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Review Article

1600 AD Huaynaputina Eruption (Peru), Abrupt Cooling, and Epidemics in China and Korea

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The 1600 AD Huaynaputina eruption in Peru was one of the largest volcanic eruptions in history over the past 2000 years. This study operated on the hypothesis that this event dramatically affected the weather and environment in China and the Korean Peninsula. Over the course of this research the Chinese and Korean historical literatures as well as dendrochronology records were examined. The historical evidence points to the conclusion that the eruption was followed by an abrupt cooling period and epidemic outbreaks in 1601 AD within both China and the Korean Peninsula. These records manifested themselves in unseasonably cold weather resulting in severe killing frosts in northern China in the summer and autumn of 1601 AD. In southern China (Zhejiang and Anhui Provinces and Shanghai Municipality), July was abnormally cold with snow, with an autumn that saw anomalously hot weather. In addition, there was unseasonable snowfall that autumn within Yunnan Province. Widespread disease outbreaks occurred in August, September, and October in northern and southern China. In Korea, the spring and early summer of 1601 AD were unusually cold, and conditions led to further widespread epidemics occurring in August.

1. Introduction

Volcanic eruptions eject massive amounts of gas and ash into the stratosphere and troposphere, reducing solar insolation and resulting in climatic and environmental effects [1–8]. Major volcanic eruptions are capable of affecting short-term climatic change on hemispheric and global scales.

For example, the 1991 AD Pinatubo eruption (Philippines) caused the largest perturbation of the 20th century to the particulate content of the stratosphere; and the radiative influence of the injected particles put an end to several years of globally warm surface temperatures [9, 10]. The 1883 AD Krakatoa eruption (Indonesia) caused dimmed suns and blood red skies in the Northern Hemisphere [11]. Similar disturbances have been reported after other major volcanic eruptions, for example, 1815 AD Tambora eruption and the unidentified eruptions in 1452 AD and circa 626 AD [12–17]. Even 2000 years ago, Plutarch and others surmised that the eruption of Mount Etna in 44 BC dimmed the sun and suggested that the resulting cooling caused crops to fail and even created famine within the Roman Empire and Egypt [6, 18]. Within China, there were dimmed suns, anomalously cold temperatures, crop failures, and famine the following year, in 43 BC, following the 44 BC Etna event [19].

Research on climatic effects using Chinese historical literature, written following major historical volcanic eruptions, has achieved encouraging progress during the past decades. Cao et al. (2012) identified evidence of climatic downturn in China following the 1815 AD Tambora eruption [20]. Fei and Zhou (2006) suggested that abrupt cooling occurred in 939–941 AD in China following the prolonged 934–939 AD Eldgjá eruption, Iceland [21].

The relationship between volcanic eruptions and abrupt cooling is therefore evident, and, recently, increasing attention has focused on the possible cause and effect relationship between volcanic eruptions and precipitation anomalies [22, 23]. It has been suggested that extreme droughts in China could be related to the volcanic eruptions during the past 500 years, because large volcanic eruptions possibly reduced the summer monsoon in East Asia [24, 25].

The epidemic effects of major volcanic eruptions have also long intrigued volcanologists [5, 26–28]. Stothers (1999) examined seven major volcanic eruptions during the past two millennia and found that most of them were followed by several years containing epidemics in Europe and the Middle East [4]. The 1783-1784 AD Laki (Lakigiga) eruption (Iceland) caused dense volcanic dry fog and a significant shift in regional climate systems that are potentially responsible for endemic diseases and high mortality rates seen in England and France during that time [29–31]. However, as a whole, the possible epidemic effects of volcanic eruptions during the past 2000 years have not been discussed in detail, and the mechanisms of contagion and spread of such epidemics have not yet been identified.

In addition, volcanic eruptions result in local disease outbreaks in the vicinity of volcanoes, due to poor hygiene and limited access to drinking water which has been contaminated with volcanic ash and debris. An example of this is following the 1815 AD Tambora volcanic eruption where populations suffering from violent diarrhea were prevalent in the vicinity of the volcano [16]. Another was a regional outbreak of measles that occurred after the eruptions of Mt. Pinatubo in 1991 AD [27].

2. The 1600 AD Huaynaputina Eruption, Peru

Huaynaputina Volcano (16.6°S, 70.9°W) is located in southern Peru, South America. The eruption in 1600 AD was the largest volcanic eruption in South America spanning the past 2000 years [32–36]. The eruption started on February 19, 1600 AD, and lasted until March [32–34, 37]. The economy of southern Peru was severely disrupted and did not recover during most of the 17th century [38, 39].

The sustained eruption column was estimated to be 27–35 km high during the Plinian phase on February 19-20, 1600 AD. The eruption reached a significantly higher altitude than the tropopause, thus making it capable of affecting the atmospheric environment on a global scale [34].

The eruption produced ~70 Mt. of global average stratospheric H_2SO_4 loading, which makes it one of the largest volcanic eruptions in world history over the past two millennia [32, 40]. For example, that of the 1815 Tambora eruption was estimated at 60 Mt. [13], 93–118 Mt. [41], and 108 Mt. [42]. However, stratospheric H_2SO_4 loading of the Huaynaputina eruption was much higher than those of the 1883 Krakatoa (22 Mt. [42]) and 1991 Pinatubo eruptions (30 Mt. [42]).

The volcanic ash from Huaynaputina formed a widespread lobe of ~95,000 km^2 within the 1-cm isopach [34]. Historical accounts indicate significant ash fall in Lima (~850 km north of the volcano) and on a ship 1,000 km off the Peruvian coast [32]. The fine ash and volcanic glass from the eruption were also identified in the South Pole ice core in Antarctica and possibly the GISP2 ice core in Greenland [32, 34, 43, 44].

Signals corresponding to the Huaynaputina eruption were identified in a large number of Antarctic and Greenland ice cores, thus indicating the potential global influence of the eruption. Volcanic acidity peaks corresponding to the Huaynaputina eruption were identified in the Greenland ice cores of Crete [45, 46], GRIP [47], and Summit [48]. Excess SO_4^{2-} peaks corresponding to the Huaynaputina event were also identified in the Greenland ice cores of GISP2 [49], and Antarctic ice cores of Law Dome [50], Plateau Remote [51], SP2001 [52], PS1 (near the Amundsen-Scott Base) [43], Talos Dome (East Antarctica) [53], and Dome Fuji [54].

It is well known that the other three tropical eruptions produced abrupt global cooling [13, 16, 55]. Considering the magnitude of the Huaynaputina eruption, it should have been capable of producing significant global climatic effects. Previous research has revealed that the Huaynaputina eruption was followed by abrupt cooling in many regions in the world [32, 36].

A series of dendroclimatology studies have brought robust evidence to bear to support dramatic abrupt cooling in 1601 AD. Briffa et al. (1998) suggested that the summer of 1601 AD has the potential of being the coldest on record over the past 600 years according to a synthesis of dendrochronological data in northern Eurasia and North America [55]. Scuderi (1990) identified that 1601 AD was abnormally cold according to the temperature-sensitive tree-ring chronologies in the Sierra Nevada [56]. Jones et al. (1995) synthesized a temperature-sensitive network of tree-ring chronologies in North America and Western Europe and suggested that 1601 AD possessed the summer with the most dramatic shifts to unseasonably cold weather patterns [57].

Low temperature was shown around 1600 AD in a ring-width record derived from the June–August Alpine temperature proxy over 951–1527 AD in the Swiss and Austrian Alps [58]. 1601 AD was shown to be extremely cold in the maximum latewood density data from trees at thirteen temperature-sensitive sites along the northern tree line of North America [59]. In the centre of Spain, 1601 AD was the most unfavourable for tree growth, representing the minimum index in the regional chronology [60].

Evidences of dramatic cooling in 1601 AD also exist in the light ring and frost ring chronologies, which record abnormally low temperature in growing seasons. LaMarche Jr. and Hirschboeck (1984) identified a very significant frost ring in 1601 AD in western USA [61]. Filion et al. (1986) and Yamaguchi et al. (1993) identified a significant light ring event in 1601 AD near Bush Lake, Canada [62, 63]. Hantemirov et al. (2004) also identified significant frost and light rings in 1601 AD in the Polar Urals and Yamal Peninsula in northwestern Siberia [64].

The review of historical records corresponds to a dramatic global cooling event from the data collected above, and the historical sources indicate that the summer of 1601 was unusually cold in England and Italy [65]. The winter of 1601 was very severe in Russia, Latvia, and Estonia [36]. In Sweden, record amounts of snow in the winter of 1601 were followed by a rainy spring. The resulting harvest was insufficient to feed the population leading to hunger and disease [66]. Fei and Zhou (2009) investigated the possible climatic effects in northern China following the Huaynaputina eruption. It was discovered that killing frost occurred in 1601 AD and resulted in widespread crop failures throughout the region [67].

Here we investigate the possible climatic and epidemic effects in China and Korea following the 1600 AD Peruvian Huaynaputina eruption. After a careful literature survey, we found that significant abrupt cooling and epidemics occurred mainly in 1601 AD in China and Korea.

3. Materials and Methods

Our study of the possible climatic and epidemic effects of the Huaynaputina eruption in China and Korea is mainly based on the available historical literature. The Chinese and Korean historical texts were examined systematically. A few thousand literary sources were examined, though it turned out that only a small fraction of the historical record contains useful information.

Most of our records were discovered in the Chinese historical local gazetteers (*Di fang zhi*) (Tables 1, 2, and 3). This type of historical source material is unique and very substantial, especially for the history of the Ming (1368–1644 AD) and Qing (1644–1911 AD) dynasties. There are a few thousand extant historical local gazetteers in China [68]. The printed and/or electronic copies are available in the Libraries of Fudan University, the Libraries of the University of Science and Technology of China, and the Shanghai Library.

Some of the records were found in the historical diaries (Table 1). This type of source is particularly valuable as it contains first-hand accounts of climatic and epidemic events.

The climatological and epidemiological records in Korea were discovered in the Annals of the Choson Dynasty (also known as *Choson Wangjo Sillok*) (Table 3), which comprises 25 parts and 1,893 volumes and covers 472 years (1392–1863 AD) of the history of the Choson Dynasty (1392–1910 AD). The annals are in classical Chinese and adopt the Chinese lunar calendar. The compilations were commenced at a specific time following shortly after a king's death by the Office for Annals Compilation of Korea. Therefore the Annals of the Choson Dynasty are highly reliable. The Annals of the King Seonjo (*Seonjo Sillok*) are a part of this record. It comprises 263 volumes and covers the reign of King Seonjo (r. 1567–1608 AD).

In addition, European and American historical records of climatic and epidemic events were also examined; most of these were carried over from relevant previous studies.

Dendrochronology records were examined extensively, in order to give a general scenario of the climatic effects around the world.

Volcanic related signals in ice cores in Greenland and Antarctica were examined carefully in order to verify the potential global influence of the eruption.

4. Abrupt Cooling and Epidemics in 1601 AD in Southern China

The year of 1601 AD witnessed anomalous summer and autumn seasons in southern China. It was cold in the summer and abnormally hot in the autumn. Following the cold summer and hot autumn, widespread disease broke out (Figures 1, 2, and 3; Tables 1, 2, 3, and 4).

The contemporary record of the abnormal weather in the summer and autumn of 1601 AD was found in a book titled Notes on Experience (*Jian wen za ji*) (Figure 1). The book is actually a diary, and it was finished in circa AD 1610 by Le Li, a retired scholar and official. (Le Li, *Jian wen za ji.* This book was written in circa 1610 AD. Here "Le" is the given name, and "Li" is the surname. Similarly hereinafter.) Le Li lived in Wuzhen (a town in Tongxiang County, Zhejiang Province) after retirement; thus the location of most of the events in the book was Wuzhen, including the record of the abnormal weather in 1601 AD.

This record is seen as the most original record of the epidemic and abnormal weather of 1601 AD, whereas similar descriptions of the event are also found in the local gazetteers of a few regions of Zhejiang Province. These regions include Hangzhou and Huzhou Prefectures (modern Hangzhou and Huzhou Cities) and Tongxiang County and Nanxun Town (modern Nanxun County of Huzhou City) (Table 1).

However, the descriptions in the Gazetteer of Shidai County (modern Shitai County, Anhui Province) and Gazetteer of Songjiang Prefecture (modern Songjiang County, Shanghai Municipality) are different from that of the Notes on Experience and should be independent from it. It is also worth noting that these two literatures were written a few decades later than the Notes on Experience (Table 1).

The spatial scale of the epidemics proved to be even larger than anticipated. We identified a plethora of records on epidemic outbreaks in 1601 AD in Anhui, Zhejiang, Fujian, Jiangxi, Hunan, and Guizhou Provinces of southern China (Figure 2). Some records indicated that the epidemics were related to drought and famine, whereas the causal link with abrupt cooling caused by the Huaynaputina event is not very clear (Table 1).

Separate from the above evidence, records were also found which described abrupt cooling which occurred in Kunming City (Yunnan Province). There was an abnormal snowfall in the autumn of 1601 AD in the area (Chengxun Fan and Jiwen Wang, General Gazetteer of Yunnan Province (*Yunnan tong zhi*) (1691), Vol. 28).

5. Abrupt Cooling and Epidemics in 1601 AD in Northern China

5.1. Historical Records. Our previous research has suggested that there were severe killing frosts in the Shanxi and Hebei Provinces in the summer and early autumn of 1601 AD (Fei and Zhou, 2009) [67]. Here we further supplemented our material with the records from Shaanxi, Gansu, and Qinghai Provinces and discovered that epidemics occurred in Shanxi and Shaanxi Provinces in 1601-1602 AD (Figures 1, 2, and 3; Tables 2 and 4). The epidemics in Shanxi and Shaanxi Provinces were possibly caused by a combination of killing frosts and drought. Supporting this information is the appearance of severe killing frosts and great epidemics in northern China in the summer and autumn of 1601 AD (Figures 1, 2, and 3; Tables 2 and 4).

It is noteworthy that killing frosts in the summer and autumn of 1601 AD in northern China were the result of outbreaks of cold waves that usually cover a large area. In some counties with records of epidemics, but without records of frost disasters (e.g., Yangqu, Qingxu Counties, and Shanxi Province), it is highly probable that frost disasters also

Table 1: Historical records of the abrupt cooling and epidemics in southern China in 1601 AD.

County, province	Description	Source
†*Wuzhen, Hangzhou, Huzhou, Tongxiang, and Nanxun, Zhejiang Province	Wanli Reign Period, 29th year (February 3, 1601 AD–January 22, 1602 AD): it was chilly in the 6th month (June 30–July 28, 1601 AD). People took on double layered and cotton clothes. It was said that there was a heavy snow in the mountains of the Fuyang County, and the county sheriff took a tank of snow and submitted it to the province governor. It was also said that there was significant snowfall in the mountains of Hangzhou Prefecture. It turned hot in the 7th month (July 29–August 27, 1601 AD) and was still hot in the 8-9th months (August 28–October 25, 1601 AD). People even soaked in water in order to keep cool. Most of the families were hit by epidemics.	Le Li, Notes on Experience (*Jian wen za ji*) (circa 1610). Similar records are found in local gazetteers, including ① Yun Zheng et al., Gazetteer of the Hangzhou Prefecture (*Hangzhou fu zhi*) (1779), Vol. 56, ② Yuanhan Zong and Shichang Guo, Gazetteer of the Huzhou Prefecture (*Huzhou fu zhi*) (1874), Vol.44, ③ Chen Yan, Gazetteer of the Tongxiang County (*Tongxiang xian zhi*) (1887), Vol. 20., ④ Rizhen Wang, Gazetteer of the Nanxun Town (*Nanxun zhen zhi*) (1859), Vol. 19.
†*Shidai County (modern Shitai County, Anhui Province)	29th year (of the Wanli Reign Period). . ., in the 6th month of this summer (June 30–July 28, 1601 AD); it was very cold. All the people took on cotton coats. Snow fell and piled up in the remote mountains. It turned hot in the 7th month (July 29–August 27, 1601 AD) and was still hot in the 8th month (August 28–September 25, 1601 AD). Most of the people fell ill in the Wu and Yue areas (including Zhejiang Province, Shanghai Municipality, and southern Jiangsu Province) and the areas to the north and south of the Yangtze River.	Zizhuang Yao and Tiyuan Zhou, Gazetteer of the Shidai County (*Shidai xian zhi*) (1675), Vol. 2.
†Songjiang county, Shanghai Municipality	Xinchou year (i.e., the 29th year of the Wanli Reign Period) 6th month, 17th day (July 16, 1601 AD): it poured all day and all night. A flood destroyed the crops in the northern area of the county. It suddenly turned freezing cold. It was said that there was more than one *chi* (1 *chi* ≈ 0.3 m) of snow in Fuyang County, Hangzhou Prefecture.	Yuegong Fang and Jiru Chen, Gazetteer of the Songjiang Prefecture (*Songjiang fu zhi*) (1630), Vol. 47.
†Kunming, Yunnan	9th month (September 26–October 25, 1601 AD): there was a heavy snowfall.	Chengxun Fan and Jiwen Wang, General Gazetteer of Yunnan Province (*Yunnan tong zhi*) (1691), Vol. 28.
*Ninggang, Jiangxi	A great epidemic. Nearly half of the people were killed.	Yuda Chen, Gazetteer of Yongning County (*Yongning xian zhi*) (1683), Vol. 1.
*Xingguo, Jiangxi	A great drought and epidemic.	Shangyuan Zhang, Gazetteer of the Lianzhui County (*Lianshui zhi lin*) (1711), Vol. 15.
*Shicheng, Jiangxi	A great epidemic.	Yaojing Guo, Gazetteer of Shicheng County (*Shicheng xian zhi*) (1660), Vol. 8.
*Dayu, Jiangxi	There was a great epidemic in this year.	Yinchang Chen, Gazetteer of the Dayu County (*Dayu xian zhi*) (1874), Vol. 24.
*Nankang, Jiangxi	4th month (May 2–May 31, 1601 AD): a great epidemic.	Ziyun Qiu, Gazetteer of the Nankang County (*Nankang xian zhi*) (1936), Vol. 10.
*Liancheng, Fujian	A great epidemic.	Shijin Du, Gazetteer of the Liancheng County (*Liancheng xian zhi*) (1666), Vol. 1.
*Xinhua, Hunan	When autumn came, there were drought and epidemic.	Xiaolong Yu and Wenzhu Yang, Gazetteer of the Xinhua County (*Xinhua xian zhi*) (1668), Vol. 11.
*Guizhou Province	4th month (May 2–May 31, 1601 AD): no rain. 5th month (June 1–June 29th, 1601 AD): a great famine. . . 7th month (July 29th–August 27th, 1601 AD): a great epidemic.	Shenji Cao and Xun Pan, General Gazetteer of Guizhou Province (*Guizhou tong zhi*) (1673), Vol. 27.

†Counties with abrupt cooling. *Counties with epidemics.

TABLE 2: Historical records of the abrupt cooling and epidemics in northern China in 1601 AD.

County, province	Description[1]	Source
†*Xincai, Henan	Since the 9th day of the 1st month (of the 29th year of the Wanli Reign Period, February 11, 1601 AD), it snowed heavily for 40 days, and the melted snow destroyed the wheat. The following epidemic killed innumerable people, and all the farmlands were deserted.	Hongxian Tan and Minfu Lü, Gazetteer of the Xincai County (*Xincai xian zhi*) (1691), Vol. 7.
†*Dingxiang, Shanxi	It did not rain in summer and autumn. There was an epidemic that killed numerous people. Even family members and relatives did not dare to have intimate physical contact with each other. There was a drought and a frost disaster that caused crop failure, and prices of crops rose to extraordinary levels.	Shijiong Wang and Hanyuan Niu, Gazetteer of the Dingxiang County (*Dingxiang xian zhi*) (1712), Vol. 7.
†*Lishi, Shanxi	A frost completely destroyed the crops (29th year of the Wanli Reign Period, 1601 AD). A great epidemic came in the spring of the 30th year of the Wanli Reign Period (1602 AD) and killed a great number of people.	Daoyi Wang, Gazetteer of the Fenzhou Prefecture (*Fenzhou fu zhi*) (1611), Vol. 16.
†Huai'an, Hebei	There was a snow in the summer.	Dakun Yang and Jizeng Qian, A Gazetteer of the Huai'an County (*Huai'an xian zhi*) (1741), Vol. 22.
†Xuanhua, Hebei	There was a frost in the summer.	Tan Chen, A Gazetteer of the Xuanhua County (*Xuanhua xian zhi*) (1711), Vol. 5.
†Chicheng, Hebei	There was a frost in the summer.	Tun Zhang, A Gazetteer of the Longmen County (*Longmen xian zhi*) (1712), Vol. 2.
†Yuxian, Hebei	There was a frost in the summer.	Ying Li, A Gazetteer of the Yu Prefecture (*Yu zhou zhi*) (1659), Vol. 1.
†Yangyuan, Hebei	There was a frost in the summer.	Chongguo Zhang, A Gazetteer of the Xining County (*Xining xian zhi*) (1712), Vol. 1.
†Laiyuan, Shanxi	A frost totally destroyed the crops.	Shizhi Liu and Wenyao Zhao, A Gazetteer of the Guangchang County (*Guangchang xian zhi*) (1630).
†Guangling, Shanxi	There was a frost in the summer.	Huandou Li and Wuding Wang, A Gazetteer of the Guangling County (*Guangling xian zhi*) (1685), Vol. 1.
†Xinzhou, Shanxi	A frost destroyed the crops in the 8th month (August 28–September 25th, 1601 AD).	Renlong Zhou and Gusui Dou, A Gazetteer of the Xin Prefecture (*Xin zhou zhi*) (1747), Vol. 4.
†Jingle, Shanxi	A wind and frost destroyed the crop on the 25th day of the 7th month (August 22, 1601 AD). There was a great famine, and people even resorted to cannibalism.	Tuchang Huang, A Gazetteer of the Jingle County (*Jingle xian zhi*) (1695), Vol. 4.
†Baode, Shanxi	A killing frost completely destroyed the crops on the 26th day of the 7th month (August 23, 1601 AD). The markets in the city were closed for nine days. People fled away and sold their children. There were victims of starvation everywhere. People were in such a weakened state they even did not care about the deaths of members of their own family.	Kechang Wang and Menggao Yin, A Gazetteer of the Baode Prefecture (*Baode zhou zhi*) (1710), Vol. 3.
†Shenchi, Shanxi	A frost destroyed the crops in the 7th month (July 29–August 27th, 1601 AD). A great famine occurred in the Jingle and Shenchi counties.	Changqing Cui et al., A Gazetteer of the Shenchi County (*Shenchi xian zhi*) (1880), Vol. 9.
†Zuoquan, Shanxi	A frost killed the crops in the 8th month (August 28–September 25, 1601 AD).	Tianxi Yang and Weitai Hou, A Gazetteer of the Liao Prefecture (*Liao zhou zhi*) (1673)., Vol. 7.
†Linxian, Shanxi	There was a bitter early frost on the 9th day of the 8th month (September 5, 1601 AD). The crops were destroyed. There was a great famine. People ate tree barks and grass roots.	Daoyi Wang, et al., A Gazetteer of the Fenzhou Prefecture (*Fenzhou fu zhi*) (1611), Vol. 16.

Table 2: Continued.

County, province	Description[1]	Source
†Lishi, Shanxi	A frost destroyed crops in Yongning County. There was a great famine.	Daoyi Wang, et al., A Gazetteer of the Fenzhou Prefecture (*Fenzhou fu zhi*) (1611), Vol. 16.
†Xixian, Shanxi	During the last ten days of the 10th month (November 15–November 24, 1601 AD), it snowed heavily. The snow was three *chi* deep. It was considered to be a propitious omen. . .. There was a frost in the 8th month (August 28–September 25th, 1601 AD) that reduced the harvest.	Yikai Qian, A Gazetteer of the Xi Prefecture (*Xi zhou zhi*) (1710), Vol. 24.
†Yulin, Shaanxi	A frost destroyed the crops in autumn.	Jicong Tan, Gazetteer of the Yansui Fort (*Yansui zhen zhi*) (1673), Vol. 5.
†Yulin, Shaanxi	There were successive snow and hail events in the 8th month (August 28–September 25, 1601 AD), and the crops were totally destroyed.	Tingyu Zhang and Zhaonan Qi, Continuation of Comprehensive Study of Documents (*Xu wenxian tong kao*) (1767), Vol. 223.
†Mizhi, Shaanxi	A frost destroyed the crops in the 7th month (July 29–August 27, 1601 AD).	Yangqi Ning, Gazetteer of Mizhi County (*Mizhi xian zhi*) (1681), Vol. 1.
†Yan'an, Shaanxi	A frost destroyed the crops in the autumn.	Hui Hong, Revised Gazetteer of Yan'an Prefecture (*Chongxiu Yan'an fu zhi*) (1802), Vol. 6.
†Ningxian, Gansu	There was a frost in the 7th month (July 29–August 27, 1601 AD).	Benzhi Zhao, New Gazetteer of the Qingyang Prefecture (*Xinxiu Qingyang fu zhi*) (1761), Vol. 37.
*Yangqu, Shanxi	There were epidemics and great famines in the 29th and 30th years of the Wanli Reign Period (i.e., 1601-1602 AD).	Mengxiong Dai, Fangtai Li and Fangfan Li, Gazetteer of the Yangqu County (*Yangqu xian zhi*) (1682), Vol. 1.
*Qingxu, Shanxi	There were a great drought and resulting epidemic.	Xunxiang Wang and Xiaozun Wang, Gazetteer of the Qingyuan Town (*Qingyuan xiang zhi*) (1882), Vol. 16.
*Linyou, Shaanxi	There were drought and epidemic outbreaks in 1601 AD in Linyou County.	Ruwei Wu and Yuantai Liu, Gazetteer of the Linyou County (*Linyou xian zhi*) (1657), Vol. 1.

†Counties with abrupt cooling. *Counties with epidemics.

[1] If a weather event is recorded in two or more local gazetteers, the most original or the most detailed one is given.

Table 3: Historical records of the abrupt cooling and epidemics in Korea in 1601 AD.

Location	Description	Source
†Kangwon Prefecture, Korea	The Magistrate of the Gangneung City (*Gangneung Bu,* a city of the Kangwon Prefecture, i.e., *Kangwon Do*), Si Sin, reported that chilly wind was always blowing, and the weather was always gloomy and hazy since the late spring. The seedlings rotted and faded away. It rained and snowed on the 5th day of this month (May 6, 1601 AD). The mountains and plains were in white. This is really abnormal as it is summer now. (The date of this report was Jiawu day, 4th month, 34th year, Seonjo Reign Period, i.e., May 28, 1601 AD.)	Annals of King Seonjo, Vol. 136.
†Hwanghae Prefecture, Korea	The Governor of the Hwanghae Prefecture (*Hwanghae Do*), I-Mun Seong, reported that there were severe droughts in all of the counties from the spring to summer. It shined one moment and rained the next, and the chilly wind always blew. The wheat failed to flower, and the rice failed to grow. The paddy fields were very dry and could not be ploughed. In the seeded fields, the seeds did not sprout. We really worried about the farm work. (The date of this report was Bingshen day, 4th month, 34th year, Seonjo Reign Period, i.e., May 30, 1601 AD.)	Annals of King Seonjo, Vol. 136.
*Near Seoul, Korea	King Seonjo said that it was very hot and wet these days, and numerous people fell ill. We should take good care of ourselves, so that the patients would recover and no longer feel miserable. (The record does not mention the location. It should refer to the entire Korean Peninsula or at least the vicinity of the capital, Seoul, because this record is an order of the king.) (The date of this report was Renyin day, 7th month, 34th year, Seonjo Reign Period, i.e., August 4, 1601 AD)	Annals of King Seonjo, Vol. 139.

†Counties with abrupt cooling. *Counties with epidemics.

Table 4: Temporal distribution and weather background of the epidemics in China and Korea in 1601 AD.

County, province	Weather background	Time
Xincai, Henan	Cold	Spring* (February 3–May 1, 1601 AD)
Nankang, Jiangxi	n/a	4th month (May 2–May 31, 1601 AD)
Korea (State)	Abnormally hot and wet	7th month (July 29–August 27, 1601 AD)
Guizhou (Province)	Drought	7th month (July 29–August 27, 1601 AD)
Shitai, Anhui	Abnormally cold and then abnormally hot	7-8th month (July 29–September 1601 AD)
Wuzhen, Zhejiang	Abnormally cold and then abnormally hot	7–9th month (July 29–October 25, 1601 AD)
Hangzhou, Zhejiang	Abnormally cold and then abnormally hot	7–9th month (July 29–October 25, 1601 AD)
Huzhou, Zhejiang	Abnormally cold and then abnormally hot	7–9th month (July 29–October 25, 1601 AD)
Tongxiang, Zhejiang	Abnormally cold and then abnormally hot	7–9th month (July 29–October 25, 1601 AD)
Nanxun, Zhejiang	Abnormally cold and then abnormally hot	7–9th month (July 29–October 25, 1601 AD)
Xinhua, Hunan	n/a	Autumn (7th–9th month, i.e., July 29–October 25, 1601 AD)
Dingxiang, Shanxi	Drought	Autumn (7th–9th month, i.e., July 29–October 25, 1601 AD)
Xingguo, Jiangxi	Drought	n/a
Qingxu, Shanxi	Drought	n/a
Linyou, Shaanxi	Drought	n/a
Yangqu, Shanxi	n/a	n/a

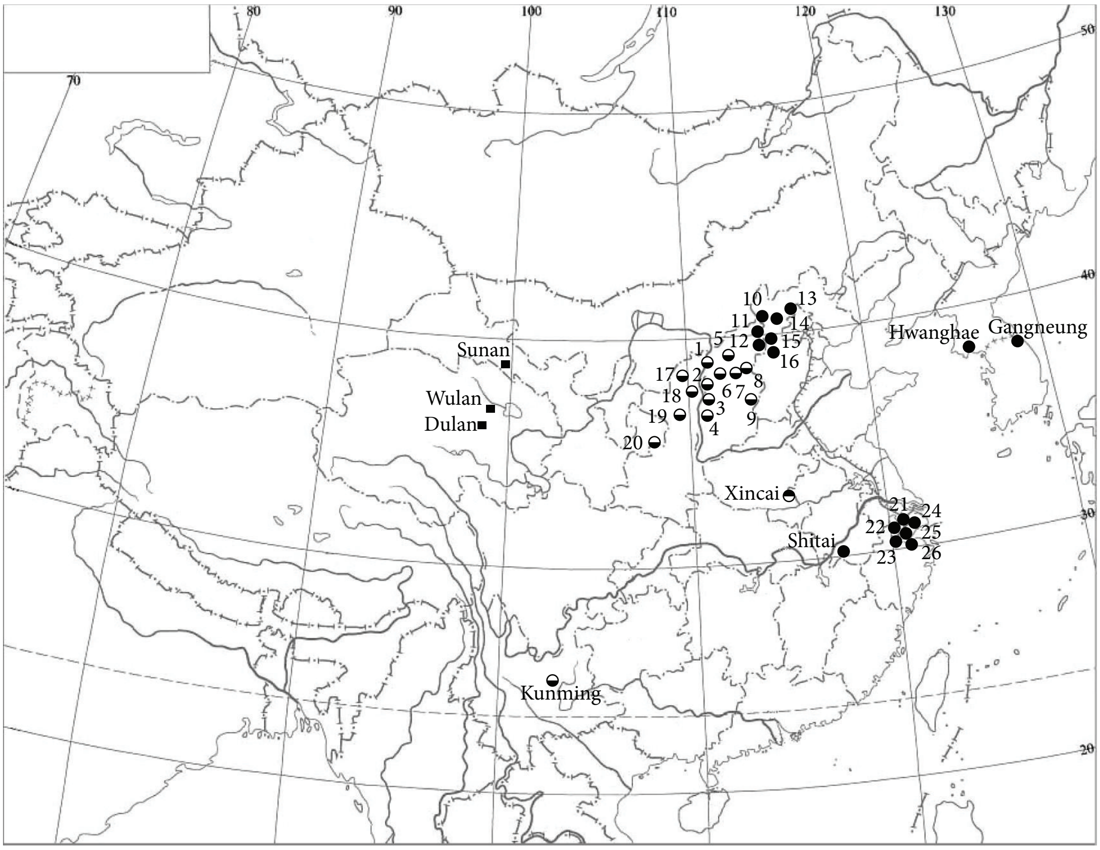
*In Chinese and Korean historical literatures, particularly histories, chronicles and gazetteers, spring refers to the 1st–3rd months of the Chinese lunar calendar, and summer, autumn, and winter refer to the 4th–6th, 7th–9th, and 10th–12th months, respectively.

occurred in these counties if there were killing frosts in the surrounding areas.

In addition, we identified a record of disease outbreaks in early 1601 AD. In the early spring of 1601 AD, excessive snows hit Xincai County (Henan Province) and resulted in the outbreak and rapid spread of disease (Tables 2 and 4; Figures 1 and 2).

The epidemics ended in 1601 AD in China, except in the Lishi County (Shanxi Province, Table 2), where disease outbreaks were reported again in the spring of 1602 AD. There were no further signs or data of widespread abrupt cooling and epidemics after 1602 AD.

5.2. Dendrochronology Records on the Northeast Tibetan Plateau. Past dendrochronological analyses were shown to be an exceptional source of information for tracking potential periods of dramatic or abrupt cooling and abnormal weather patterns. In addition, a few rigidly dated tree ring chronologies have been developed, which reveal past temperature changes on the northeast Tibetan Plateau, China (Figure 1).



◓ ● ◒ Abrupt cooling in spring, summer, and autumn

■ Sites of tree ring chronologies

Abbreviations

(1) Baode
(2) Linxian
(3) Lishi
(4) Xixian
(5) Shenchi
(6) Jingle
(7) Xinzhou
(8) Dingxiang
(9) Zuoquan
(10) Huai'an
(11) Yangyuan
(12) Guangling
(13) Chicheng
(14) Xuanhua
(15) Yuxian
(16) Laiyuan
(17) Yulin
(18) Mizhi
(19) Yan'an
(20) Ningxian
(21) Nanxun
(22) Huzhou
(23) Hangzhou
(24) Songjiang
(25) Wuzhen
(26) Tongxiang

FIGURE 1: Abrupt cooling in 1601 AD in China and Korea. Dots denote records of abrupt cooling and epidemics, and different dots denote different seasons. Squares denote sites of relevant tree ring chronologies.

Liu et al. (2005) reconstructed the winter half-year (prior December to current April) temperature change history of Sunan County (99°56′E, 38°26′N), Gansu Province, northeast Tibetan Plateau [69]. Zhu et al. (2008) established a tree ring width chronology at Wulan County (98°40′E, 37°03′N), Qinghai Province, thus reconstructing the winter half-year (prior September to current April) temperature change history over the past 1000 years in this region [70]. Liu et al. (2009, 2011) established a new chronology of annual temperature change over the past 2485 years at Dulan and Wulan Counties (98-99°E, 36-37°N), Qinghai Province, east Tibetan Plateau [71, 72].

However, 1601-1602 AD was not abnormally cold or warm in these three chronological records.

6. Abrupt Cooling and Epidemics in Korea

After a careful literature survey, we identified a total of three records on abnormal weather and disease outbreaks in Korea in 1601 AD (Tables 3 and 4; Figures 1 and 2). Accordingly, the spring and early summer of 1601 AD were anomalously gloomy and cold. The middle summer was hot and wet, with a resulting epidemic ensuing in the prevalent conditions of the time.

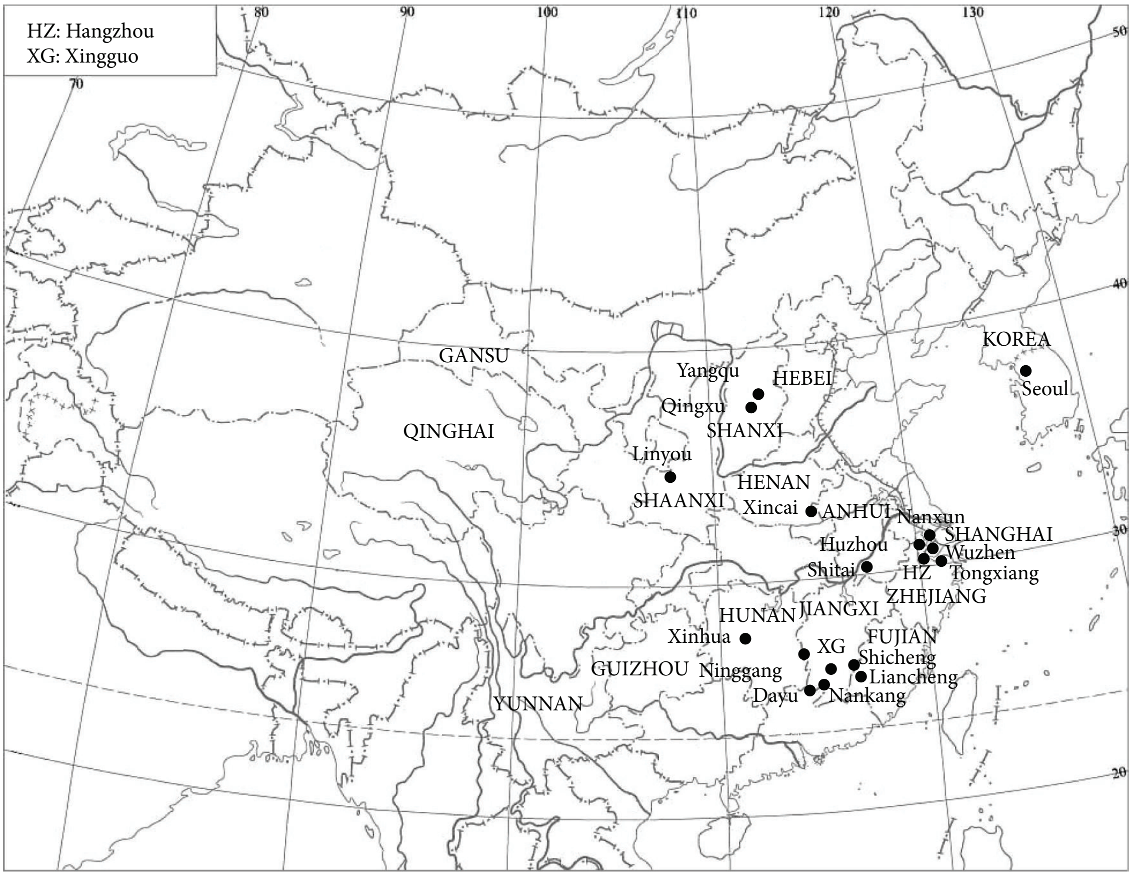


Figure 2: Epidemics in 1601 AD in China and Korea. Capitalized place names are Korea and provinces of China.

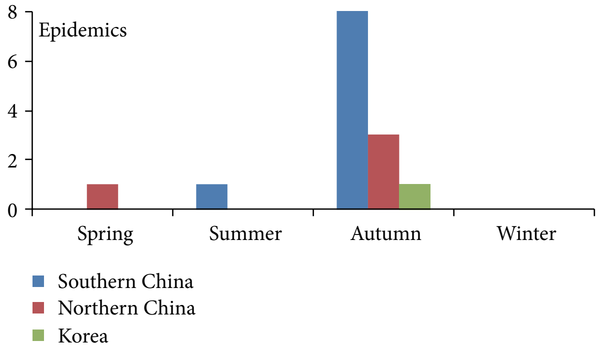


Figure 3: Seasonal variation of the number of records of epidemic in 1601 AD in southern China, northern China, and Korea.

7. Discussion

According to the records with detailed dates, we identify a very interesting phenomenon in many areas of China and Korea; that is, most of the epidemics occurred in the summer and autumn (Table 4, Figure 3). The areas include the Korean Peninsula and the provinces of Zhejiang, Anhui, Shanxi, Guizhou, and Hunan in China (Figure 2). The epidemics were recorded simultaneously with the abnormal weather patterns, thus indicating a weather background and a possible causal link.

However, if the epidemics were related to the anomalous weather background, why did the epidemics break out almost simultaneously in different weather backgrounds (Table 4, Figure 3)? In Korea, the background was abnormally hot and wet weather. In Zhejiang and Anhui Provinces, the background was an abnormally cold July and a hot autumn. In Guizhou and Shanxi Provinces, the background was drought (Table 4). In Hunan province, the weather background was unidentified (Table 4).

With regard to the spatial distribution for the spread of endemic diseases, it is interesting that Korea, Zhejiang and Anhui Provinces, Shanxi Province, Guizhou, and Hunan Province are thousands of kilometres apart from each other (Figure 2). The epidemics in these four regions should be independent of one another. That is to say, weather backgrounds were different, and regions were independent; however, the records correlate multiple epidemics breaking out almost simultaneously across these regions.

It may seem to be overreaching to directly attribute the potential cause of these disease outbreaks to the 1600 AD Huaynaputina eruption. However, because the eruption reduced solar insolation and resulted in global abrupt cooling, it is not reasonable to exclude it as one of the major causes of the epidemics in China and Korea in August, September, and October, 1600 AD. In other words, while investigating the possible causes of the epidemics, the effects of the Huaynaputina eruption should not be neglected.

8. Conclusion

Historical records on the abrupt cooling and epidemics in 1601 AD in China and Korea were investigated, and its causal relationship with the 1600 AD Peruvian Huaynaputina eruption is discussed. We suggest that abrupt cooling occurred in 1601 AD in China and Korea following the Huaynaputina eruption. Near, thereafter, widespread epidemics occurred in the summer and autumn of 1601 AD in China and Korea.

There were severe killing frosts in the summer and autumn of 1601 AD in Shanxi, Hebei, Shaanxi, and Gansu Provinces of northern China, as well as an unseasonable snow in that summer in Hebei Province.

In Zhejiang and Anhui Provinces, and Shanghai Municipality in southern China, July of 1601 AD was abnormally cold with unseasonable snows, differentiated from August, September, and October which were abnormally hot. There were widespread epidemics following this anomalous weather. Simultaneously, disease outbreaks also occurred in Guizhou and Hunan Provinces.

In Korea, the spring and early summer of 1601 AD were abnormally cold; however, middle summer was hot and wet, which was followed by epidemics.

It is worth further discussion that widespread epidemics occurred almost simultaneously in Korea and the Chinese provinces of Zhejiang, Anhui, Guizhou, Hunan, and Shanxi. Apparently, the weather background of the epidemics was different; however, we suppose that the Huaynaputina eruption possesses a major burden of responsibility for these concurrent epidemic outbreaks.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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