Possible impact of the 43 BCE Okmok volcanic eruption in Alaska on the climate of China as revealed in historical Document~~s~~

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Abstract. The~~A massive eruption of~~ Okmok 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 Some Chinese climate records of 43 - 33 BCE in historical documents have been found that provide descriptions of observed environmental abnormities that appear to be consistent with the anticipated changes due to volcanic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 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.

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We provide detailed translation of some abnormal meteorological conditions in 43-33 BCE described in Chinese historical documents possibly related to the Okmok volcanic eruption in Alaska in early 43 BCE.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

36 the sun point to the clear link to the volcanic impact. The reported duration for the visual

37 condition of the sun to return normal should be useful for researchers modeling the volcanic

38 impact on climate.

39

40 **1. Introduction**

41 It has been known for some time that volcanic eruptions are an important forcing in

42 shaping the global climate (Bradley 2015; Gao et al. 2008) and some recent events, such as

43 the eruption of Pinatubo in 1991 that caused discernable climate cooling have been studied

44 and reported (e.g., McCormick et al. 1995; Sukhodolov et al. 2018). Since climate change is

45 a globally urgent issue facing the human society and that predictions of future climate change

46 rely mainly on climate models which, at present generation, still produce results with large

47 uncertainties (IPCC, 2023), it is of great importance to improve and validate these models.

48 One common practice is to run these models to back-predict the past climate during a certain

49 period with known forcing terms and compare the model results with observations. An

50 example of such activities is PMIP which stands for Paleoclimate Model Intercomparison

51 Project (see, e.g., Jungclaus et al., 2017). But this requires high quality past climate data and

52 evidence of events that might indicate important climate forcing. Given high impact of

53 volcanic forcing on climate change, obtaining accurate volcanic eruption records is evidently

54 highly important.

55 Large explosive volcanic eruptions exert short-term cooling on the global climate which

56 counteracts the greenhouse gas-induced warming and, by doing so, may alter climate

57 conditions of certain regions. For example, this cooling has been suggested to reduce land-

58 sea thermal contrast and suppress summer precipitation, especially in low-latitude monsoon

59 regions (Gao and Gao, 2018; Iles & Hegerl, 2014; Schneider et al., 2009; Robock et al.,

60 2008). Changes in monsoon rainfall have great repercussions on the food production and

61 human societies in these areas. Thus, it is obviously important to understand these large

62 eruptions and their impacts on climate.

63 A recent study revealed a previously unreported volcanic eruption occurred in Mount

64 Okmok in Alaska with an unprecedented accurate dating technique and pinpointed that the

65 eruption occurred in early 43 BCE (McConnell et al. 2020). Such accurate dating is very

66   important in that it can link unambiguously with other records describing climate-related

67   phenomena observed at the same time to form a complete cause-and-effect chain, and such a

68   chain becomes a valuable data for climate model validation: Only those models that include

69   the right causes at the right moment through the right physical sequence and produce the

70   accurate effect as observed can be considered as validated for this forcing. The records

71   discussed here reveal such a cause-and-effect chain.

72   In interpreting the climate change, we also need to keep in mind that the climate is

73   governed by the complex interactions among various external forcing and internal modes,

74   and volcanic responses can invoke but also easily ~~overwritten~~ overridden by internal modes

75   such as ENSO. This is certainly true in East Asia also. Sometimes the climate signals of these

76   factors overlap and render the determination of the causes difficult. In addition, the

77   reconstructed climate change may look different when interpreted by different sets of proxy

78   data. For example, Gao et al. (2017) demonstrated that a discrepancy exists between the

79   reconstruction by Anchukaitis et al. (2010) based on the tree ring-derived Monsoon Asia

80   Drought Atlas (MADA, see Cook et al., 2010) and that by Chinese historical documents

81   when analyzing the climatic responses in China after the 1815 Tambora eruption. Later, Feng

82   et al. (2013) used a multiproxy-based reconstruction that supports the document-based

83   reconstruction (Gao and Gao, 2018). This underlines the importance of accurate data sets for

84   climate studies.

85

86   **2. Okmok eruption in 43 BCE and contemporary Chinese climate records in 43-33 BCE**

87   Chinese historical documents contain many records that contain information about the

88   climate conditions of the time. Many of these have been utilized for the reconstruction of past

89   climate in China in the historical time (see, e.g., Wang, 1979, 1980; Wang & Zhang, 1988,

90   1991, 1992; Zhang & Wang, 1991). We have recently digitized the climate records in China

91   in the past 3000 years listed in Zhang (2013) by designing an extensive dictionary to convert

92   these records into digital form to build a climate database called REACHES such that

93   researchers can utilize these records even if they are not familiar with Chinese language

94   (Wang et al. 2018; Lin et al. 2020).

95   Among these ancient records, one that had caught our attention long time ago is the 'cold

96   summer' record dated at 43 BCE as it is the first such report with precise timing in an official

97   national chronicle, *Han Shu* (literally the History of Han Dynasty), about which more will be

98   said later. This and other sequel records at that time are, in our opinion, of importance for

99   understanding the impact of volcanic eruptions on global climate. They had been briefly

100   mentioned in McConnell et al. (2020) but without much details. It is felt that by providing the

101   full contents of these Chinese records, climate researchers can profit by digging deeper into

102   this event and scrutinizing the meaning of the descriptions of the records. This will lead to a

103   better understanding of the volcanic impact on climate both qualitatively and quantitatively.

104   In the following, we will provide full translations of these records that we deem relevant

105   to the Okmok eruption along with our observations and interpretations that we believe would

106   be useful.

107   We use the online utility http://www.nongli.net/sxwnl/ to convert the Chinese calendar to

108   Gregorian calendar. The approximate latitudes and longitudes of the locations mentioned in

109   these records were determined using the historical GIS developed in Academia Sinica (Liao

110   and Fan 2012). If a record contains no specific location name, then it was an event usually

111   observed at the national capital at the time, i.e., Changan (長安, 34.03899° N, 108.9311° E).

112   All events discussed below occurred during the reign of Emperor Yuan of Han Dynasty (漢

113   元帝) who ruled China in the period 48-33 BCE. Starting in 140 BCE, it became a tradition

114   of Chinese imperial systems to give a special name to the years of a certain period, called era

115   name, during the reign of an emperor. There might be several such eras during the reign of an

116   emperor if deemed necessary. Even though Emperor Yuan only reigned 16 years, he had four

117   such eras: Chu Yuan (初元 48-44 BCE), Yong Guang (永光 43-38 BCE), Jian Zhao (建昭

118   38-33 BCE), and Jing Ning (竟寧 33 BCE).

119   All records discussed below were derived from the following five original Chinese

120   historical documents as well as in Zhang (2013):

121   #1 – Annals of Emperor Yuan, *Han Shu* (漢書 元帝紀)

122   #2 – Records of Five Elements, *Han Shu* (漢書 五行志)

123   #3 – Biography of Feng Fengshi, *Han Shu* (漢書 馮奉世傳)

124   #4 – *Lord Fu's Notes of Ancient and Contemporary Affairs* (伏侯古今注)

125   #5 – *Comprehensive Reflections to Aid in Governance* (資治通鑑)

126   The first three documents are all from *Han Shu* authored by Ban Gu (32-92 AD) who was

127   the pioneer of Chinese chronological history. #2 contains a large amount of observed

128   abnormal environmental phenomena. #4 was written by Fu Wuji (circa 130 AD). Both Ban

129   Gu and Fu Wuji lived in Han Dynasty. #5 was a comprehensive reference compiled in Song

130   Dynasty led by Sima Guang (1019-1086 AD) based on the imperial historical documents. We

131   use the numerical indices to indicate the source of the records (at the end in parenthesis) in the

132   following discussions. The records are listed in chronological order.

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

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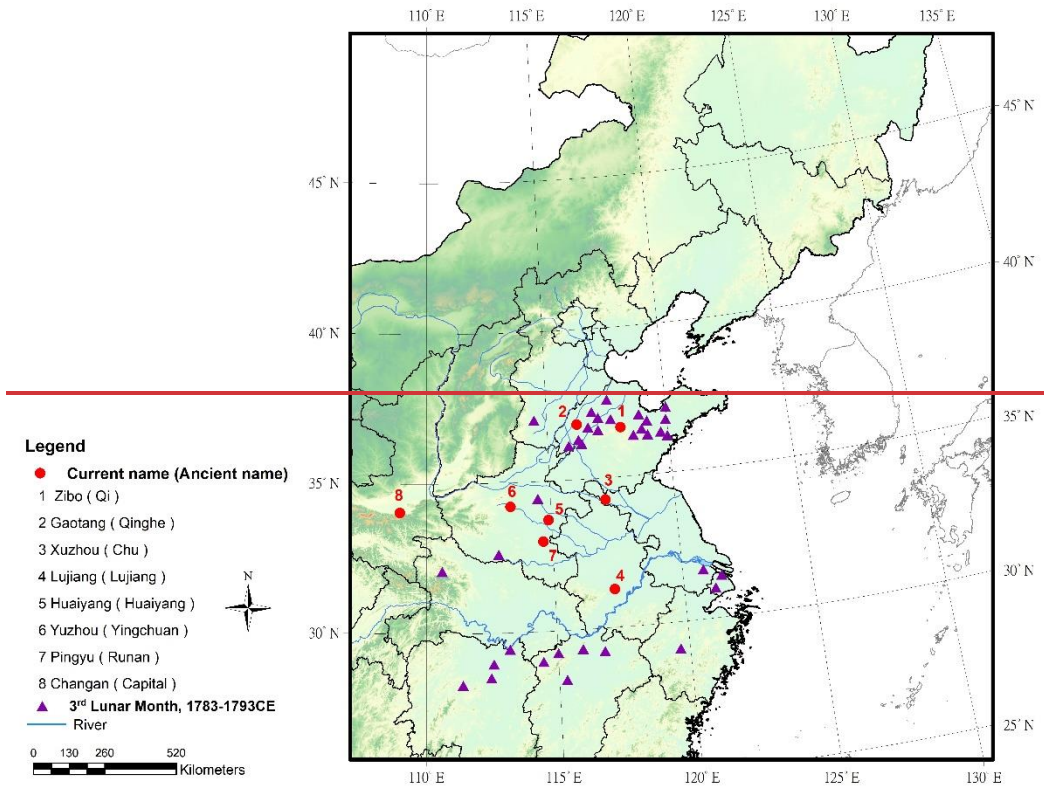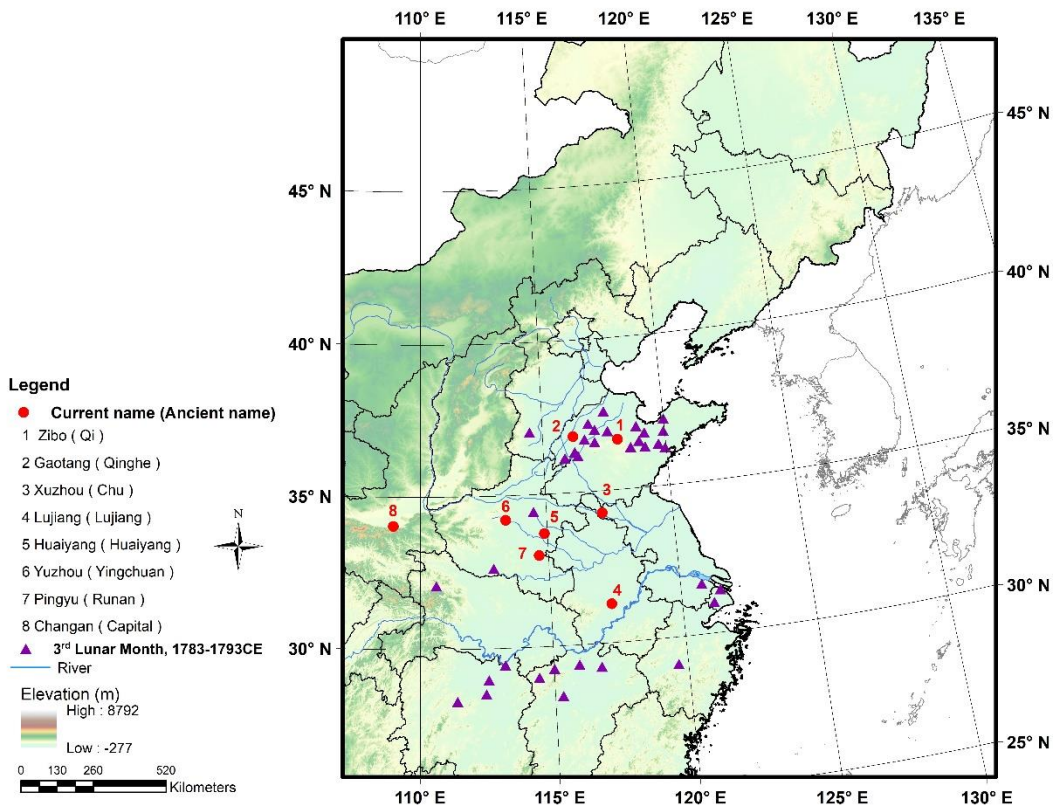
136   Fig. 1. A map showing the locations mentioned in the text. Red circular dots are those

137 associated with the Han dynasty records (location names in the legend). ~~Blue~~ Purple triangles

138 are those associated with the cold records in the general area of central China in the period of

139 ~~1733~~1783 - ~~1833~~1793.

140   **a) 43 BCE (Yong Guang 1st year)**

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

142   the fall" (#1)

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

144   iii) "In 4th Month (7 May – 5 June), the sun was bluish-white in color and casted no

145   shadow. When the sun reached the zenith, it did cast shadow but had no glare. The

146   summer was cold. The glare of the sun recovered in the 9th Month (2 - 31 October)"

147   (#2)

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

149   country" (#2)

150   Of the above four records, iii) is the most directly relevant to the volcanic eruption, hence

151 we will discuss it first. Coloration of the sky and that of the celestial objects in it can be an

152 important indication of the presence and the altitude level of the volcanic dusts. For example,

153 Guillet et al. (2023) utilized the coloration of the moon during total moon eclipses to

154 determine the stratospheric turbidity so as to infer the occurrence of climate-forcing volcanic

155 eruptions. In this record, the original Chinese characters describing the color of the sun in this

156 record was 青白 (qing bai) which can be translated as "greenish-white" or "bluish-white" due

157 to the somewhat ambiguity of the meaning of "qing" in ancient Chinese language, as it could

158 mean either "bluish" or "greenish", but we shall use bluish-white for our discussion here. The

159 description of sun color here already indicated that it was unusual, and the most likely cause,

160 in light of the discovery of Okmok eruption, was that the sun was veiled by a thin layer of

161 volcanic dusts in the sky. Such blue sun (and moon) phenomenon caused by volcanic ash has

162 been observed repeatedly and lasted hours for a time during the 1883 Krakatau eruption

163 (Minnaert, 1993).

164   The second important indication of the presence of volcanic ash is that the sun casted no

165 shadow except when it was at zenith. Again, this was likely due to the presence of the

166 volcanic dusts that scattered sunlight, rendering the sky light a diffuse light source which

167 therefore casted no shadow (Minnaert, 1993). This effect is more pronounced when the sun

168 angle is low in the morning or in the later afternoon as the sun's rays have to go through a

169 thick layer of the atmosphere. When the sun is at the zenith, its rays go through a much

170 thinner layer of the atmosphere and therefore suffers less scattering and is capable of casting a

171 shadow. But obviously the scattering was substantial enough to reduce the glare of the sun as

172 described by the record.

173 The record indicates that that summer was cold. The use of 'cold' (寒) to describe summer

174 condition was rather unusual in Chinese historical records and must indicate a rather severe

175 departure from the norm. A few cold days in a summer may be not so unusual, but a whole

176 cold summer season must be extremely rare. Thus, we feel that the estimate of 2°C colder

177 than normal mean given in Tan et al (2003) is reasonable. ~~It is little doubt that s~~Auch cooling

178 of such a magnitude was possible under ~~must have been due to~~ the ~~very~~ strong volcanic

179 radiative forcing associated with the Okmok eruption.

180 The record then says that the sun glare recovered in the 9th Month, roughly 5 months after

181 the sighting of the unusual sun color. This should indicate how long the volcanic dust~~s~~

182 hovered over northern China in 43 BCE. This information should be of importance to

183 researchers trying to model the cooling and those interested in modeling the transport of

184 volcanic dust~~s~~ to China from Okmok.

185 Now we can go back to examine records i) and ii), both indicate cold condition in the 3rd

186 month. Even though these events occurred before the sighting of the volcanic dusts, it was

187 still possible that the cold climate was caused by the volcanic forcing as the Spring time

188 weather of northern China is usually influenced strongly by the movements of polar air

189 masses. Okmok is located much further north than China, and the cold air mass originated in

190 Alaskan polar region can certainly influence the spring weather in Northern China. The

191 volcanic forcing could have caused colder-than-normal air masses that resulted the frosty 3rd

192 Month in China when they moved south.

193   Record iv) can be interpreted in a similar way. Even if the volcanic dusts had disappeared,

194   it is still possible that forcing effect lasted longer and hence the frost and famine could still be

195   attributed to the volcanic event.

196   **b)** After 43 BCE

197   It is known that the impact of volcanic eruption on climate can last many years if the dusts

198   reach high in the stratospheric level such as the case of Pinatubo eruption in June 1991

199   (McCormick et al. 1995). Hence it is also useful to list relevant climate records a few years

200   after the eruption event. In the next section, we list those records within 10 years after the 43

201   BCE Okmok eruption.

202   **i).**   **42 BCE (Yong Guang 2nd year)**

203   •   In 6th Month (24 July – 22 August), the imperial decree declared "Recently, there

204   are years of poor harvest and all areas are in serious condition. People worked hard

205   on tilling but received no produce. They are suffering from famine and there is no

206   relief" (#1)

207   •   At this time, there were many crop failures, …, all areas are suffering famine" (#3)

208   These two records are essentially saying the same thing, namely, poor crop yield led to

209   famine which could be attributed to the cold climate. However, the term 'years' could

210   mean two or more years and therefore the climate that resulted in famine might or might

211   not relate to the Okmok eruption.

212   **ii) 41 – 40 BCE (Yong Guang 3rd year)**

213   •   In 11th Month (7 December, 41 – 5 January, 40 BCE), the imperial decree declared

214   "(It) rained in mid-winter and heavy fog (occurred)" (#1)

215   The words in parenthesis are added by us to render the sentence easier to understand in

216   English. Rain in mid-winter is extremely rare in northern China now as well as then where

217   the capital of Han Empire, Changan, is located and this statement must indicate a severe

218   anomaly. Rain occurred in midwinter was presumably because the unusual warm weather

219   at this time. This was obviously not directly due to the negative radiative forcing of the

220   volcanic dusts, but could it be a climatic repercussion of the severe coldness of the

221   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) 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) 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) 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.

250   • In 11ᵗʰ Month, big blizzard occurred in Qi (齊 36.64394°N, 118.0556°E) and Chu

251   (楚 34.27161°N, 117.2056°E) areas and was 5 *chi* （尺）deep (#2)

252   The information in this record is essentially the same as he one above but it gave an

253 additional information on the snowfall amount, 5 *chi*. *Chi* is a Chinese length unit whose

254 length varied from time to time historically. There were Han rulers unearthed and it was

255 determined that one *chi* in Han dynasty is roughly 23.1 – 23.3 cm (Hsu 2009). 5 *chi* is

256 therefore roughly 116 cm or 46.4 in, certainly an unusually heavy blizzard in these

257 locations that could cause the disasters reported in the previous record.

258   • Jing Fang (77-37 BCE)from Dong Jun spoke to Emperor Yuan about the

259   disasters and abnormities, "Ever since Your Majesty ascended the throne, the sun and

260   the moon had lost their glares, stars orbited reversely, mountains collapsed and springs

261   gushed out from underground, the earth quaked and rocks fell, frost appeared in

262   summer and thunders heard in winter, plants withered in spring and flowered in fall,

263   frost unable to kill plants, and flood/drought and locust outbreaks occurred. People

264   suffer from famine and plagues, bandits cannot be suppressed, and prisoners are

265   everywhere. All the disasters and abnormities mentioned in *Chun Chiu* (a chronicle of

266   Lu Dukedom edited by Confucius) have happened" (Vol. 21, History of Han, #5)

267   According to traditional Chinese belief, abnormal natural phenomena, be it

268 astronomical or earth environmental, occur because they reflect the health state of the

269 political system. When auspicious phenomena (such as colorful clouds or large group

270 gathering of cranes) occur, it must indicate that the system is running well and the

271 emperor was considered virtuous and fit to rule. If ominous signs (such as what

272 mentioned in this records) occur, then there must be something wrong in the system, and

273 ideally a faithful government official should not be afraid to tell the truth to the emperor.

274 These uncomplimentary comments from Jing Fang, a procurator and scholar known for

275 his studies in divination, must have been very unpleasant to the royal ears as he attributed

276 all these disasters and abnormities to the incompetent rule of Emperor Yuan. It took a

277 great courage for a low-level official to take such an action but this also indicates that

278   what he said about the abnormal climate events must have occurred, for otherwise it

279   would be purely suicidal to make such statements.

280   Unfortunately, Jing Fang was framed by the head eunuch, Shi Xian, whom was the

281   real target of Jing Fang's attribution, and eventually died in jail. Attributing these climate

282   abnormities to political incompetence is obviously unscientific, but there is no way Jing

283   Fang could have known that the real culprit was a volcano some 6000 km from his

284   country!

285   **vi) 35 BCE (Jian Zhao 4th year)**

286   • Dustfall (#4)

287   Unfortunately, there is no precise month given in this record and it was unclear whether this

288   had a connection with the volcanic eruption or not.

289   There is another record listed under this year stating that "In 3rd Month, snowfall occurred

290   and many swallow died". However, this is possibly an error and the event should belong to one

291   in 29 BCE, and the month should be 4th Month (Shi, 1994). This is beyond the 10-year period of

292   interest here and will not be discussed.

293   **vii) 33 BCE (Jing Ning 1st year)**

294   • Heavy fog. All trees turned white. (#4)

295   Like the previous record, this record does not contain the month information and we don't

296   know which season it belonged. It is also unknown why trees turned white. However, one

297   possibility of trees turning white is that this was a freezing fog event such that fog droplets stuck

298   on trees and turned into ice. If so, then this record can possibly be interpreted as indicating a

299   colder-than-usual condition, especially if the fog did not happen in winter.

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

301   As mentioned before, the climate is governed by the complex interaction of many factors,

302   therefore what described in the previous section should be taken as possible, but not definite,

303   climate response of the Okmok eruption in China. Nevertheless, we believe the possibility is

304   high, as we observe a similar climate fluctuation pattern in central China after another large

305   eruption in 1783-1784, the Laki eruption in Iceland. Like Okmok case, the Laki eruption was a

306   high-latitude event and a strong one with a VEI (volcanic eruption index) at 4, and therefore we

307   would expect that it would have impact on the climate fluctuation in China at that period. Since

308   the winter season is normally cold in central and northern China, it would be more difficult to

309   attribute cold winters to the influence of volcanic eruption. Instead, we show the evidence of

310   cold climate in the 3rd month which corresponds to late spring in Chinese lunar calendar. This

311   season was generally regarded as warm and a time for flowers to blossom. Frost or snow in this

312   season should then indicate colder than normal condition. Fig. 2 shows the frequency of frost

313   and/or snow records in the 3rd month of the period 1733-1833 in northern and central China as

314   those mentioned in the last section. The exact locations of the records associated with the post-

315   Laki decade (1783-1793 are) are shown in Fig. 1 as purpleblue triangles. We can see that they

316   overlap generally with those locations mentioned in Section 2.the last section.

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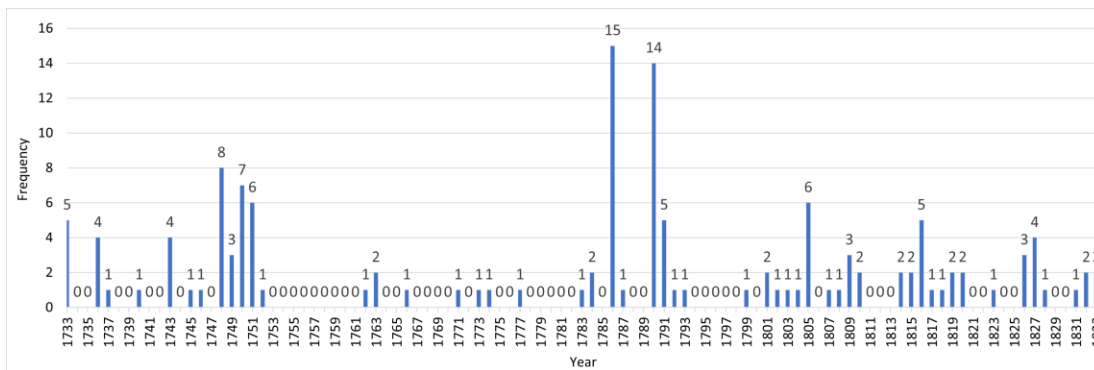
319   Fig. 2. Annual number of cold condition records in northern and central China in the period

320   of 1733-1833 derived from REACHES database.

321   Fig. 2 shows that the annual number of cold records in northern and central China had a high

322   period in 1748-1751 which, if due to volcanic factor, could be associated with the Oshima-

323   Oshima eruption in Japan in 1741-1742 (Smithsonian Institute, 2013) but the impact would occur

324   many years later. The cold condition then subsided considerably for the next 35 years. Then two

325   very high peaks in 1786 and 1790 and a moderate peak at 1791 occurred, several years after the

326   Laki eruption. After that, a series of peaks occurred at 1805, 1816, and 1827, a roughly 11-year

327   periodicity. The timing of the 1786-1791 peaks suggests that they could be due to the volcanic

328   radiative forcing of Laki eruption as the impact can occur a few years after the eruption. On the

329   other hand, it is less certain what were 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) 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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