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Historical analogues of the 2008 extreme snow event over Central and Southern China

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ABSTRACT: We used weather records contained in Chinese historical documents from the past 500 yr to search for extreme snow events (ESEs) that were comparable in severity to an event in early 2008, when Central and Southern China experienced persistent heavy snowfall with unusually low temperatures. ESEs can be divided into 3 groups according to the geographical coverage of snowfall, using the following criteria to define an ESE: >15 snowfall days, 20 snow-cover/icing days, and 30 cm total cumulated snow depth for an individual winter. The first group covers the whole of Eastern China (East of 105° E), and ESEs occurred in 1654, 1660, 1665, 1670, 1676, 1683, 1689, 1690, 1700, 1714, 1719, 1830–32, 1840, 1877 and 1892; the second group is located mainly in the area south of Huaihe River (~33° N), and ESEs occured in 1694, 1887, 1929, and 1930; and the third group is confined within the central region between Yellow River and Nanling Mountain (roughly 26° to 35° N), and ESEs occurred in 1578, 1620, 1796, and 1841. We also examined the relationship between ESE occurrence and the temperature regimes within the 500 yr period. From the 20th century reanalysis data set of global atmospheric circulation available since 1871, we found a close association between the ESEs and the anomalous 500 hPa geopotential heights. This study presents cases of extreme winter snowfall occurring because of natural variability in global atmospheric circulation that can be used for paleo-climatology simulations and provide clues to understanding future extremes over China.

KEY WORDS: Precipitation extremes · Historical record · China · Atmospheric circulation

1. INTRODUCTION

From January 10 to February 2, 2008, continuous heavy snowfall occurred over Central and Southern China (Ding et al. 2008, Wen et al. 2009). This extreme snow event (ESE) caused 1.7 million people to be displaced for periods ranging between a few days to a month, and affected critical infrastructure including electric power grids and communication systems. Food production, forests, wildlife and buildings all suffered heavy damage (Zhou et al. 2011). The 2008 ESE caused direct economic losses of over 151.65 billion Yuan (~US $21 billion; Ministry of Civil Affairs 2008). Several meteorological parameters—e.g. persistent low-temperature days, maximum continuous snowfall amount, and maximum persistent freezing days—broke 50 yr records in Central and Southern China (Wang et al. 2008). Concurrently, extreme climate events also occurred in other regions of the world (www.wmo.int/pages/mediacentre/news/documents/wmo1075_map_en.pdf).

Extreme events such as the 2008 ESE beg the question of whether historical analogues can be found, and if so, how often they occurred in connection with the main temperature phase (cold/warm). In this study, we overviewed the 2008 ESE meteorological conditions (anomalous temperature, snowfall and icing) and its atmospheric circulation patterns based on quantitative data. We then used historical documents to identify ESEs in China over the past 500 yr,

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plotting individual maps of their location and spatial coverage. Finally, we examined the role of the temperature phase variation in China during the extreme winter snow occurrences.

2. METEOROLOGICAL OVERVIEW OF THE 2008 ESE

We use the 20th Century Reanalysis V2 data set (Compo et al. 2011) to illustrate the meteorology, and the 500 hPa geopotential heights to plot atmospheric circulation. This data set is provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (www.esrl.noaa.gov/psd/; Compo et al. 2011 for details), and contains objectively analyzed 4-dimensional weather maps (including uncertainty values) with a global grid of 2.0° latitude × 2.0° longitude (180 × 91 grids), 6-hourly temporal coverage, and daily and monthly average values of climatic variables for January 1, 1871 to December 31, 2008. The total mean of this data set is based on 1968–1996 climatology. Fig. 1 outlines the study area.

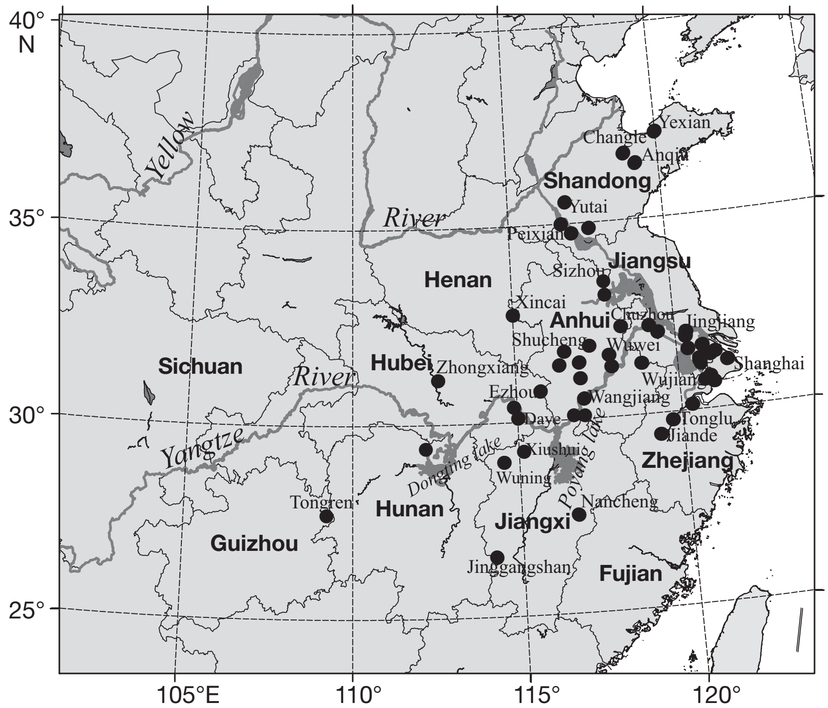

Fig. 1. Location of provinces, cities and rivers mentioned in this study

2.1. Temperature, snowfall and icing conditions

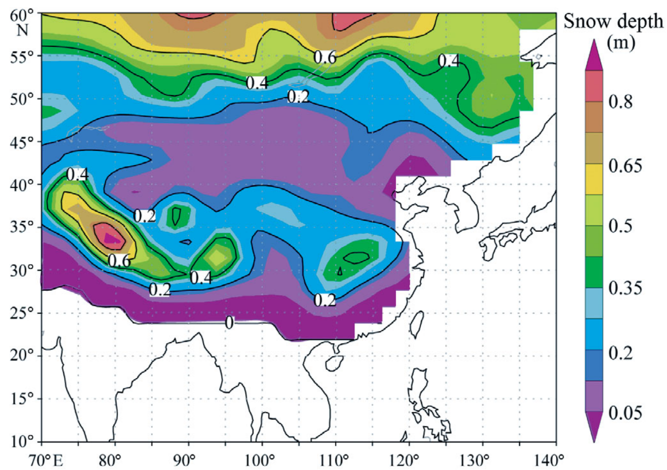

Fig. 2. Total snow depth, January 10 to February 2, 2008

The 2008 ESE lasted a total of 24 d, consisting of 4 periods of continuous heavy snowfall spanning January 10–16, 18–22, 25–29 and January 31–February 2, with 12 to 17 snowfall days and 15 to 25 snow cover/icing days for each meteorological station in the middle and lower reaches of the Yangtze River. The accumulated snow depth from January 10 to February 2 was 0.2 to 0.3 m in most parts of Central China, and 0.3 to 0.4 m in the middle and lower reaches of the Yangtze River (28° to 34° N and 107° to 117° E) (Fig. 2), a region that does not normally have continuous snow cover during winter. In particular, snow depths reaching 0.47 and 0.5 m in the Chuxian and Huoshan Counties of Anhui Province, respectively, were observed at local meteorological stations. The period of continuous snowfall caused anomalous low temperatures in Central and Southern China. Fig. 3 shows that the mean temperature for Central China in January and February 2008 was 2 to 3°C below normal (with respect to 1968–1996 climatology), which is similar to the winter of 1954, the second-coldest winter over the last 6 decades (Wang et al. 2008). Temperature anomalies in the disaster area affected by the 2008 snow storm were between −5 and −6°C, while in other regions of China, such as the Northeast and Tibet, temperature anomalies were positive. During the 2008 ESE period, Southern China also experienced frequent freezing rain, which together with the persistent low temperature caused icing up of roads, trees, and power lines. For example, in Jiangxi Province, ice thicknesses between 36 and 52 mm were observed on powerlines, values that

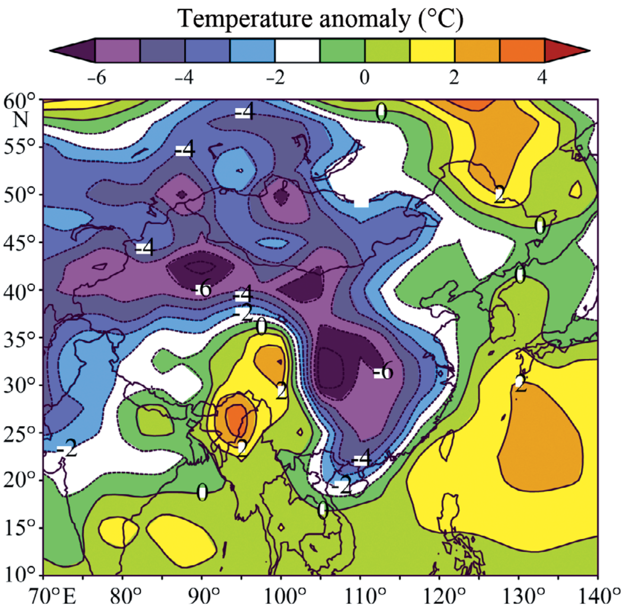

Fig. 3. Temperature anomaly (with respect to 1968–1996 climatology), January 10 to February 2, 2008

have not been recorded since 1951; and ice thicknesses of 80 to 100 mm were observed on road surfaces in Hunan and Guizhou Provinces on January 29, 2008 (Zhou et al. 2011).

2.2. Atmospheric circulation analysis

Because the 2008 ESE severely affected a large region, several studies (see below, this paragraph) have analyzed its synoptic conditions and discussed the driving mechanisms but came to different conclusions. Liu et al. (2008) concluded that the La Niña event, which began in 2007, was the main cause of the disaster; Gao (2009) stated that anomalous atmospheric circulations, including the Siberia high and the north polar vortex at the high latitudes, may have played an important causative role; according to Li & Gu (2010), the positive sea surface temperature anomaly (SSTA) in the North Atlantic may have acted as the main forcing; Wen et al. (2009) noted an anomalous positive Arctic Oscillation exhibiting strong precursory signals of January temperature variability over Central-Southern China; and Bao et al. (2010) suggested that anomalous Tibetan Plateau warming could have contributed to the ESE. There is, however, some agreement that the strong and persistent Ural blocking high in the mid-high latitudes (45°–65° N) played an important role in the 2008 ESE (Ding et al. 2008, Li & Gu 2010, Zhou et al. 2011).

During the 2008 ESE, the strong 500 hPa westerlies split into 2 branches (Fig. 4). The northern branch over the Ural Mountains (55° to 65° N, 70° to 90° E) extended northward to the polar region, and then shifted southward, which together with the low trough in the middle of Asia (30° to 40° N, 65° to 75° E) and the persistent Arctic polar vortex, led directly to the sustained invasion of cold air via Central Asia, arriving in China along the western route. The duration of the Ural blocking high, >20 d (3 times the mean value from 1951–2008), was the longest since 1951. Under this circulation pattern, cold air was advected continuously from the northern parts of Siberia to Central Asia and invaded China along the eastern Hexi corridor, combining to create conditions that were conducive to an extreme winter (Ding et al. 2008). The southern branch of the westerlies, passing through the south of the Qinghai-Tibet Plateau, helped to intensify the southern branch trough in the Bay of Bengal, which transported the warm-wet airflow northward across the Yun-Gui Plateau, and provided moisture for the snow event in Southern China. In addition, the ridge line of the western Pacific subtropical high reached its northernmost latitude since 1951, with extensive positive anomalies over the central-western Pacific Ocean (Fig. 4). At an early stage in the development of the 2008 ESE, the warm and wet air along the western edge of the subtropical high was transported northward to meet cold air from the mid- and high latitudes over the middle and lower reaches of the Yangtze River, and then later met over the south of China, causing the persistent snowfall in Central and Southern China (Ding et al. 2008).

3. IDENTIFICATION OF HISTORICAL ESEs

3.1. Data sources

ESEs that occurred during the past 500 yr were identified using Chinese historical documents, which contain detailed descriptions of weather and/or climate conditions. Specifically, 2 types of documents were used in this study: (1) Zhang (2004) extracted information on floods, droughts, snowstorms, freezing events and frost disasters from local gazettes, 24 official histories, imperial encyclopedias, institutional conventions, and numerous personal notes; and (2) the *Yu-Xue-Fen-Cun* archives recorded soil infiltration depths of rain, and snow depths on the ground (including dates and durations) for individual precipitation events in 273 prefectures of 18 provinces from

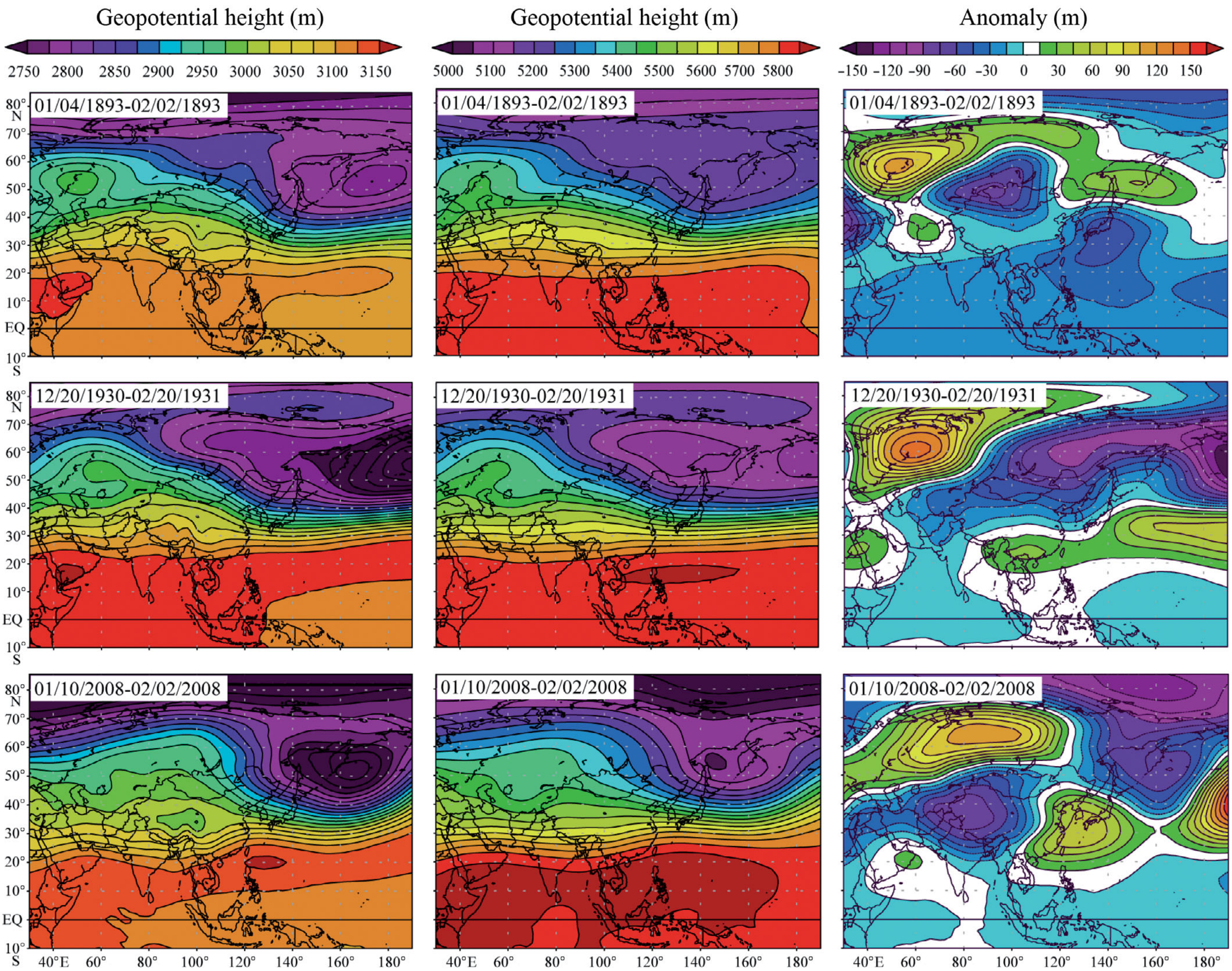

Fig. 4. 700 hPa (left) and 500 hPa (middle) mean geopotential height patterns and their anomalies (right) for the winters of 1892, 1930 and 2008 (top, middle and bottom, respectively). Dates are mm/dd/yyyy

1736 to 1911 (Ge et al. 2005). For both these sources, the recording systems, uncertainties and reliabilities have already been examined at length (e.g. Ge et al. 2005, 2007, Zheng et al. 2011).

In addition, we used the winter half-year temperature reconstruction to reveal decadal temperature change over central Eastern China for the years 1500 to 2000, and to provide a climatic background for the ESEs that occurred. This reconstruction was developed from phenological cold/warm records found in Chinese historical documents, with a 10 yr time resolution (Ge et al. 2003). In addition, the 20th Century Reanalysis V2 data set (Compo et al. 2011) was used to check the atmospheric circulation for historical ESEs since 1871.

3.2. Methods

Chinese historical documents contain very abundant weather information for each county, and many descriptions such as '20 days of heavy snow', 'over 40 days of heavy snow', and reports of cumulative snow depth reaching 1 chi (Chinese unit of ~32 cm) can be found (Zhang 2004). It is possible to identify ESEs over the past 500 yr from these records, in terms of duration, depth and large-scale spatial distribution of snowfall. Based on the weather or climatic conditions observed during the 2008 extreme event, we defined an ESE over Eastern China as >15 d of snowfall, snow cover/icing for >20 d, and snow depth ≥30 cm (Table 1). The specific snow days and snow depth for a number of years before 1736

Table 1. Historical extreme snowfall events (ESEs) (source: Zhang 2004), including duration (period over which high incidence of heavy snowfall occurred), days of snowfall and snow cover or icing, and snow depth (ranges given because of geographical variability among sites). (–) Data not available. For spatial pattern descriptions see Section 4.1

Winter	Duration of event (dd/mm)	Snowfall days	Snow cover/ icing days	Snow depth (cm) Mean	Snow depth (cm) Max. record	Spatial pattern
1578–1579	29/11 to 01/02	>20	>30	>30	>100	III
1620–1621	15/12 to 20/02	15 to 30	>30	30 to 50	>60	III
1654–1655	21/12 to 05/02	15 to 40	20 to 40	40 to 50	>60	Ib
1660–1661	04/12 to 29/01	–	>30	–	–	Ic
1665–1666	01/01 to 02/02	–	>30	–	–	Ic
1670–1671	15/12 to 05/02	>15	>30	30 to 50	>100	Ia
1676–1677	10/12 to 01/02	–	>30	>50	>100	Ic
1683–1684	28/12 to 12/02	–	>30	30 to 50	>60	Ia
1689–1690	28/12/ to 15/01	–	>30	–	>60	Ic
1690–1691	21/12 to 15/02	>15	>30	30 to 60	>100	Ia
1694–1695	17/12 to 10/03	–	>30	–	–	II
1700–1701	10/12 to 10/02	–	>20	–	>100	Ia
1714–1715	06/01 to 03/02	>15	>30	>30	>50	Ib
1719–1720	01/02 to 08/03	–	>20	>30	>60	Ib
1796–1797	29/12 to 30/01	15 to 25	20 to 30	30 to 40	>50	III
1830–1831	10/01 to 23/02	15 to 25	15 to 40	30 to 40	>50	Ic
1831–1832	14/12 to 07/02	15 to 30	25 to 50	30 to 50	>100	Ia
1832–1833	19/01 to 20/02	15 to 20	20 to 35	30 to 50	>90	Ia
1840–1841	18/12 to 01/02	15 to 20	25 to 40	30 to 50	>100	Ic
1841–1842	09/12 to 10/01	15 to 30	25 to 50	~50	>100	III
1877–1878	30/12 to 09/02	~15	20 to 50	>30	>45	Ia
1887–1888	13/01 to 13/02	~15	20 to 35	30 to 40	>90	II
1892–1893	04 to 06/01, 13 to 30/01, 25/01 to 02/02	~15	>25	30 to 50	>90	Ia
1929–1930	16/12 to 25/02	>15	>25	30 to 40	>60	II
1930–1931	20/12 to 20/02	>15	>25	30 to 40	>60	II
2007–2008	10 to 16/01,18 to 22/01, 25 to 29/01, 31/01 to 02/02	12 to 17	15 to 25	30 to 35	50	III

were difficult to derive from Zhang (2004) (indicated by '–' in Table 1) after 1736, however, we can determine the number of snow days and snow depth from the *Yu-Xue-Fen-Cun* archive.

4. ANALYSES AND RESULTS

Including the event in 2008, 26 ESEs were identified (Table 1). The historical events are comparable to the extreme snow event in 2008 in terms of snowfall days, snow cover/icing days and snow depth, but they have different spatial patterns and different anomalous atmospheric circulations (according to available data after 1871).

4.1. ESE spatial patterns

On the basis of different geographical snow coverage during ESEs (Fig. 5), the 26 ESEs can be divided into 3 categories. (I) A snow front moving from the north to the south of China over the winter; occasionally heavy snow occurring in the east coast of China or scattered small areas, possibly due to insufficient warm wet airflow being transported from south to north. This category is divided into 3 sub-categories: (Ia) continuous snowfall over most of Eastern China (e.g. 1892 in Fig. 5); (Ib) an ESE occurring on the east coast of China (e.g. 1714 in Fig. 5); and (Ic) heavy snow over scattered regions of Eastern China, with cold dry conditions for Eastern China (e.g. 1676 in Fig. 5). (II) Continuous snowfall over Southern China, from Huaihe River to the southern border (e.g. 1887, 1929, and 1930 in Fig. 5). (III) Persistent snowfall in the region between the Yellow River and Nanling Mountain (ca. 26°–35°N) (e.g. 1578, 1620 and 1796 in Fig. 5); this pattern is consistent with that of 2008. Thus, analogues to the 2008 ESE were found in the winters of 1578, 1620, 1797, and 1841.

Because the historical documents were mainly recorded in Eastern China (i.e. east of ca. 105° E), it is difficult to compare the spatial coverage of historical ESEs with that of the 2008 ESE for the whole of

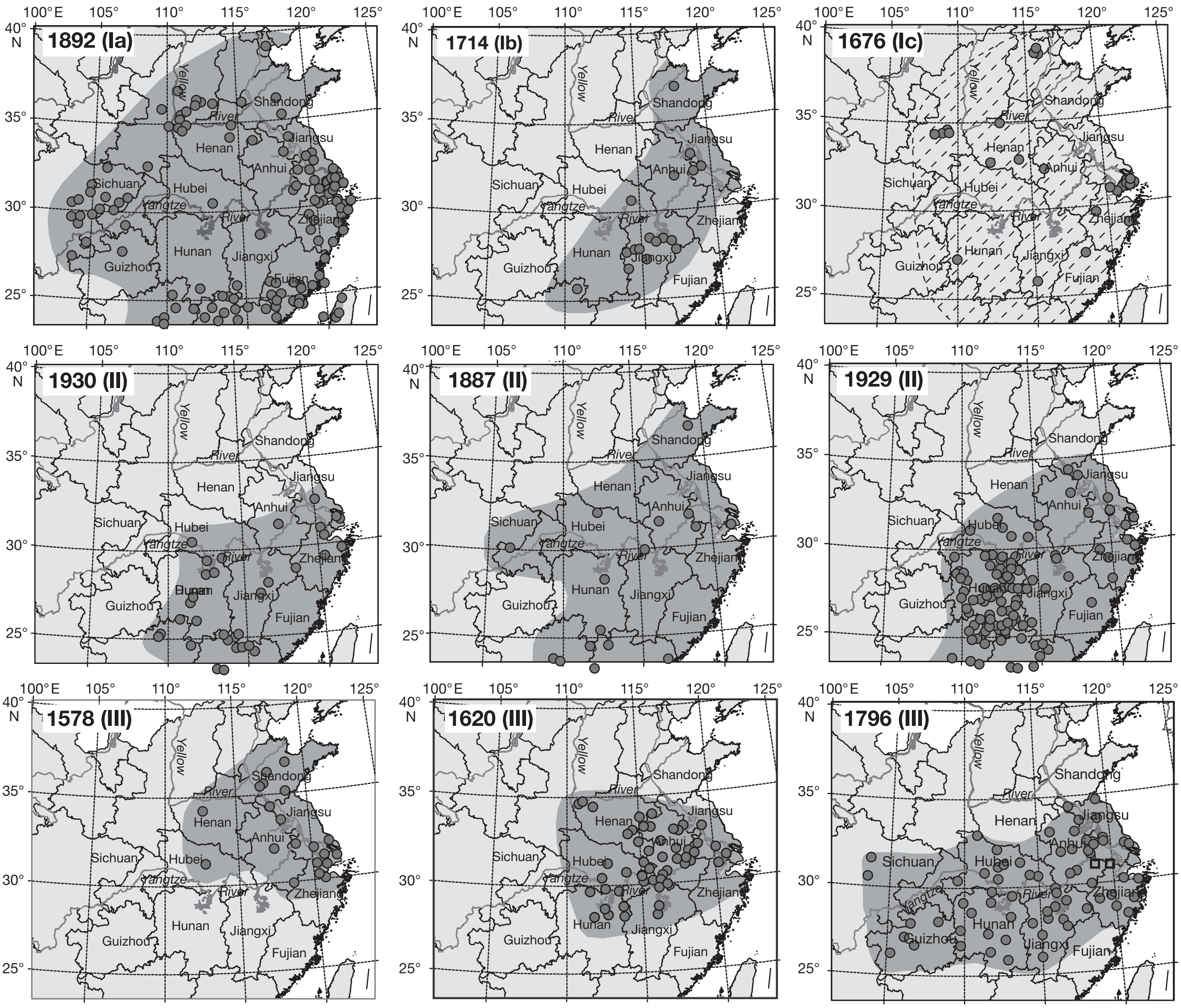

Fig. 5. Spatial pattern of extreme snow events over the last 500 yr. (●) Sites with persistent heavy snowfall records; dark gray shading: areas with long duration (>15 d) snow coverage; dashed hatching: persistent heavy snowfall in winter of 1676 only occurred at scattered sites, while the entire eastern part of China experienced dry and cold conditions. Panels indicate areas with long snowfall days (≥15 d) or long persistent snow cover/icing days (≥20 d) and accumulated snow depth ≥30 cm (see Table 1 for more details)

China. Thus, the spatial comparison of the main disaster area between the 2008 ESE and historical ESEs can only be made for Eastern China. The main disaster area for the 2008 ESE in Eastern China was located between just south of the Yellow River and Nanling Mountain, ~26°–35° N (see Fig. 2). By comparison, the spatial distributions of ESEs in the winters of 1578, 1620, 1796 and 1841 are consistent with that of 2008 (the main disaster areas were located between ca. 29°–35° N for 1578, 27.5°–35° N for 1620, 25°–33° N for 1796 and 27°–34° N for 1841; Fig. 5, the map of 1841 is omitted because its main disaster area is consistent with that of 1620). The large-scale climate characteristics of 2008-type ESEs usually have connections to large-scale atmospheric circulations, so it is necessary to analyze the synoptic situations occurring during the ESEs to provide relevant references for the prediction of ESEs for the future and incorporation into climate models.

4.2. ESEs and atmospheric circulation

Compo et al. (2011) developed a reanalysis data set that includes geopotential heights since 1871, which provided basic data for circulation analysis for the ESEs since 1871. Analysis of the atmospheric circulation, anomalous climate and impact conditions (e.g. lakes/rivers frozen, icy roads, stock loss) of the years after 1871 in which ESEs occurred (i.e. 1877, 1887, 1892, 1929, 1930, and 2008), reveals that the synoptical situations in 1877 and 1887 are very close to that in 1892, and 1929 has similar patterns compared to 1930, but the circulation pattern in 2008 is distinctly different to the other events (see Fig. 4). We selected the persistent snowfall periods of January 4 to February 2, 1893 (representing Category I with heavy snow over the whole of Eastern China) and December 20, 1930 to February 20, 1931 (representing Category II with heavy snow in the whole of Southern China), and the January 10 to February 2, 2008 (representing Category III with heavy snow between Yellow River and Nanling Mountain) to plot the 700 hPa and 500 hPa geopotential height patterns (Fig. 4).

The spatial patterns of the 700 hPa and 500 hPa geopotential heights vary greatly among the 3 cases (Fig. 4). In the winters of 1892 and 1930, a strong blocking high lay over the Ural mountains; the East Asian Trough moved westward (to ~110° E–130° E) compared to a normal winter (~120° E–150° E), and the Southern Branch Trough was not very noticeable, which caused cold air to move directly from north to south. However, in the winter of 1892, the geopotential height of the whole of China was in negative anomaly, which is favorable to the cold air moving southward. In the winter of 1930, although most parts of China were in negative anomaly, there was a weak positive anomaly south of the Nanling Mountains (26° N), and the convergence of the cold airflow from the north and the warm airflow from the south occurred south of the middle and lower reaches of the Yangtze River. Compared with the 1892 and 1930 winters, the stronger Ural blocking high and deepened Southern Branch Trough, together with the eastward and deeper East Asian Trough, formed into the positive-negative-positive spatial pattern of anomalies found in the winter of 2008, which is favorable to cold air coming into the China region. This circulation pattern led to the persistent and large-area snowfall in the region of the Huaihe and Yangtze Rivers and surrounding areas.

Table 2. Winter snowfall records in winter of 1796 from Yu-Xue-Fen-Cun archive. Dates are mm/dd,yyyy

Location	Snowfall dates	Snow depth (cm)	Sources
Jiangning, Suzhou, Songjiang, Changzhou, Zhenjiang, Yangzhou, Huaian, Xuzhou, Taicang, Tongzhou and Haizhou of Jiangsu, Anqing, Huizhou, Chizhou, Ningguo, Taiping, Luzhou Province, Fengyang, Liuan, Guangde, Chuzhou and Hezhou of Anhui Province and Nanchang of Jiangxi Province	11/29–12/3,1796 12/8–10,1796 12/29–30,1796 1/4–6,1797 1/18–19,1797	6.4–16	Su Linga, Governor General of Jiangsu, Anhui and Jiangxi
Jiangning, Yangzhou, Songjiang, Changzhou, Zhenjiang and Tongzhou	1/5–6, 1797 1/9–10, 1797	3.2–12.8	Fei Chun, Governor General of Jiangsu
Changsha, Yuezhou, Changde, Chenzhou, Yongshun, Yuanzhou, Lijing and Guiyang	1/3–5, 1797 1/18–19, 1797 1/28–29, 1797	9.6–25.6	Jiang Sheng, Governor General of Hunan
Thirteen cities in Anhui province	1/4–6, 1797 1/8–11, 1797 1/14–16, 1797 1/18,19,24, 1797 1/29–30,1797	3.2–19.2	Zhu Gui, Governor General of Anhui
Jiangning, Huaian, Yangzhou, Xuzhou, Tongzhou, Suzhou, Songjiang, Changzhou, Zhenjiang and Taicang of Jiangsu Province, and Anqing, Huizhou, Taiping, Luzhou, Fengyang, Liuan, Sizhou, Chuzhou and Hezhou of Anhui Province	1/9–11, 1797 1/17,18,20, 1797 1/23–25, 1797 1/28–30, 1797	6.4–16	Su Linga, Governor General of Jiangsu, Anhui and Jiangxi

4.3. ESEs and climate change

The frequency of ESEs during each century shows that these events were most prevalent during the 2 periods 1601 to 1700 (10 winters) and 1801 to 1900 (8 winters), and were least prevalent in the 3 periods 1501 to 1600 (1 winter), 1701 to 1800 (4 winters) and 1901 to 2000 (2 winters). Several ESEs occurred sequentially, such as the winters of 1689 and 1690, 1830, 1831 and 1832, 1840 and 1841, 1929 and 1930. However, the frequency of occurrence differs greatly among the spatial categories during the past 500 years: Category I = 18 winters (i.e. frequency 3.5%), Category II = 4 winters (0.8%) and Category III = 4 winters (0.8%). This may suggest that 2008 was a 'hundred year' snow event.

We also compared these ESEs together with reconstructed winter half-year temperatures (Fig. 6). Most ESEs occurred during the cold phases of 1650–1690 and 1800–1900, 3 of the ESEs (in the winters of 1578, 1620, and 1796) all occurred in a relative warm phase followed by a cold phase. For example, the average value of winter half-year temperature from 1622 to 1700 in Eastern China is a −0.57°C anomaly compared to the mean value for the period 1951–1980. After a rather long cooling period (about 100 yr), the temperature increased again. During the warming period (ca. 1700–1790) before the 1796 ESE, the winter half-year mean temperature in Eastern China increased slightly at the rate of 0.03°C per 10 yr. After this increase phase, another rapid cooling period began, and lasted for almost a century from the end of the 1790s to the early 1900s. Mean winter half-year temperature during this period dropped 0.8°C.

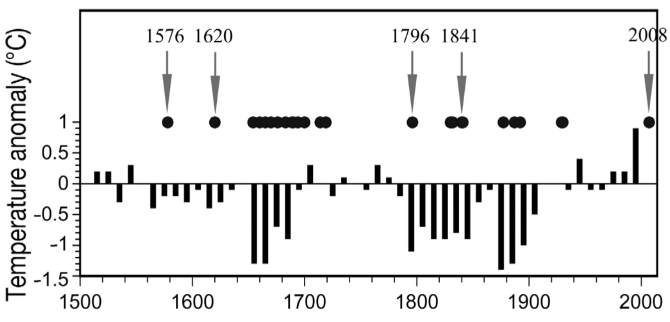

Fig. 6. Winter half-year temperature anomalies (bars; with respect to 1951–1980 climatology) reconstructed from Chinese historical documents covering the past 500 yr for Eastern China, and the years with extreme snow event (ESE) occurrences (dots). Arrows: ESEs analogous to the 2008 event

5. DISCUSSION AND CONCLUSIONS

Using meteorological records and weather information contained in Chinese historical documents, 25 individual yearly ESEs were identified during the past 500 years, that had comparable snowfall days, snow cover/icing days and snow depth to the winter of 2008. However, these historical ESEs have varying spatial patterns (classifiable into 3 categories) and only the ESEs located in central Eastern China that occurred in the winters of 1578, 1620, 1796 and 1841 had comparable snowfall to the 2008 event, with a probability of occurrence once every 100 yr.

The 3 spatial patterns of the 26 ESEs were closely associated with large-scale circulation, based on the available data after 1871. For the first (snowfall over the whole of Eastern China) and second (snowfall confined to south of the Huaihe River [~33° N]) patterns, a strong Ural blocking high stays in the north, the East Asian Trough moves further westward than normal, and the Southern Branch Trough over the Bay of Bengal is not evident. But the third pattern (i.e. the analogue of the ESE in 2008; snowfall mainly in the central Eastern China region [ca. 26° to 35° N] has the strong Ural blocking high, but an eastward shift of the East Asian Trough, and a noticeable Southern Branch Trough, resulting in persistent snowfall in the Huaihe-Yangtze River region and surrounding areas.

For the third pattern, except for the winter of 1841, the other 3 ESEs analogous to that of 2008 all occurred in a relative warm phase that was soon followed by a cooling phase. However, it is difficult to speculate if there is the probability of a cooling phase to follow after 2008, because the 3 historical analogues were the consequence of past natural climate variability. The 2008 ESE occurred in the context of global warming, possibly driven by anthropogenic activities and natural forcings. In addition, the implication of a climate shift from warm phase to cool phase was concluded from only 3 extreme cases, and it is necessary to study more analogous cases, using longer-term historical records, to increase the robustness of this finding. Although we collected as many and varied historical records as possible, due to the inherent errors, especially those resulting from changing observers, our results still have uncertainties.

Currently, one of the many active research topics under 'climate change' is 'extremes', which are defined either as 'severe drought/flood', 'cold/warm' or 'the probability of occurrence (e.g. once every hundred years)' (PAGES 2009, Hegerl et al. 2011). This study presents a few historical analogues to the 2008

ESE (i.e. in the winters of 1578, 1620, 1796, and 1841) in the context of past climate change, and demonstrates what we have learned from the past. In future work, it is necessary to conduct a comparison between these extreme events and results from climate model simulations, to see whether ESEs analogous to that of 2008 could be more frequent in the future.

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Appendix 1. The descriptions for the analogues of 2008 ESE in historical documents are shown below

Winter of 1578: In Zaozhuang, Shandong Province, the ground surface was covered by about 10 chi (~300 cm) of snow after 1 mo of continuous heavy snowfall; houses were buried and many people froze to death on the roads; fruit trees, bamboo stands, and animals (including birds, rabbits, and fish) were decimated. In Anqiu County, Shandong Province, heavy snowfall left a snow depth of 3 chi (~96 cm) in the 11th month of the Chinese Lunar Calendar (i.e. November 29 to December 27); nearly half of the livestock and trees were wiped out. In Si County, Anhui Province, there was heavy snow, the Huaihe River froze over, and mountain valleys were covered with snow; many animals and plants succumbed to the cold, and the snow lasted from November to February of the next year (1579). In Pei County, Jiangsu Province, heavy snow lasted over 20 d. In Jiaxing, Zhejiang Province, rain froze on trees in the 11th month of the Chinese Lunar Calendar (hereafter '*n*th month'), and in Xincai, Henan Province, the winter was extremely cold, and on some trees bark was cleft by frost. Many homeless people froze to death. In Zhongxiang, Hubei Province, heavy snow continued for 1 mo during the winter. Besides describing the severity of the weather, these records also indicate the spatial distribution of snowstorms in the winter of 1578, which covered the Shandong, Henan, Anhui, Jiangsu, Zhejiang, and Hubei Provinces and lasted ~1 mo from early in the 11th month.

Winter of 1620: In Yanzhou, Yutai and Yanggu Counties, Shandong Province, rain and snow froze on the ground surface, and the branches of trees were broken by heavy snow. Heavy snow in Hefei, and Shucheng, Wuwei, Chao, Chaohu, Anqing, Tong cheng, Wangjiang, Wuhe, Dongzhi and Liu'an Counties, Anhui Province, lasted from the 11th month of 1620 to the 2nd month of 1621, and snow depth in the shadow of the mountains was >10 chi (~300 cm). In Shishou, Hubei Province, ~70 d of heavy snow occurred from the 11th month of 1620 to the 2nd month of 1621, and many birds starved to death. In addition to records of dates and durations of snowfall, the freezing of rivers and lakes was also noted. In Xiu shui, Wuning, and Jinxian Counties, Jiangxi Province, heavy snow started falling in the middle of the 10th month of 1620, and ended in the middle of the 2nd month of 1621. In Ezhou, Hubei Province, heavy snow lasted 40 d and the rivers were frozen; in Daye and Yingshan Counties, people had to use wood taken from their houses as firewood, since they were cut off from other supplies by heavy snow; in addition, innumerable animals and humans died in the severe cold. In Anxiang, Hunan Province, heavy snow fell continuously for ~40 d up to the 1st month of 1621, many fish died, and gharries could be driven on the frozen river surface. In particular, Poyang Lake (in Jiangxi Province) and Dongting Lake (on the border of Hubei and Hunan Provinces) were icebound, and many birds and fish were frozen or starved to death.

Winter of 1796: For this winter, heavy snow records were derived both from the local gazettes and the *Yu-Xue-Fen-Cun* archives. From the local gazettes, Changle, Ye, and Rongcheng Counties, Shandong Province, all received heavy snow throughout the winter of 1796. The weather was so extremely cold that more than half of the winter wheat was destroyed by the low temperatures. Heavy snow also occurred in Shanghai, and in Wu, Kunshan, Taicang, Wuxi, Jiangyin Counties, Jiangsu province, snow depth was up to 1 chi (~32 cm), and such winter severity had not been seen for at least a century. In Linan, Jiande, Tonglu, Xiaoshan, Jiashan, and Pinghu, and Zhejiang Province, winter wheat, bamboo and fruits were damaged by cold, and the lakes or rivers were icebound, with the ice thick enough for people to walk on the surface. For winter 1796, the *Yu-Xue-Fen-Cun* records of the Qing dynasty also clearly document a long-lasting snow event, with snow falls on December 29–30, 1796 and on January 4–6, 8–11, 14–20, 23–25 and 28–30, 1797. In total, this ESE lasted 33 d, with 15–25 snow days (see Table 2 for each snow event *Yu-Xue-Fen-Cun* record for 1796).

Winter of 1841: For this winter, the historical records describe that spells of heavy snow started in Eastern China in the last 10 d of the 10th month of 1841, and ended in the 1st month of 1842 (i.e. December 3, 1841 to March 11, 1842). However, in Shanghai, and many counties of the Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei and Hunan Provinces, the heavy snow in winter of 1841 occurred from December 9, 1841 to January 10, 1842; the average snow depth reached ~50 cm and the duration of snow cover/icing lasted 25 to 50 d. For example, in the Nanhui, Jinshan, Qingpu, Baoshan and Fengxian Counties, and in Shanghai, the heavy snow starting on December 9, 1841 lasted more than 1 mo, with snow depth more than 2 chi (~64 cm). In the Gaochun, Suz hou, Taicang, Changshu, Wujiang, Dantu, Yizheng, and Jingjiang Counties, Jiangsu Province, continuously heavy snowfall started on December 9, 1841 with the snow cover/icing lasting more than 1 mo and the maximal snow depth reaching 10 chi (~320 cm). Similar descriptions were also recorded in many counties (e.g. Zhejiang, Anhui, Jiangxi) in Hubei Province and in several counties in the Hunan and Guizhou Provinces.

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