate conditions of the time. Many of these have been utilized for the reconstruction of past climate in China in the historical time (see, e.g., Wang, 1979, 1980; Wang & Zhang, 1988, 1991, 1992; Zhang & Wang, 1991). We have recently digitized the climate records in China in the past 3000 years listed in Zhang (2013) by designing an extensive dictionary to convert these records into digital form to build a climate database called REACHES such that researchers can utilize these records even if they are not familiar with Chinese language (Wang et al., 2018; Lin et al., 2020).

Among these ancient records, one that had caught our attention long time ago is the ‘cold summer’ record dated at 43 BCE as it is the first such report with precise timing in an official national chronicle, *Han Shu* (literally the History of 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 global climate. They had been briefly mentioned in McConnell et al. (2020) but without much details. 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, 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 use the online utility http://www.nongli.net/sxwnl/ to convert the Chinese calendar to Gregorian calendar. The approximate latitudes and longitudes of the locations mentioned in these records were determined using the historical GIS developed in Academia Sinica (Liao and Fan 2012). If a record contains no specific location name, then it was an event usually observed at the national capital at the time, i.e., Changan (長安，34.03899° N, 108.9311° E). All events discussed below occurred during the reign of Emperor Yuan of 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 to the years of a certain period, called era name, 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 as well as in 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 (32-92 AD) who was the pioneer of Chinese chronological history. #2 contains a large amount of observed abnormal environmental phenomena. #4 was written by Fu Wuji (circa 130 AD). Both Ban Gu and Fu Wuji lived in Han Dynasty. #5 was a comprehensive reference compiled in Song Dynasty led by Sima Guang (1019-1086 AD) based on the imperial historical documents. We use the numerical indices to indicate the source of the records (at the end in parenthesis) in the following discussions. The records are listed in chronological order.

Fig. 1 shows a map of the locations mentioned in the discussions below.

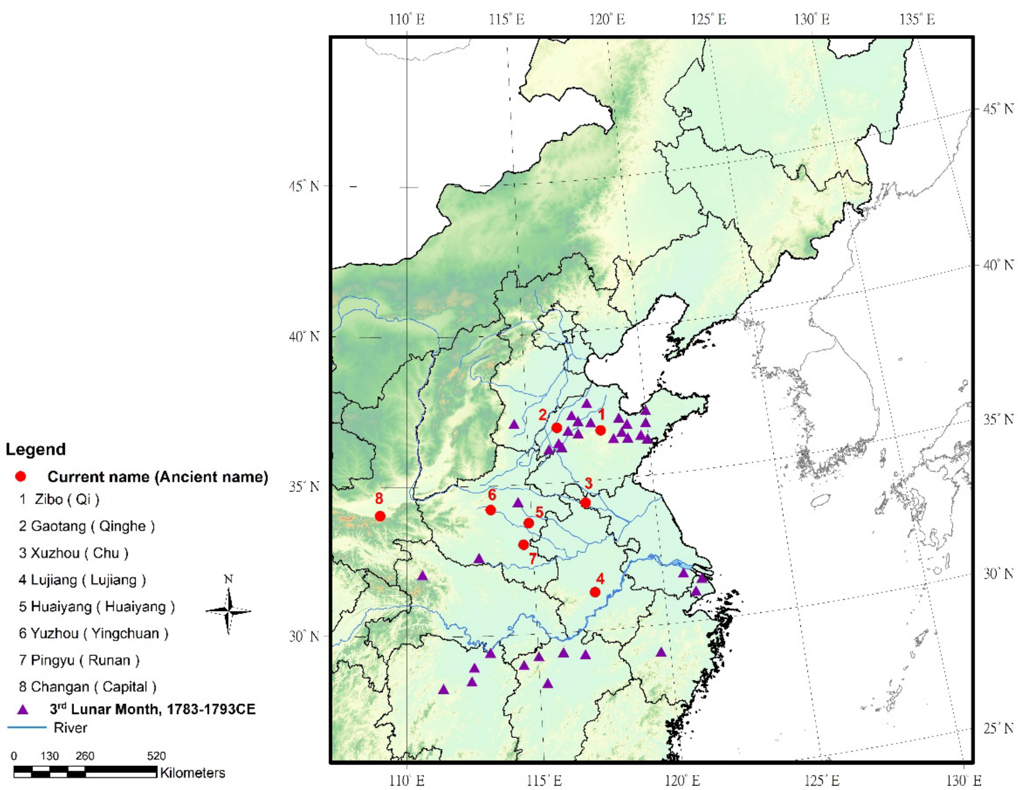

Fig. 1. A map showing the locations mentioned in the text. Red circular dots are those associated with the Han dynasty records (location names in the legend). Blue triangles are those associated with the cold records in the general area of central China in the period of 1733-1833.

a) 43 BCE (Yong Guang 1st year)

i) "In 3rd Month (8 April – 6 May), snowfall. Frost damaged wheat crops. No harvest in the fall" (#1)

ii) "In 3rd Month, frost damaged mulberry" (#2)

iii) "In 4th Month (7 May – 5 June), the sun was bluish-white in color and casted no shadow. When the sun reached the zenith, it did cast shadow but had no glare. The summer was cold. The glare of the sun recovered in the 9th Month (2 - 31 October)" (#2)

iv) "On 2nd Day of 9th Month, frost damaged crops. Severe famine occurred in the whole country" (#2)

Of the above four records, iii) is the most directly relevant to the volcanic eruption, hence we will discuss it first. ~~The~~ Coloration of the sky and that of the celestial objects in it can be an important indication of the presence and the altitude level of the volcanic dusts. 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 was 青白 (qing bai) which can be translated as "greenish-white" or "bluish-white" due to the somewhat ambiguity of the meaning of "qing" in ancient Chinese language, as it could mean either "bluish" or "greenish", but we shall use bluish-white for our discussion here. The description of sun color here already indicated that it was unusual, and the most likely cause, in light of the discovery of Okmok eruption, was that the sun was veiled by a thin layer of volcanic dusts in the sky. Such blue sun (and moon) phenomenon caused by volcanic ash has been observed repeatedly and lasted hours for a time during the 1883 Krakatau eruption (Minnaert, 1993).

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

The record indicates that that summer was cold. The use of ‘cold’ (寒) to describe summer condition 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 be not so unusual, but a whole cold summer season must be extremely rare. Thus, we feel that the estimate of 2°C colder than normal mean given in Tan et al (2003) is reasonable. It is little doubt that such cooling ~~was~~ must have been due to the very strong volcanic radiative forcing associated with the Okmok eruption.

The record then says that the sun glare recovered in the 9th Month, roughly 5 months after the sighting of the unusual sun color. This should indicate how long the volcanic dusts 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 dusts to China from Okmok.

Now we can go back to examine records i) and ii), both indicate cold condition in the 3rd month. Even though these events occurred before the sighting of the volcanic dusts, it was still possible that the cold climate was caused by the volcanic forcing as the Spring time weather of northern China is usually influenced strongly by the movements of polar air masses. Okmok is located much further north than China, and the cold air mass originated in Alaskan polar region can certainly influence the spring weather in Northern China. The volcanic forcing could have caused colder-than-normal air masses that resulted the frosty 3rd Month in China when they moved south.

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

b) ~~2.2~~ After 43 BCE

It is known that the impact of volcanic eruption on climate can last many years if the dusts reach high in the stratospheric level such as the case of Pinatubo eruption in June 1991

(McCormick et al., 1995). Hence it is also useful to list relevant climate records a few years after the eruption event. In the next section, we list those records within 10 years after the 43 BCE Okmok eruption.

i). ~~2.2.1~~ 42 BCE (Yong Guang 2nd year)

- In 6th 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 and therefore the climate that resulted in famine might or might not relate to the Okmok eruption.

ii) ~~2.2.2~~ 41 – 40 BCE (Yong Guang 3rd year)

- In 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 parenthesis are added by us to render the sentence easier to understand in English. Rain in mid-winter is extremely rare in northern China now as well as then where the capital of Han Empire, Changan, is located and this statement must indicate a severe anomaly. Rain occurred in midwinter was presumably because the unusual warm weather at this time. This was obviously not directly due to the negative radiative forcing of the volcanic dusts, but could it be a climatic repercussion of the severe coldness of the previous year? Similarly, the fog must have been extraordinary heavy to deserve a mention in the decree. In addition, fog consists of liquid droplets (since the statement did not say ice fog) and therefore this also indicated abnormally warm climate that winter. It is not known that 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) ~~2.2.3~~ 39 BCE (Yong Guang 5th year)

- In the fall (7 August – 6 November), Yingchuan (潁川 34.19589N, 113.3792E) flooded and killed people (#1)
- Heavy flood 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 (廬江 31.26964°N, 117.3212°E) damaged houses in rural areas and causing flood that killed people. (#2)
- In this year, the Yellow River flooded at Lingmingdu Mouth （靈鳴犢口）of Qinghe (清河 36.83046°N, 116.2479°E), but River Tunshi (屯溪 a tribute of Yellow River) dried out. (Vol. 21, History of Han, #5)

All of these records mentioned flood 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 might be its climatic repercussion.

iv) ~~2.2.4~~ 38 BCE (Jian Zhao 1st year)

- In 8th Month (7 September – 6 October), 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 condition due to the repercussion.

v) ~~2.2.5~~ 37 – 36 BCE (Jian Zhao 2nd year)

- In 11th Month (23 December, 37 – 20 January, 36 BCE), earthquake occurred in Qi and Chu. Big blizzard broke trees and damaged houses (#1)

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

- In 11th Month, big blizzard occurred in 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 he one above but it gave an additional information on the snowfall amount, 5 *chi*. *Chi* is a Chinese length unit whose length varied from time to time historically. There were Han rulers unearthed and it was determined that one *chi* in 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 cause 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 had 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 heard in winter, plants withered in spring and flowered in fall, frost 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 Lu Dukedom edited by Confucius) have happened" (Vol. 21, History of Han, #5)

According to traditional Chinese belief, abnormal natural phenomena, be it astronomical or earth environmental, occur because they reflect the health state of the political system. When auspicious phenomena (such as colorful clouds or large group gathering of cranes) occur, it must indicate that the system is running well and the emperor was considered virtuous and fit to rule. If ominous signs (such as what mentioned in this records) occur, then there must be something wrong in the system, and ideally a faithful government official should not be 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 a great courage for a low-level official to take such an action but this also indicates that what he said about the abnormal climate events must have occurred, for otherwise it would be purely suicidal to make such statements.

Unfortunately, Jing Fang was framed by the head eunuch, Shi Xian, whom 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) ~~2.2.6~~ 35 BCE (Jian Zhao 4th year)

- Dustfall (#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 3rd Month, snowfall occurred and many swallow died". However, this is possibly an error and the event should belong to one in 29 BCE, and the month should be 4th Month (Shi, 1994). This is beyond the 10-year period of interest here and will not be discussed.

vii) ~~2.2.7~~ 33 BCE (Jing Ning 1st year)

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

Like the previous record, this record does not contain the month information and we don't know 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, then this record can possibly be interpreted as indicating a colder-than-usual condition, especially if the fog did not happen in winter.

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

As mentioned before, the climate is governed by the complex interaction of many factors, therefore what described in the previous section should be taken as possible, but not definite, climate response of 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 Okmok case, the Laki eruption was a high-latitude event and a strong one with a VEI (Volcanic Eruption Index) at 4, and therefore we would expect that it would have 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 volcanic eruption. Instead, we show the evidence of cold climate in the 3rd month which corresponds to late spring in 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 colder than normal condition. Fig. 2 shows the frequency of frost and/or snow records in the 3rd month of the period 1733-1833 in northern and central China as those mentioned in the last section. The exact locations of the records are shown in Fig. 1 as blue triangles. We can see that they overlap generally with those locations mentioned in the last section.

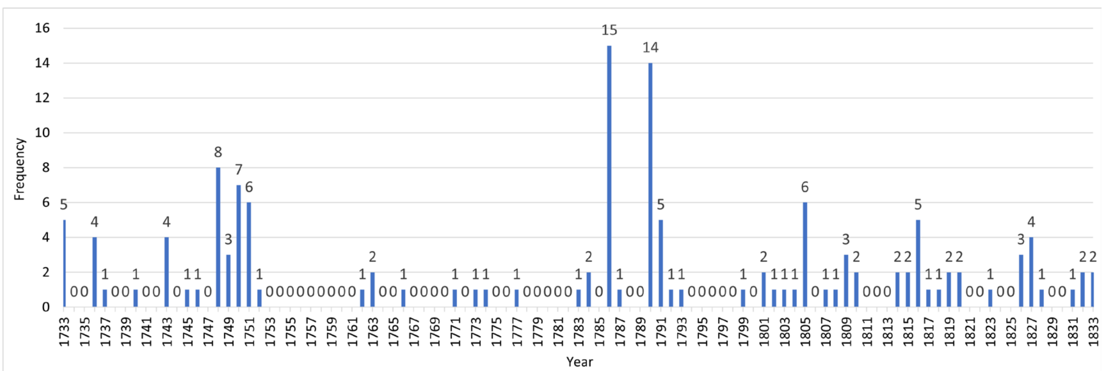

Fig. 2. Annual number of cold condition records in northern and central China in the period of 1733-1833 derived from REACHES database.

Fig. 2 shows that the annual number of cold records in northern and central China had a high period in 1748-1751 which, if due to volcanic factor, could be associated with the Oshima-Oshima eruption in Japan in 1741-1742 (Smithsonian Institute, 2013) but the impact would occur many years later. The cold condition then subsided considerably for the next 35 years. Then two very high peaks in 1786 and 1790 and a moderate peak at 1791 occurred, several years after the Laki eruption. After that, a series of peaks occurred at 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 Laki eruption as the impact can occur a few years after the eruption. On the other hand, it is less certain what were responsible for the cold peaks in the 19th century.

4. ~~3.~~ Conclusions

In the above, we translated several climatic records kept in Chinese historical chronicles for the 10-year period (43 – 33 BCE) after the Okmok eruption at 43 BCE recently identified (McConnell et al., 2020). These records clearly portrait 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 dusts, and the veiling 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 be 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 the Chinese history which otherwise would always remain as 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 done in Gao et al. (2008) can significantly advance our knowledge about the science of climate change (Wang et al. 2018; Lin et al. 2020).

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Data Availability. No new data is used in this work.

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