THE POSSIBLE CLIMATIC IMPACT IN CHINA OF ICELAND'S ELDGJÁ ERUPTION INFERRED FROM HISTORICAL SOURCES

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Abstract. Based on Chinese historical sources, the possible climatic impact in China of the prolonged Eldgjá eruption starting around 934 AD was investigated. An extremely hot summer was reported in 934 AD; hundreds of people died of the intense heat of this summer in Luoyang, the capital of the Later Tang Empire (923–936 AD). Snowless (and possibly also mild) winters probably occurred successively following the Eldgjá eruption until 938 AD. In 939 AD, cold weather set in abruptly and lasted for about 3 years; whereas peak cooling occurred in 939AD. In the summer of 939 AD, it snowed in the southeast of the Inner Mongolia Plateau (about 40–44°N, 113–123°E). From 939AD to 941 AD, hard winters occurred successively in China. Worse, unprecedented drought and plague of locusts broke out in 942 AD and persisted in 943 AD. More than several hundred thousand people were starved to death. This catastrophe was at least partly responsible for the collapse of the Later Jin Dynasty in China. By comparison with the tree-ring evidence and uncovered European historical evidence, the spatial response to the Eldgjá eruption appeared to be complex, whereas hemispheric or global cooling occurred in 939–942 AD.

1. Introduction

The Eldgjá fissures are situated in southern Iceland. The prolonged basaltic flood lava eruption starting around 934 AD is one of the largest terrestrial basaltic flood lava eruptions in the last two millennia (Stothers, 1998; Thordarson et al., 2001).

The Eldgjá eruption occurred during the European Dark Ages. The relevant European historical sources are understandably few and fragmental. But a multi-disciplinary approach has made it evident that the Eldgjá fissure did erupt during the early 10th century. The evidence includes the Icelandic historical sources studies (Ogilvie, 1991; Stothers, 1998), the tephro-chronological studies and the lava flow studies (Larsen, 1979, 1993; Miller, 1989; Thordarson and Self, 1998), and the ice cores studies of GISP2 and Crête (Zielinski et al., 1994, 1995; Hammer et al., 1980), and so on.

In what year did the Eldgjá fissure erupt? McCarthy and Breen (1997) identified the date of the Eldgjá eruption as the springtime of 939 AD after they collated and examined the Irish historical astronomical data. In the Crête ice core in Greenland, the largest acidity excess spanning about 3 years was dated at 934 ± 2 AD with high certainty (Hammer et al., 1980; Hammer, 1984). In the GISP2 ice core in Greenland, elevated SO_4^{2-} concentrations spanning three to six annual layers fall at

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938±4 AD (Zielinski et al., 1994, 1995). The similarity in the chemical composition of basaltic glass shards found in that section of the GISP2 core compared to proximal glass from the Eldgjá eruption verifies the presence of Eldgjá debris (Zielinski et al., 1995). Signals of the Eldgjá eruption probably also exist in Greenland ice cores including Dye 3, Summit and Camp Century (Herron, 1982; Hammer et al., 1984; Johnson et al., 1992).

Stothers (1998, 2002) synthesized the relevant European historical evidence and deduced that the Eldgjá eruption started about 934 AD and would have lasted several years. Detailed studies of the tephra deposits indicated that the eruption featured at least eight distinct episodes and might have lasted for 3–8 years (Thordarson et al., 2001). There were, volcanologically, two major phases of the long lasting Eldgjá eruption: one phase occurred in 934 AD and another in 939 AD (Thordarson et al., 2001). This agreed well with the climatic cooling process indicated by European historical records (Stothers, 1998).

The total volume of erupted magma of the Eldgjá eruption exceeded $\sim$19.6 km^3. It carried 232 Mt of SO_2 to the surface, where vent and lava flow degassing released 219 Mt into the atmosphere (Thordarson et al., 2001). Approximately 79% of the original sulfur mass was released at the vents, indicating $\sim$185 Mt SO_2 were discharged into the atmosphere above the Eldgjá fissures and carried aloft by the eruption columns to upper tropospheric and lower stratospheric altitudes ($\sim$15 km). Consequently, only $\sim$35 Mt SO_2 escaped from the lava into the lower troposphere (Thordarson et al., 2001). The atmospheric SO_2 mass loading of the Eldgjá eruption exceeded that of 1600 AD Huaynaputina eruption by a factor of over 4 (De Silva and Zielinski, 1998), and exceeded that of 1783 AD Lakagígar (Laki) eruption and 1815 AD Tambora eruption by factors of 1.8 and 2.0–2.8 respectively (Clausen and Hammer, 1988; Harington, 1992; Thordarson et al., 1996, 2001).

Before looking into the climatic impact of the Eldgjá eruption, we examine several famous cases of volcanic climatic cooling. After the 1600 AD Huaynaputina eruption, Europe experienced a chilly summer in 1601 AD (Pyle, 1998). Pattern of tree growth across the Northern Hemisphere confirms that the most severe short-term Northern Hemisphere cooling event of the past 600 years occurred in 1601 AD (Briffa, et al., 1998). Following the 1815 AD Tambora eruption, 1816 AD became known as 'the year without a summer' according to historical reports and tree ring data, and the summers of 1817 and 1818 AD were also very cold (Stothers, 1984; Harington, 1992; Briffa et al., 1998; Pyle, 1998).

The temperature response of the Iceland's Lakagígar (Laki) eruption, an analogue of Eldgjá, was comparably complex (Pyle, 1998; Stothers, 1999; Jacoby et al., 1999; Highwood and Stevenson, 2003). Historical records suggested that the summer of 1783 AD was dry and hot in southwestern, western, and northwestern Europe (Fiacco et al., 1994; Grattan and Brayshay, 1995; Stothers, 1996; Demarée and Ogilvie, 2001; Highwood and Stevenson, 2003). However, tree ring data indicated 1783 AD, year of the Lakagígar (Laki) eruption, as the coldest summer in northwest Alaska for at least 400 years, probably for more than 900 years (Jacoby et al., 1999). Late 18th-century temperature records of Europe and North America indicated that in 1784–1786 AD, the years immediately following the Lakagígar (Laki) eruption, temperatures were about −1.3 to −1.4 °C below the 31 yr mean of 1768–1798 AD (Fiacco et al., 1994).

Considering the magnitude of the Eldgjá eruption, it should have the potential to cool off the northern troposphere by injecting large quantities of sulfur dioxide gas into the stratosphere (Devine et al., 1984; Stothers et al., 1986; Rampino et al., 1984, 1988).

2. European Historical Evidence of the Climatic Cooling Following the Eldgjá Eruption

Notwithstanding the poor record keeping endemic to the Dark Ages in Europe, fragmental documentation of unusual weather exists (Stothers, 1998; Thordarson et al., 2001). Extant European historical documents have been successfully used to trace the eruption's possible climatic impact (Table I).

These records indicate occurrences of unusual cold weather in Europe and the Middle East in 934–935 AD and 939–940 AD. Probably, climatic cooling following the Eldgjá eruption featured two stages in Europe and the Middle East, that is, 934–935 AD and 939–940 AD respectively.

TABLE I

Historical evidence of the climatic cooling in Europe and the Middle East following the Eldgjá Eruption. (Revised from Thordarson et al. (2001). Data are from Stothers (1998))

Date	Location	Descriptions
The winter of 934–935 AD	Baghdad, Iraq	Unaccustomed snowfall.
	Constantinople, Turkey	On Dec. 25, 934 AD, intolerably cold weather set in, such that the Earth was frozen over for 120 days. A great famine followed, exceeding those that had ever happened before. Because of this, there was high mortality, as the living were unable to carry out the dead for burial.
	Ireland	A long and bitterly cold winter.
935 AD	Iraq	In the June the weather was chilly and very rainy at Nisibis on the northern Tigris River.
939 AD	Switzerland	A hard year.
The winter of 939–940 AD	Germany	A very harsh winter in northern Germany.
	Ireland	A 'great frost' in Ireland that made lakes and rivers passable struck in probably the same winter all across the island.
	Iraq	The Tigris River is reported to have widely flooded the country in 940 AD. This implies abnormally heavy winter rainfalls or snowfalls in the river's upper reaches.

The medieval chroniclers tended to report only the extreme, not the routine, weather events (great storms, cold years, etc. Stothers, 1998). Very severe winters in Western Europe occurred at an average rate of once or twice a century during the period 800–1100 AD (Lamb, 1977; Stothers, 1999). This makes it less likely that the unusually harsh winter immediately following the Eldgjá eruption was a random event (Stothers, 1998, 1999).

3. Tree-Ring and Other Evidences of Climatic Cooling

The climatic cooling following the Eldgjá eruption was widely recorded by tree-ring chronologies. Scuderi (1990) found a severe ring-width minimum at 936 AD in the ring-width chronology from temperature-sensitive upper timberline sites in the Sierra Nevada. Abrupt negative departures in reconstructed summer temperatures at 936 AD and 940 AD are evident in Fennoscandian dendro-chronologies (Briffa et al., 1990, 1992). Briffa (2000) reconstructed northern 'high-latitude' temperature changes over the last 2000 years utilizing temperature-sensitive tree-ring chronologies with extensive coverage, unambiguous climatic responses and rigid dating control. In the reconstruction, a significant negative growth signature existed at 940 AD. In the warm season (prior November to current April) temperature reconstruction since 1600 BC of Lake Johnston (Australia), a very significant cold spell peaked in 942 AD exists (Cook et al., 2000). D'Arrigo et al. (2001) presented frost ring evidence at 938 AD in Solongotyn Davaa, Mongolia. In the 752–1992 AD summer temperature reconstruction from varved sediments of Donard Lake in the Baffin Island (Canada), temperature declines seem to center around 935 AD and 940 AD (Moore et al., 2001).

4. Climatic Cooling in China Following the Eldgjá Eruption

While Europe was in the Dark Ages, the Empire of Tang (618–907 AD) collapsed in 907 AD in China. The following half-century is called the Five Dynasties (907–959 AD). In this period, the Yellow River Basin in northern China was in the reign of five successive dynasties, while ten independent states existed in southern China. At the same time, the Khitan (Liao) Empire reigned in Mongolia and the northeast of China over 907–1125 AD (Figure 1).

The ancient Chinese chroniclers tended to chronicle events dynasty by dynasty. We searched the historical sources in the time period of 923–960 AD, which included four successive dynasties: the Later Tang Dynasty (923–936 AD), the Later Jin Dynasty (936–947 AD), the Later Han Dynasty (947–950 AD) and the Later Zhou Dynasty (950–960 AD). For unknown historical reasons, no relevant materials in the period 955–960 AD were found. So, we only obtained the materials in the time period of 923–954 AD. For the historical sources of the indepen-

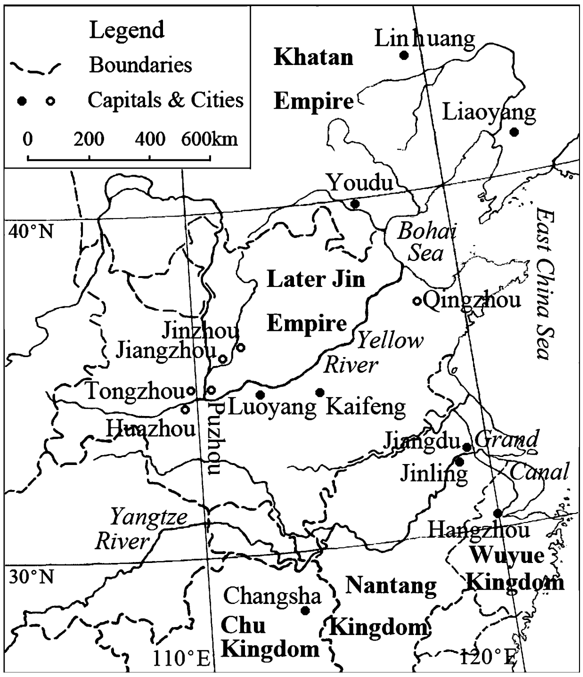

Figure 1. Schematic map showing the Chinese locations mentioned in this paper.

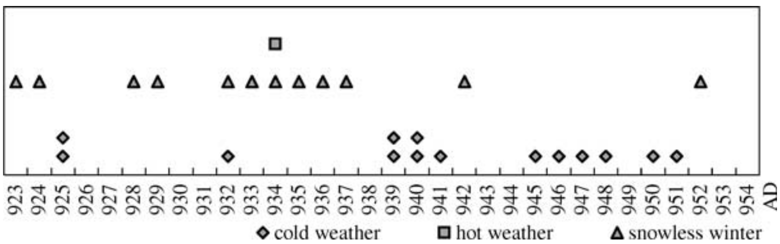

Figure 2. The ancient Chinese weather records during 923–954 AD.

dent states in southern China and the Khitan Empire, we also searched those of 923–954 AD.

All the historical sources about the cold and hot weather during 923–954 AD were gathered (Figure 2). Among which, sources about cold weather were found to be much more abundant that those of hot weather (Table II). Only one item on hot weather was found, i.e. the scorching summer of 934 AD. Besides that, snowless winters in the Luoyang-Kaifeng Area (34–35°N, 112–115°E), where all of the five dynasties established their capital cities, were found to be in especial detail.

Like the medieval European chroniclers, the Chinese chroniclers also tended to report the unusual weather events. We were not able to translate this classical Chinese literature into English word for word. We have to paraphrase them on the premise of interpreting their climatic information correctly.

TABLE II
Chinese historical sources about the cold weather occurrence during 923–954 AD

Date (AD)	Location	Descriptions
Mar. 10, 925	Near Luoyang	The laborers on the embankments of the Yellow River fled away because it snowed and became bitterly cold (*Jiuwudaishi*, Vol. 32).
Winter of 925–926	Near Luoyang	During Jan. 7–11, 926 AD, an emperor went hunting on the outskirts of Luoyang. The attendants died of heavy snow and harsh coldness on the way (*Jiuwudaishi,* Vol. 33).
Apr. 16, 932	Hangzhou	This night, it snowed heavily (*Shiguochunqiu,* Vol. 77).
Jul. 26, 939	The southeast of the Inner Mongolia Plateau (40–44°N, 113–123°E)	It snowed today (*Liaoshi*, Vol. 4).
Winter of 939–940	Kaifeng	On Jan. 12, 940 AD, the ceremony of *Ruge* (a regular ceremony chaired by an emperor on the first day of a month of the Chinese calendar) had to be canceled because of heavy snow. On Feb. 1, the emperor said to his officials that it had snowed heavily over fifty days without any sign of ceasing. He had ordered to pray in all of the temples, but it had produced no effect. He suspected that he had done something wrong and annoyed the God. Then he ordered relief for the people with charcoal and food (*Jiuwudaishi*, Vol. 78; *Cefuyuangui*, Vol. 145).
Winter of 940–941	Near Jinling (32.1°N, 118.8°E) and Jiangdu (32.4°N, 119.4°E)	On Nov. 20, 940 AD, the king of the Nantang Kingdom left Jinling (modern Nanjing) for Jiangdu (modern Yangzhou) and arrived on Nov. 24. He wished to live there, but the Grand Canal nearby was frozen so that goods could not be shipped to Jiangdu. Finally he had to go back, and reached Jinling on Jan. 5, 941 AD (*Zizhitongjian*, Vol. 282).
	Near Qingzhou (36.7°N, 118.5°E)	On Feb. 3, 941 AD, an official of Qingzhou reported to the emperor that the sea there (the Bohai Sea, *i.e.* Gulf of Chihli) froze scores of kilometers off shore (*Jiuwudaishi*, Vol. 79).
Winter of 941–942	Near Kaifeng	It was very cold in this winter (*Jiuwudaishi*, Vol. 98; *Xinwudaishi*, Vol. 39).
Apr. 4, 945	Kaifeng	It snowed heavily (*Jiuwudaishi*, Vol. 83).
Winter of 946–947	Near Kaifeng	Jan. 31, 947 AD, It snowed over ten days, and was freezing cold (*Jiuwudaishi*, Vol. 86; *Xinwudaishi,* Vol. 17; *Zizhitongjian*, Vol. 286).
Winter of 947–948	Kaifeng	Dec. 16, 25, 947 AD, Jan. 6, 948 AD, rime (*Jiuwudaishi*, Vol. 100; *Xinwudaishi*, Vol. 59).
Oct. 24, 948	Kaifeng	It snowed in Kaifeng (*Jiuwudaishi*, Vol. 101).

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TABLE II
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Date (AD)	Location	Descriptions
Winter of 950–951	Near Changsha (28.2°N, 113.0°E)	This winter, it snowed heavily; two armies had a long waiting for a decisive battle (*Zizhitongjian*, Vol. 289).
Winter of 951–952	Near Jinzhou and Jiangzhou (35–37°N, 111–112°E)	This winter, it was snowy and cold (*Jiuwudaishi*, Vol. 135; *Xinwudaishi*, Vol. 70).

*The longitude and latitude denote approximate geographic coordinates. A winter denotes current December, next January and February.

The ancient Chinese chroniclers usually related issues following strict chronological order and noted the dates clearly; therefore these Chinese historical sources shared a great advantage of accurate dating. The ancient Chinese people used a unique lunar calendar. We have transformed the Chinese calendar dates into AD dates.

It is note worthy that winters with low/high snowfall are usually mild/cold in the Luoyang-Kaifeng Area. Winter snowfall seemed to be a possible genuine representation of temperature. The correlation between the mean temperature and number of total snowy days in winters (current December to next February) were examined. In the Luoyang-Kaifeng area, the longest available series of daily meteorological records is that of the Bo'ai Station (35.1°N, 113.0°E). The correlation coefficient (r) of Bo'ai from 1956 to 1974 was -0.7256 ($N = 19$). It is statistically significant ($P < 0.001$). In fact, the correlations between the mean temperature and total snowy days in winter have been proved to be significant in nearby regions such as Xi'an (34°N, 109°E. Hao et al., 2003) and Hefei (31.9°N, 117.3°E. Zhou et al., 1994).

From the winter of 923–924 AD to that of 931–932 AD, snowless (and possibly also mild) winters probably appeared 4 times (Table III). From the winter of 938–939 AD to that of 952–953 AD, snowless winters seldom appeared. But from the winter of 932–933 AD to that of 937–938 AD, every winter appeared to be snowless. Therefore, winter warming possibly occurred following the Eldgjá eruption until 938 AD. This complicated the climatic impact of the Eldgjá eruption but resembled warm winters following some major eruptions (Robock and Mao, 1992; Kirchner et al., 1999).

The snow in the July of 939 AD and the extremely snowy winter of 939–940 AD would be the two most extremely cold anomalies during 923–954 AD. The snow in the July of 939 AD was the only record of snow in high summer in that area during the Khitan Dynasty (907–1125 AD) (Deng, 1998). The snowy winter of 939–940 AD was also extreme. Modern meteorological records show that in Bo'ai (35.1°N, 113.0°E), a station close to Kaifeng (34.7°N, 114.4°E), the maximum total snowy

TABLE III

Chinese historical sources about the possible snowless winters in the Luoyang-Kaifeng Area during 923–954 AD

Winter (AD)	Descriptions
923–924	On Jan. 29, 924 AD, an emperor dispatched his officials to pray for snow because it rarely snowed in this winter (*Cefuyuangui*, Vol. 145).
924–925	On Jan. 11, 925 AD, an emperor dispatched his officials to pray for snow because the snowfall was a little low in this winter. On Jan. 18, 925 AD, the emperor went to a temple and prayed for snow himself (*Jiuwudaishi*, Vol. 32; *Cefuyuangui*, Vol. 145).
928–929	Sometime between Jan. 14 and Feb. 12, 929 AD, an emperor dispatched his officials to pray for snow, because it rarely snowed in this winter (*Cefuyuangui*, Vol. 145).
929–930	On Jan. 13, 930 AD, an official reported to an emperor that it did not snow in this winter, so it was necessary to pray for snow (*Cefuyuangui*, Vol. 145).
	On Feb. 12, 930 AD, an emperor asked his officials why it rarely snowed in this winter (*Jiuwudaishi*, Vol. 41).
932–933	This winter, it rarely snowed (*Jiuwudaishi*, Vol. 43).
933–934	This winter, it rarely snowed (*Cefuyuangui*, Vol. 145).
934–935	On Dec. 23, 934 AD, an emperor dispatched his officials to pray for snow because it rarely snowed in this winter (*Cefuyuangui*, Vol. 145).
	On Jan. 29, 935 AD, an emperor dispatched his officials to pray for snow because it rarely snowed in this winter. Two days later, the emperor went to a temple and prayed for snow himself (*Jiuwudaishi*, Vol. 46; *Cefuyuangui*, Vol. 145).
935–936	On Jan 19, 936 AD, an emperor said that the climate was abnormal; it rarely snowed in this winter. Then he dispatched his officials to pray for snow (*Cefuyuangui*, Vol. 145).
	On Feb 3, 936 AD, an emperor went to a temple and prayed for snow because it rarely snowed in this winter (*Jiuwudaishi*, Vol. 48; *Cefuyuangui*, Vol. 145).
936–937	On Jan. 21, 937 AD, an emperor dispatched his officials to pray for snow because it rarely snowed in this winter (*Jiuwudaishi*, Vol. 76; *Cefuyuangui*, Vol. 145).
937–938	Jan. 29, 938 AD, an emperor went to a temple and prayed for snow (*Jiuwudaishi*, Vol. 76; *Cefuyuangui*, Vol. 145).
942–943	On Dec. 28, 942 AD, an emperor dispatched his officials to pray for snow (*Jiuwudaishi*, Vol. 81).
952–953	This winter, it rarely snowed (*Jiuwudaishi*, Vol. 112).
	On Feb. 2, 953 AD, an emperor dispatched his officials to pray for snow because it rarely snowed in this winter (*Cefuyuangui*, Vol. 145).

days in winter (current December to next February) is 17 days during 1956–1973 AD. That of Xi'an (34°N, 109°E. Hao et al., 2003) is 24 days (1951–1996 AD). According to the correlation between the mean temperature and total snowy days in winter, the winter of 939-940 AD should also be extremely cold.

The snowy winter of 939–940 AD in China agreed well with the widespread hard winter in Europe and the Middle East. Together with the very cold winters of 940–941 AD and 941–942 AD, it seemed that a cold spell existed in 939–942 AD in China. This also agreed well with the tree ring evidence and the European historical evidence.

5. The Scorching Summer of 934 AD

The only known record of unusual hot weather during 923–954 AD was the extremely hot summer of 934 AD. We read of an extremely dry and hot summer in 934 AD in the official chronicle, *Jiuwudaishi* (Vol. 46). Accordingly, it was scorching hot in the sixth month of the year (Jul. 15–Aug. 12, 934 AD); over a hundred people died of the intense heat in the capital (Luoyang. 34.7°N, 112.4°E).

Cefuyuangui (Vol. 145) recorded this event in detail, and the text follows. The capital (Luoyang) was extremely hot due to a long drought. Up to Jul. 21, 934 AD, tens of people had died of the intense heat in the capital (Luoyang). From Jul. 21 to Jul. 27, 934 AD, hundreds of people died of the extremely hot weather. There were corpses everywhere on roads. The contemporary emperor, *Congke Li*, dispatched his officials to pray for rain until it rained on Jul. 27, 934 AD. Again, on Aug. 13, 934 AD, the emperor dispatched officials to pray for rain. On Aug. 18, 934 AD, the emperor went to pray for rain himself.

Worse, when the autumn came, it rained too much. The authority prayed for sun on Sept. 27, Oct. 8 and Oct.12 (*Cefuyuangui*, Vol. 145; *Jiuwudaishi* Vol. 46). When winter came, it rarely snowed (Table III). Severe drought swept through the Yellow River Basin. People were forced to flee their homes (*Zizhitongjian*, Vol. 279). The area near Tongzhou, Huazhou, Puzhou and Jiangzhou (34–36°N, 109–112°E) was especially hard hit.

In 1783 AD, the year of the Lakagígar (Laki) eruption, which resembled the Eldgjá eruption greatly, southwestern, western and northern Europe also experienced a dry and hot summer (Fiacco et al., 1994; Stothers, 1999; Highwood and Stevenson, 2003). The Eldgjá eruption seemed to be a potential cause of the scorching summer of 934 AD. The climatic extremes in 934 AD as well as those of 939 AD were compatible with the conjecture of Thordarson et al. (2001) that the prolonged Eldgjá eruption featured two major explosive episodes and high lava output in 934 AD and 939 AD respectively.

6. Severe Drought and Plague of Locusts in 942–943 AD

The most terrible catastrophe in China following the eruption broke out in 942 AD. Unprecedented drought and plague of locusts with widespread famine swept through the Later Jin Empire in 942–943 AD.

Historical accounts about this unprecedented drought and plague of locusts are startling. Crop failure and famine widely spread from the Yellow River Basin to the Yangtze River Basin and affected an area as vast as several million square kilometers (*Cefuyuangui* Vol. 26; *Zizhitongjian* Vol. 283). The mortalities reached 70 to 80% of the total population in some areas; over several hundred thousand people starved to death; innumerable people were forced to flee their homes (*Cefuyuangui* Vol. 26, 145; *Jiuwudaishi* Vol. 80, 81, 82, 141; *Xinwudaishi* Vol. 8, 9; *Zizhitongjian* Vol. 283; *Shiguochunqiu* Vol. 15). The vitality of Later Jin Empire was fatally sapped; from then on, the Later Jin Empire was withering away (*Jiuwudaishi* Vol. 141).

After the catastrophe, Emperor of the Later Jin Empire, *Chonggui Shi*, issued an imperial edict in 944 AD. The general idea is that these years natural disasters were extremely severe; People suffered severe famine and died of hunger everywhere. The fields were strewn with the bodies of the starved. The empire was deep in national crisis and had gloomy prospects (*Cefuyuangui* Vol. 145). Two years later, the Later Jin Empire was conquered by the Khitan Empire (*Zizhitongjian* Vol. 285; *Xinwudaishi* Vol. 9; *Jiuwudaishi* Vol. 85). Successive years of famine had been considered as one of the main causes of the collapse of the Later Jin Empire (*Jiuwudaishi* Vol. 85).

It is not definite whether the 942–943 AD drought and plague of locusts was caused by the Eldgjá eruption. However, we should note that after the Lakagígar (Laki) eruption, China also experienced severe drought and plague of locusts in 1784–1787 (Central Meteorological Bureau of China, 1981; Liu, 1994; Zhang, 2000). The Lakagígar (Laki) eruption lasted about eight months, whereas the Eldgjá eruption lasted 3–8 years. The atmospheric SO_2 mass loading of the Eldgjá eruption exceeded that of the Lakagígar (Laki) eruption by a factor of 2.0–2.8 (Thordarson et al., 1996, 2001). Thus climate forcing would be much more prolonged, and hence stronger, in the case of Eldgjá. In fact, this kind of extraordinary persistence is, more the rule than the exception after very large volcanic eruptions (Stothers, 1998, 1999).

7. Other Volcanic Eruptions that Occurred Around the Same Time Period as the Eldgjá Eruption

Did any other volcanic eruptions occur around the same time period as the Eldgjá eruption? As far as we know, a minor eruption of Fuji Volcano in Japan occurred on Dec. 18, 937 AD. This eruption seemed to be too small to have global climatic impact, as the erupted magma is less than 0.1% of that of Eldgjá (Koyama, 1998; Hayakawa, 1999). In 945 AD, Kirishimayama Volcano in Japan possibly erupted, but its magnitude remains unclear (*Japanese chronological table of natural disasters*).

Hayakawa and Koyama (1998) suggested that the Baitoushan (Tianchi) Volcano on the Sino-Korea border had erupted explosively in 946–947 AD. However, a detailed radiocarbon dating study and the discovery of the Korean historical accounts obtained a date of 1199–1200 AD (Liu et al., 1997; Cui et al., 2000). But some unidentified volcano might erupt in 946–947 AD near Japan.

Some other volcanoes maybe erupted around the same time period as the Eldgjá eruption but with dating uncertainties. These eruptions include the mid-tenth century Tolbachick and Bezymianny eruptions in Kamchatka, the circa 950 AD eruption of Ceboruco in Mexico and the tenth century eruption of Oshima, Japan (Zielinski et al., 1995; Hayakawa, 1996).

The glaciochemical studies and the evaluation of the tephra in the GISP2 ice core carried out by Zielinski et al. (1995) did not completely exclude the possibility that another eruption in the 930's contributed to the Eldgjá signal, but their results was more easily explained by the lack of this additional eruption (Zielinski et al., 1995).

We have not found any evidence of other possible causes of the unusual climatic events besides volcanism, but absence of evidence is not evidence of absence. We cannot completely exclude the existence of other potential climatic modifiers.

8. Conclusion

The possible climatic impact in China of Iceland's Eldgjá eruption in the tenth century was investigated utilizing Chinese historical sources.

Successive snowless (and possibly also mild) winters probably followed the Eldgjá eruption in the Luoyang-Kaifeng Area (34–35°N, 112–115°E) until 938 AD. An extremely hot summer occurred in 934 AD and killed hundreds of people in Luoyang (34.7°N, 112.4°E). A sudden temperature drop occurred in 939 AD. In the July of this year, it snowed in the southeast part of the Inner Mongolia Plateau (40–44°N, 113–123°E). This winter, i.e., the winter of 939–940 AD, it was extremely snowy and cold at least in Kaifeng (34.7°N, 114.4°E). The cold spell lasted about 3 years, and probably ended in 942 AD. Then, unprecedented drought and plague of locusts with widespread famine ensued swept through the Yellow River Basin and the Yangtze River Basin in 942–943 AD and caused several hundred thousand deaths.

Climatic cooling in 934–935 AD recorded by European historical sources seems to be not evident in Chinese historical sources. Both in China and in Europe/Middle East, the winter of 939–940 AD was apparently very cold. The reports for these two regions agree. The cold spell of 939–942 AD in China agrees well with the tree ring records and European historical evidence. We thus suggest that hemispheric or global climatic cooling following the Eldgjá eruption probably occurred in 939–942 AD.

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References

Briffa, K. R.: 2000, 'Annual climatic variability in the Holocene: Interpreting the message of ancient trees', *Quaternary Science Reviews* **19**, 87–105.

Briffa, K. R., Bartholin, T. S., Eckstein, D., Jones, P. D., Karlen, W., Schweingruber, F. H., and Zetterberg, P.: 1990, 'A 1,400-year tree-ring record of summer temperatures in Fennoscandia', *Nature* **346**, 434–439.

Briffa, K. R., Jones, P. D., Bartholin, T. S., Eckstein, D., Schweingruber, F. H., Karlen, W., Zetterberg, P., and Eronen, M.: 1992, 'Fennoscandian summers from A.D. 500: Temperature changes on short and long timescales', *Climate Dynamics* **7**, 111–119.

Briffa, K. R., Jones, P. D., Schweingruber, F. H., and Osborn, T. J.: 1998, 'Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years', *Nature* **393**, 450–455.

Central Meteorological Bureau of China: 1981, *Yearly charts of dryness/wetness in China for the last 500-year Period*. Cartographic Press of China, Beijing, pp. 163, 327–328 (in Chinese).

Clausen, H. B. and Hammer, C. U.: 1988, 'The Laki and Tambora eruption as revealed in the Greenland ice cores from 11 locations', *Ann. Glaciol.* **10**, 16–22.

Cook, E. R., Buckley, B. M., D'Arrigo, R. D., and Peterson, M. J.: 2000, 'Warm-season temperatures since 1600 BC reconstructed from Tasmanian tree rings and their relationship to large-scale sea surface temperature anomalies', *Climate Dynamics* **16**, 79–91.

Cui, Z., Jin, D., and Li, N.: 2000, 'The discovery of the historical records of the major 1199–1200 AD eruption of the Tianchi volcano, Mount Changbaishan', *Acta Petrologica Sinica* **16**, 191–193 (in Chinese).

D'Arrigo, R., Jacoby, G., Frank, D., and Pederson, N.: 2001, 'Spatial response to major volcanic events on or about AD 536, 934 and 1258: Frost rings and other dendrochronological evidence form Mongolia', *Climatic Change* **49**, 239–246.

Demarée, G. R., and Ogilvie, A.: 2001, 'Bons Baisers d'Islande: Climatic, environmental and human dimensions impacts of the Lakigígar eruption (1783–1784) in Iceland,' in: Jones et al. (ed.), *History and Climate: Memories of the Future*, Kluwer Academic/Plenum Publishers, pp. 219–246.

Deng, H.: 1998, 'Reconstruction of climatic series of the north Yanshan Mountains region in Liao Dynasty', *Quaternary Sciences* **18**, 46–53 (in Chinese).

De Silva, S. L. and Zielinski, G. A.: 1998, 'Global influence of the AD 1600 eruption of Huaynaputina, Peru', *Nature* **393**, 455–458.

Devine, J. D., Sigurdsson, H., Davis, A. N., and Self, S.: 1984, 'Estimates of sulfur and chlorine yield to the atmosphere from volcanic eruptions and potential climatic Effects', *Journal of Geophysical Research* **89**, 6309–6325.

Fiacco, R. J., Thordarson, T., Germani, M. S., Self, S., Palais, J. M., Whitlow, S., and Grootes, P. M.: 1994, 'Atmospheric aerosol loading and transport due to the 1783-84 Laki eruption in Iceland, interpreted from ash particles and acidity in the GISP2 ice core', *Quaternary Research* **42**, 231–240.

Grattan, J. P. and Brayshay, M.: 1995, 'An amazing and portentous summer: Environmental and social responses in Britain to the 1783 eruption of an Iceland volcano,' *The Geographical Journal* **161**, (Part 2), 125–134.

Grattan, J. P. and Pyatt, F. B.: 1999, 'Volcanic eruptions dry fogs and the European Palaeoenvironmental record: Localized phenomena or hemispheric impacts?', *Global and Planetary Change* **21**, 173–179.

Guo, Z., Liu, J., Sui, S., Liu, Q., He, H., and Ni, Y.: 2001, 'The estimation of volatile (S, F, Cl, H_2O) yield to the atmosphere from Baitou Volcano eruption (1199/1200) in China and its potential climatic effects', *Science in China (Series D)* **31**, 668–676 (in Chinese).

Hammer, C. U.: 1984, 'Traces of Icelandic eruptions in the Greenland ice sheet', *Jokull* **34**, 1–65.

Hammer, C. U., Clausen, H. B., and Dansgaard, W.: 1980, 'Greenland ice sheet evidence of post-glacial volcanism and its climatic impact', *Nature* **288**, 230–235.

Hao, Z., Zheng, J., and Ge, Q.: 2003, 'Climate change and harvest in Xi'an since 1736: The high-resolution data from the archives in the Qing Dynasty', *Acta Geographica Sinica* **58**, 735–742 (in Chinese).

Harington, C. R. (ed.): 1992, *The Year Without Summer: World climate in 1816.* Canadian Museum of Nature, Ottawa, 576 p.

Hayakawa, Y.: 1996, 'Catalog of volcanic eruptions during the past 2000 years in the world', Http: //www.edu.gunma-u.ac.jp/∼hayakawa/catalog/2000w.

Hayakawa, Y. and Koyama, M.: 1998, 'Dates of two major eruptions from Towada and Baitoushan in the 10th century', *Bulletin of the Volcanological Society of Japan* **43**, 403–407 (in Japanese).

Hayakawa, Y.: 1999, 'Catalog of volcanic eruptions during the past 2000 years in Japan', *Journal of Geography* **108**, 472–488 (in Japanese).

Herron, M. M.: 1982, 'Impurity sources of F^-, Cl^-, NO_3^- and SO_4^{2-} in Greenland and Antarctic precipitation', *Journal of Geophysical Research* **87**, 3052–3060.

Highwood, E. J. and Stevenson, D. S.: 2003, 'Atmospheric impact of the 1783–1784 Laki Eruption: Part II, climatic effect of sulphate aerosol', *Atmospheric Chemistry and Physics* **3**, 1177–1189.

Jacoby, G. C., Workman, K. W., and D'Arrigo, R. D.: 1999, 'Laki eruption of 1783, tree rings, and disaster for northwest Alaska Inuit', *Quaternary Science Reviews* **18**, 1365–1371.

Japanese chronological table of natural disasters. Http://www.netlaputa.ne.jp/∼kitsch/tenpen/ihen01.htm (in Japanese).

Johnsen, S. J., Clausen, H. B., Dansgaard, W., Fuhrer, K., Gundestrup, N., Hammer, C. U., Iversen, P., Jouzel, J., Stauffer, B., and Steffensen, J. P.: 1992, 'Irregular glacial interstadials recorded in a new Greenland ice core', *Nature* **359**, 311–313.

Kirchner, I., Stenchikov, G., Graf, H. F., Robock, A., and Antuna, J.: 1999, 'Climate model simulation of winter warming and summer cooling following the 1991 Mount Pinatubo volcanic eruption', *Journal of Geophysical Research* **104**, 19039–19055.

Koyama, M.: 1998, 'Reevaluation of the eruptive history of Fuji Volcano, Japan, mainly based on historical documents', *Bulletin of the Volcanological Society of Japan* **43**, 323–347 (in Japanese).

Lamb, H. H.: 1977, *Climate Present, Past and Future*, Vol. 2, Methuen, London, pp. 566–567.

Larsen, G.: 1979, 'About the age of the Eldgjá lavas', *Náttúrufrædingurinn* **49**, 1–26 (in Icelandic).

Larsen, G.: 1993, 'Tephra layer from the 10th century Eldgjá fissure eruption in South Iceland', *EOS* **74**, 132–133.

Liu, R., Qiu, S., Cai, L., Wei, H., Yang, Q., Xian, Z., Bo, G., and Zhong, J.: 1997, 'The dating research and its significance of the last major eruption of the Tianchi Volcano, Mount Changbaishan', *Science in China (Series D)* **27**, 437–441 (in Chinese).

Liu, Z.: 1994, *Chinese Historical Climatic Change*, Commercial Press, Taipei, pp. 172–174, 200–238 (in Chinese).

McCarthy, D. and Breen, A.: 1997, 'An evaluation of astronomical observations in the Irish annals', *Vistas in Astronomy* **41**, 117–138.

Miller, D. J.: 1989, 'The 10th century eruption of Eldgjá, southern Iceland', *Nord. Volcanol. Inst., Publ.* 8903, Reykjavik, Iceland.

Moore, J. J., Hughen, K. A., Miller, G. H., and Overpeck, J. T.: 2001, 'Little Ice Age recorded in summer temperatures from varved sediments of Donard Lake, Baffin Island, Canada', *Journal of Paleolimnology*, **25**, 503–517.

Ogilvie, A.: 1991, 'Climatic changes in Iceland AD c. 865 to 1598', *Acta Archaeologia* **61**, 233–251.

Pyle, D. M.: 1998, 'How did the summer go?' *Nature* **393**, 415–417.

Rampino, M. R. and Self, S.: 1984, 'Sulfer-rich volcanic eruptions and stratospheric aerosols', *Nature* **310**, 677–679.

Rampino, M. R., Self, S., and Stothers, R. B.: 1988, 'Volcanic winters', *Annual Review of Earth and Planetary Sciences* **16**, 73–99.

Robock, A., and Mao, J.: 1992, 'Winter warming from large volcanic eruptions', *Geophysical Research Letters* **12**, 2405–2408.

Scuderi, L. A.: 1990, 'Tree-ring evidence for climatically effective volcanic eruptions', *Quaternary Research* **34**, 67–85.

Stothers, R. B.: 1984, 'The great Tambora eruption in 1815 and its aftermath', *Science* **224**, 1191–1198.

Sothers, R. B.: 1996. 'The great dry fog of 1783'. *Climatic Change* **32**, 79–89.

Stothers, R. B.: 1998, 'Far reach of the tenth century Eldgjá eruption, Iceland', *Climatic Change* **39**, 715–726.

Stothers, R. B.: 1999, 'Volcanic dry fogs, climatic cooling, and plague pandemics in Europe and the Middle East', *Climatic Change* **42**, 713–723.

Stothers, R. B.: 2002, 'Cloudy and clear stratospheres before A.D. 1000 inferred from written sources', *Journal of Geophysical Research* **107**, No. D23, 4718, doi: 10.1029/2002JD002105, 2002.

Stothers, R. B., Wolf, J. A., Self, S., and Rampino, M. R.: 1986, 'Basaltic fissure eruptions, plume heights, and atmospheric aerosols', *Geophysical Research Letters* **13**, 725–728.

Thordarson, Th., Self, S., Óskarsson, N., and Hulsebosch, T.: 1996: 'Sulfur, chlorine, and fluorine degassing and atmospheric loading by the 1783–1784 AD Laki (Skaftár Fires) eruption in Iceland', *Bulletin of Volcanology* **58**, 205–225.

Thordarson, Th. and Self, S.: 1998, 'The Roza Member, Columbia River Basalt Group: A gigantic lava flow field formed by endogenous processes', *Journal of Geophysical Research* **103** (special volume on solid Earth), 27411–27445.

Thordarson, T., Miller, D. J., Larsen, G., Self, S., and Sigurdsson, H.: 2001, 'New estimates of sulfur degassing and atmospheric mass-loading by the 934 AD Eldgjá eruption, Iceland', *Journal of Volcanology and Geothermal Research* **108**, 33–54.

Zhang, D.: 2000, '1784–1787 drought occurrence over East China in a warm climatic background', *Acta Geographica Sinica* **55**, 106–112 (supplementary issue, in Chinese).

Zhou, Q., Zhang, P., and Wang Z.: 1994, 'Reconstruction of annual winter mean temperature series in Hefei area during 1736–1991 AD', *Acta Geographica Sinica* **49**, 332–337 (in Chinese).

Zielinski, G. A.: 2000, 'Use of paleo-records in determining variability within the volcanism-climate system', *Quaternary Science Reviews* **19**, 417–438.

Zielinski, G. A., Mayewski, P. A., Meeker, L. D., Whitlow, S., Twicker, M. S., Morrison, M., Meese, D., Alley, R. B., and Gow, A. J.: 1994, 'Record of volcanism since 7000 B.C. from the GISP2 Greenland ice core and implications for the volcano-climate system', *Science* **264**, 948–952.

Zielinski, G. A., Germani, M. S., Larsen, G., Baillie, M. G. L., Whitlow, S., Twicker, M. S., and Taylor, K.: 1995, 'Evidence of the Eldgjá (Iceland) eruption in the GISP2 Greenland ice core:

Relationship to eruption processes and climatic conditions in the tenth century', *The Holocene* **5**, 129–140.
Cefuyuangui. This book is an encyclopedia of ancient China (prior to 960 AD). It totals 1000 volumes. The compilation was commenced at imperial request, and it was accomplished in 1013 AD. The chief compiler is *Qinruo Wang*. A quality photocopy was published in 1960 by the Zhonghua Shuju Press.
Jiuwudaishi. This book is an official chronicle of the Five Dynasties (907–960 AD). It totals 150 volumes. The compilation was commenced at imperial request, and it was accomplished in 974 AD. The chief compiler is *Juzheng Xue*. A quality version was published in 1976 by the Zhonghua Shuju Press.
Liaoshi. This book is the official chronicle the Khitan (Liao) Dynasty (907–1125 AD). It totals 116 volumes. The compilation was at imperial request, and it was accomplished in 1344 AD. The chief compiler is *Tuotuo*. A quality version was published in 1974 by the Zhonghua Shuju Press.
Shiguochunqiu. This book is the only chronicle of the ten independent states mostly in south China during the Five Dynasties Period (907–960 AD). It totals 114 volumes. Although it is not the original historical resource of the histories of the ten states, it is based on a wide variety of now lost original historical materials. It was finished compiling in 1669 AD by a famous historian *Rencheng Wu*. A quality version was published in 1983 by the Zhonghua Shuju Press.
Xinwudaishi. This book is another official chronicle of the Five Dynasties (907–960 AD). It totals 74 volumes. The compilation was commenced at imperial request, and it was accomplished in 1053 AD. The chief compiler is *Xiu Ouyang*. A quality version was published in 1974 by the Zhonghua Shuju Press.
Zizhitongjian. This book is a chronicle of China from 403 BC to 959 AD laying emphasis on political history. The compilation was commenced at imperial request, and it was accomplished in 1084 AD. The chief compiler is *Guang Sima.* A quality version was published in 1963 by the Zhonghua Shuju Press.

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