Exceptional drought events over eastern China During the last five centuries

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Exceptional drought events over eastern China during the last five centuries

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Abstract Climate extremes, particularly the droughts sustaining over a prolonged period and affecting extended area (defined as "exceptional drought events"), can have long-lasting effects on economic and social activities. Here we use the Chinese drought/flood proxy data of the past five hundred years to identify the cases of exceptional drought events over eastern China (east of 105°E), and to study their spatial patterns and temporal evolutions. The associated circulations for the contemporary case are analyzed using available meteorological data. Possible linkage of these cases to climatic forcing and natural climate events is also explored. After considering the intensity, duration, and spatial coverage, we identified three exceptional drought events, which occurred in 1586–1589, 1638–1641, and 1965–1966 in chronological order. They were the most severe droughts of last five centuries in eastern China, with more than 40% of affected area and the drought center encountered a significant summer rainfall reduction (about 50% or more). These three droughts all developed first in North China (34–40°N), and then either expanded southward or moved to the Yangtze River Valley (27–34°N) and the northern part of the southeastern coastal area (22–27°N). For the 1965–1966 case, the significant reduction of summer precipitation was caused by a weakening of summer monsoon and an anomalous westward and northward displacement of the western Pacific subtropical high. Our analyses also suggest that these three exceptional drought events might be triggered by large volcanic eruptions and amplified by both volcanic eruptions and El Niño events.

1 Introduction

In recent years, climate extremes (such as floods and droughts) have received increasing concerns due to their significant impacts on economy, society, and environment (Easterling et al. 2000; Changnon et al. 2001; IPCC 2002). In particular, the severe drought, because of its long-lasting and wide area coverage, such as the droughts during the dust bowl years (1930s) in the Great Plains of the United States (Karl and Koscielny 1982; Woodhouse and Overpeck 1998) and during 1980s in Africa's Sahel region (Vogel et al. 2000), can have

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devastating effects. China is located in the East Asian monsoon region, which is highly vulnerable to any anomalous monsoon rainfall, yielding droughts or floods. The focus of the present study is to identify *exceptional* drought events during historical times in eastern China where most of the population resides.

There are three criteria – intensity, duration, and spatial coverage – to determine the severity of a drought. In recent decades the available instrumental data (precipitation, temperature and others; Wilhite 2000) make it possible to categorize the droughts. But during the last few centuries, the historical records and tree rings are the only data providing the needed information for categorizing the droughts (Bradley and Jones 1995). Tree rings have been used to determine the intensity, duration, and spatial coverage of droughts for certain areas (e.g., the North America, Cook et al. 1999). Very few tree-ring chronologies are available in China, but there are abundant historical records. The historical data is particularly abundant in China due to the fact that more governmental archives ("Official History") have survived and that the compilation of local gazettes had become a more common practice for counties and districts since the Ming Dynasty (Zhang 1988). A great amount of government archives and local gazettes thus provide abundant data resources with regard to weather and climate over the last five centuries (Wang and Zhao 1981; Zhang 1988; Wang and Zhang 1991, 1992; Wang et al. 1992; Liu et al. 2001). In particular, a network of drought/flood (D/F) index was compiled from hundreds of archives, mainly from county (*Xian*) and district (*Fu* or *Zhou*) gazettes by Chinese researchers in the 1970–1980s (CNMA 1981), which can provide a wide spatial coverage, in addition to the information of intensity and duration.

In the past several decades, great efforts have been made in China to study droughts using instrumental and historical data. The earlier work, based on the historical data, focused mainly on characteristics of drought such as frequency, spatial pattern, and decadal to centennial variability, and elucidated the relationship between drought and temperature (e.g., Wang and Zhao 1979; Zhang 1988; Zhang and Crowley 1989; Yan et al. 1992; Qian et al. 2003). Wang et al. (2000b) used 1951–1996 observational data to study possible causes for drought in North China, and found that the western Pacific subtropical high and meridional circulation in the middle latitudes over East Asia are responsible for the occurrence of summer rainfall in North China. The instrumental and historical data were also used to study the trend of extreme climate (e.g., Sun et al. 1998) and the linkage of drought and flood to other global issues such as El Niño/Southern Oscillation (ENSO; e.g., Huang and Wu 1989; Liu and Ding 1992; Whetton and Rutherford 1994; Zhang and Xue 1994; Lau and Weng 2000; Li et al. 2005) and Pacific decadal oscillation (PDO, e.g., Zhu and Yang 2003; Shen et al. 2006). However, few works focused on the exceptional drought events, although work to date has revealed some extreme drought years over the last five centuries in China (e.g., Zhang et al. 1988). In this study, we will examine the occurrence of exceptional drought events in eastern China over the last five centuries, elucidate their spatial patterns and temporal evolution, and explore possible causes for exceptional drought events using historical proxy data and available meteorological data.

2 Climate data

2.1 500-years drought/flood index

We identify the exceptional droughts using the D/F index published by CNMA (1981) and recently extended by Zhang et al. (2003a). The D/F index is defined as a measure of rainfall in the main rainy season (Zhang 1988). As summarized in Table 1, this index uses five grades, 1 – very wet, 2 – wet, 3 – normal, 4 – dry, 5 – very dry, to describe climate conditions. The relative frequencies of five grades, i.e., 10, 25, 30, 25, and 10%, are defined by observed summer rainfall anomalies (Zhang 1988; Wang et al. 2000b). While the grades for the period 1500–1950 were compiled based on a statistical evaluation of historical descriptions, the values for the late 1951–2000 were converted from observed summer rainfall, assuming this distribution of the relative frequencies of five grades is constant through the historical times and observed times. Comparing this index with a drought classifications: moderate (11–20%), severe (6–10%), extreme (3–5%) and exceptional (0–2%) used by the U.S. National Drought Mitigation Center http://www.drought.unl.edu/; Svoboda et al. 2002) from the aspects of occurrence probability and SPI (standardized precipitation index) values, grade 5 approximately corresponds to droughts of severe and worse, and grade 4 to moderate drought.

The D/F index dataset has 120-stations covering the whole of China, but the stations over eastern China have less missing data. After considering the factors concerning the data gaps, station homogeneity, and locations subject to more drought occurrences, we identify 64-stations which cover the area located mainly in eastern China (22–40°N, 105–122°E; Fig. 1) where the East Asia summer monsoon dominates the rainfall (Ding 1991). The study area covers 17 provinces in the North China (NC, 34–40°N), the middle and lower Yangtze River Valley (MLYRV, 27–34°N), and the southeastern coastal area (SEC, 22–34°N). Within each province, three to five regions are located. Each region is designated by a city

Table 1 The norms of grading and their typical descriptions (Zhang 1988)

Grade	Norm	Typical description in archives
1 (very wet)	Protracted heavy rain	In spring or summer, excessive rain continued over a month
	Extensive flood	Heavy rain for several days, land flooded, boating on land
	Unusually heavy typhoon rain	Cropland and houses of several counties were inundated by heavy rain or typhoon
2 (wet)	Spring or autumn protracted rain with moderate damage	Spring or autumn protracted rain
	Local flood	Some counties flooded in certain months
		Drought in spring but heavy rain in summer
3 (normal)	Favorable weather	Good weather for crops
		A bumper harvest
4 (dry)	Light disaster caused drought in single season	Spring drought
		Autumn drought
	Local light drought disaster	Short of rainfall in summer, drought in some month
		Drought and plague of locusts
5 (very dry)	Severe drought over a season	Drought from spring to summer or from summer to autumn
	Drought continued for several months, or for two seasons	Grave drought in summer
		No rain in four months, and rivers dried out.
		A thousand miles of barren land
	Grave drought in extensive area	Severe drought throughout south of the lower reach of The Yangtze River.

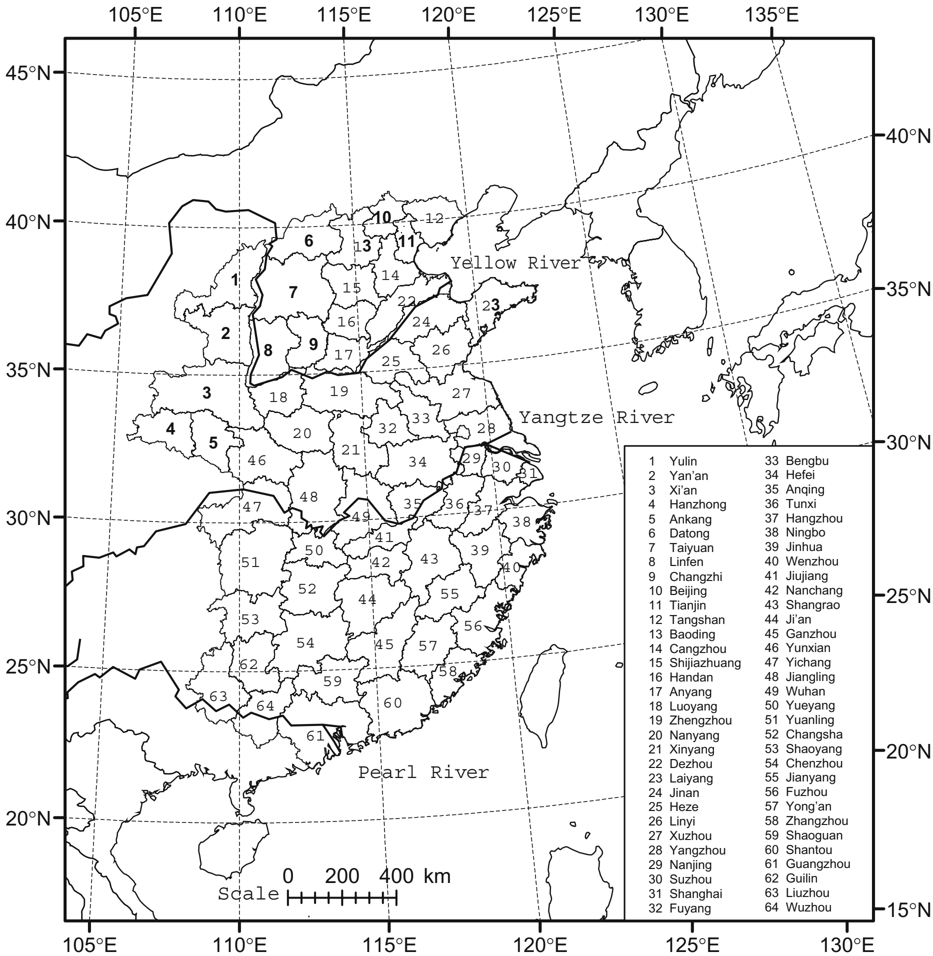

Fig. 1 The study region and a network of historical drought/flood index data. Sixty-four regions mainly consist of one or two districts in the historical times of China, each denoted by a city. Climatic conditions in each region are relatively homogenous

that is the political and economic center of the region. From an administrative perspective, each region includes about ten counties, which is roughly equal to one or two districts in the historical times of China (Zhang 1988). Consequently, the region here does not correspond to climatic region such as that used in some studies of droughts (e.g., Kiladis and Sinha 1991; Hayes et al. 2000). Nevertheless, the climatic condition was relatively homogenous in these regions for an assigned grade (Tang 1988), especially for grade 5 as illustrated in Table 1.

To consider the spatial coverage of droughts, we calculate the area of these regions shown in Fig. 1 using the GIS (geographic information system) technique (Chapman and Thornes 2003). The boundary of each region was created using present-day boundaries of the counties. Although the boundaries may be different (versus present-day) during the historical times, we anticipate the errors introduced would be small. Area and area percentage of the study region (total area of 2,062,760 km^2) for each grade was subsequently calculated.

Here, only the area percentages for grade 5 (i.e., very dry) were used as a criterion to detect drought years for eastern China as a whole. Grade 5 was chosen because it reflects the degree of drought intensity for a region rather than a local one, as mentioned above.

2.2 Instrumental data of recent decades

We also used instrumental data of 1951–2000 to study the spatial and temporal patterns of summer monsoon rainfall for the purpose of quantifying the droughts that occurred during recent decades as well as to examine the associated large-scale circulation during drought events. Data used here are monthly precipitation of 64 meteorological stations from these regions in eastern China. In addition, we also used the monthly mean geopotential height, wind, and relative humidity of the 1948–2000 NCEP reanalysis (http://dss.ucar.edu/pub/reanalysis) to investigate the contrast in large-scale circulations between climatological mean conditions and those years when droughts occurred.

It is also worthwhile here to briefly summarize the northward migration of the summer monsoon, which has a direct effect on the rainfall distribution. Eastern China is located in a monsoon region, where the summer monsoon contributes about 70% of the total annual rainfall. Previous studies have demonstrated that the summer monsoon affecting the study region originates in three airflows, i.e., the southeast monsoonal airflow from the southern flank of the subtropical high over the western Pacific, the cross-equatorial airflow from the Australian region, and the Indian summer monsoonal airflow (Ding 1991). On average, the summer monsoon onset occurs in early to mid-May when heavy convective rainfall develops over southern China along the pre-Meiyu front. Meiyu, or "Plum Rains", is a Chinese term for a regional rainy season in June and July over the Yangtze River Valley in East China. This is normally followed by abrupt northward shifts of the summer monsoon. It first shifts to the Yangtze River Valley after mid-June, causing an elongated rain belt referred to as Meiyu in this region. The summer monsoon then shifts to northern China in July, triggering the rainy seasons of northern China. At the end of August, the summer monsoon begins to withdraw southward (Tao and Chen 1987; Ding 1991; Samel et al. 1999; Chang et al. 2000).

3 Exceptional drought events

Figure 2 shows the time series of area percentage of eastern China under very dry conditions (grade 5) over the last 500 years. Clearly it exhibits fluctuation on the interannual, decadal and centennial time scales, with a maximum of 53.4% during the past 500 years. On the decadal time scale, relatively high values occurred during 1520s, 1590s, and 1920s, and low values in 1520s, 1730–1770, 1840–1870, 1880s, and 1950s; on the centennial scale, 16th (8.5% on average), 17th (9.2%), and 20th (11.2%) centuries encountered more occurrences of drought conditions than 18th (5.5%) and 19th (6.4%) centuries.

In the present study, we used 20, 30, and 40% as thresholds to classify the severity of drought into three types – *severe*, *extreme*, and *exceptional* – which correspond closely to the drought classification scheme of 10, 4, and 1% of occurrence used by the U.S. National Drought Mitigation Center (Svoboda et al. 2002). In this classification, there were 49 years when more than 20% of the area was in very dry condition (*severe* drought), of which 25 occurred individually and the rest consecutively in two, three or even 4 years. More *severe* droughts occurred during 1500–1590, 1630–1680, 1780–1820, 1920–1940, and 1960–2000. The number of *extreme* drought year is 19, with more cases identified in the 20th

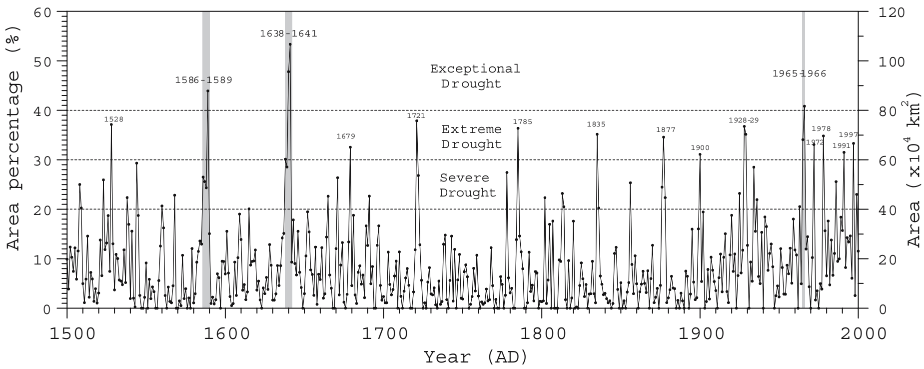

Fig. 2 A time series of area percentage over eastern China in very dry conditions (severe drought or worse) during the last five centuries, created by using GIS technique based on the network of drought/flood index in China. Severe, extreme, and exceptional drought years stand out, with area percentages reaching 20, 30 and 40%. These three thresholds of area percentage were defined by occurrence rates of droughts at different categories in the drought classification scheme used by the U.S. National Drought Mitigation Center. Three exceptional drought events were identified. The greatest extent occurred in the later 2 years of 1638–1641 event, peaking at about 50%; the secondary peak of about 44% occurred in 1589 of 1586–1589 event, and the third peak of about 41% in 1966 of the most recent event

century, especially in the past 40 years. It is needed to point out that this marked trend toward increased frequency of extreme droughts in late 20th century seems not an artifact of different data, although different methodologies in data sources might induce somewhat errors in the classification of the drought. The *exceptional* droughts occurred four times, in 1589, 1640, 1641, and 1966, with areas affected about 43.9, 47.8, 53.4, and 40.8% respectively. In the following, we focus the discussion on three events with consecutive *severe*, *extreme*, and *exceptional* droughts, occurring during 1586–1589, 1638–1641, and 1965–1966.

3.1 1586–1589 event

The earliest event persisted for 4 years, from 1586 to 1589. In its first year, the climatic pattern showed a north/south dipole (Fig. 3). Very dry conditions occupied the NC with a total of 26.5%, whereas the other parts of eastern China were in wet or very wet conditions. The pattern in the following year is similar to that of the first year with the drought center still located in the NC, and 25.6% of the area in very dry conditions. However, the climatic conditions in 1587 over the southern parts were not as wet as that in 1586. The area in very wet conditions decreased from 28.5 to 7%. The drought center moved to the MLYRV and spread to more regions in 1588, when 30.8 and 24.4% of the area was in dry and very dry conditions. The area in very dry conditions then expanded dramatically to reach its maximum (43.9%, 906, 000 km^2) in its exceptional drought year (1589). The climatic conditions in the late 2 years of this event exhibited a three-belts-like pattern, different from that in the early 2 years. The northern and southern parts of eastern China were in normal and wet or very wet conditions, whereas the central part was in dry or very dry conditions.

Historical records also show that this event had great drought intensity. Entries of the descriptions of this exceptional drought included, “Thousands of *li* (a traditional Chinese measurement unit equaling 0.5 km) of barren land”, “no water flows in rivers”, “Lakes, wells, and springs dried up”, and “severe drought caused great famine, and people ate each

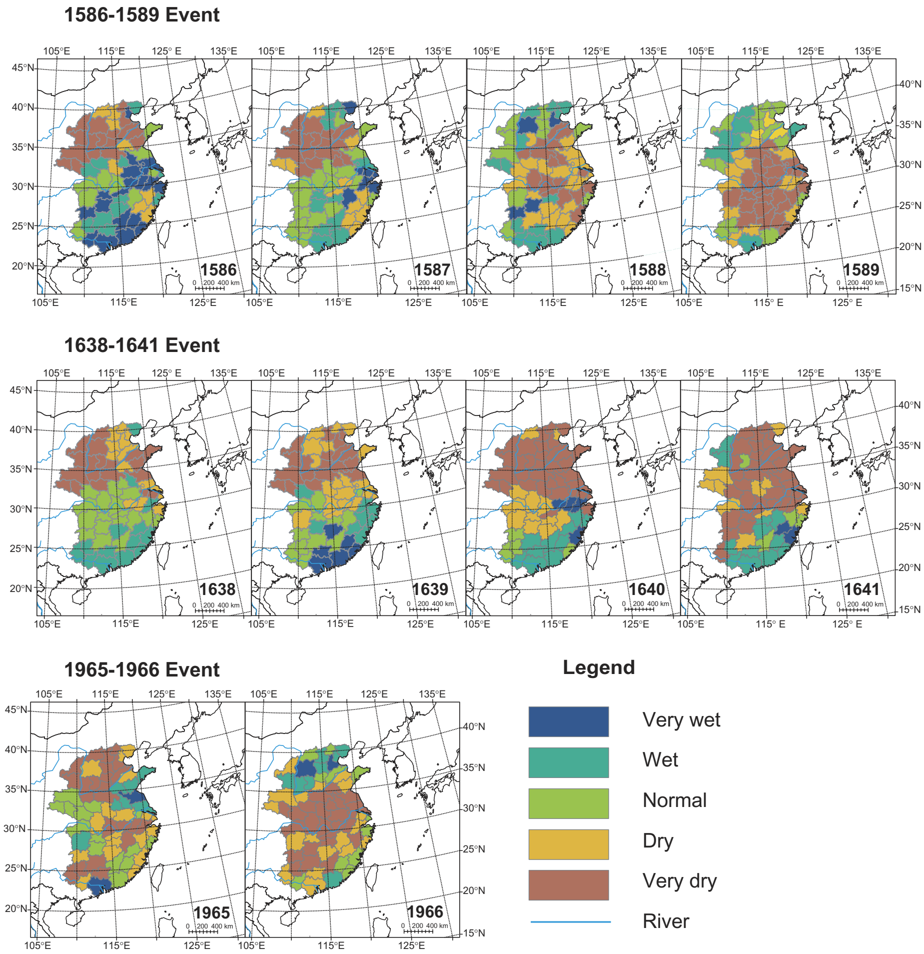

Fig. 3 Spatial patterns and temporal evolution of climatic conditions during three exceptional drought events. Drought center was located in the NC at their early stages. It then moved southward to the MLYRV and expanded, or it simply extended southward to the MLYRV to reach its maximum spatial coverage at their late stages

other" (Tang 1988; Tan 2003). Moreover, some major hydrological events provide an estimate of summer rainfall in some regions during this event (Table 2). Taihu Lake, the third largest freshwater lake in China, dried up in 1588 and 1589. In instrumental records from 1924 to 2000, the driest year is 1934 in the Taihu catchments, when Suzhou recorded a 116 mm of summer rainfall (June to August) with a departure of −72% from the normal (420 mm). This drought caused the decline of the lake level and desiccation of channels on the shores of Taihu Lake, but the lake itself did not dry up. Thus, the intensity of drought in 1588 and 1589 would have been greater than that of 1934 in this region. In 1589, one section of the Huaihe River near Huoqiu county in the Hefei region dried up, indicating a much greater drought intensity in comparison with the most recent exceptional drought, since this did not happen in 1966.

Table 2 Major hydrological events during exceptional drought events in historical times

Year	Hydrological event	Inferred summer rainfall departure	Source
1588	Taihu Lake dried up	<−70% in Taihu catchments	明史
1589	Taihu Lake became land		明史
1589	Huaihe River dried up	<−50% in Huaihe catchments	霍丘县志
1640	Yellow River dried up	<−50% in middle and lower reaches of the Yellow River	明史
1641	Grand Canal dried up		明史
1640	Spring flow stopped	<−50% in Jinan	历城县志
1641	Spring flow stopped		历城县志

3.2 1638–1641 event

The event in 1638–1641 was the most extensive one over the last five centuries. The spatial distribution in the first 2 years was characterized by a north/south dipole pattern, with dry or very dry conditions occurred in the NC (44.3 and 53.2% respectively in 1638 and 1639) where the drought centers were located for both years (Fig. 3). The spatial pattern in 1640–1641 was still a north/south dipole, but drought conditions apparently expanded southward to the MLYRV in these 2 years and the area in normal and wet or very wet conditions decreased significantly from about 50% in the early 2 years to 30%, limited to the southern part of eastern China. In 1640, 24.2% of the area was in dry conditions, mainly occupying the middle Yangtze River Valley, while 47.8% of the area was in very dry conditions, occurring in the NC and the lower Yangtze River Valley. In 1641, more area was in very dry conditions, covering an area of 1,100,000 km^2, more than 50% of eastern China, including all of the NC and the MLYRV.

This event significantly exceeded the first one in its spatial extent. And evidence in historical documents suggests that its intensity was likely as large as the first one. The common descriptions of both exceptional droughts documented in historical archives were similar to each other (Tan 2003). During this event, a noted hydrological event is the desiccation of the Yellow River and some of its tributaries such as the Fenhe River, Xinhe River, and Yihe River in 1640 (Table 2). In recent decades, the drought year with drought intensity comparable to this case is the extreme drought year of 1997, in which there was no outflow of the Yellow River to the sea for more than 300 days. About 700 km of the lower reach of the Yellow River dried up. Meanwhile, its major tributaries in its middle reach, including the Fenhe River, Xinhe River, Yihe River, Yanhe River, and Weihe River were desiccated. Observational data in the late 20th century shows that summer rainfalls significantly declined in 1997 in the regions of the middle reaches of the Yellow River. The anomalies of summer rainfall for Taiyuan, Changchi, Linfen, Zhengzhou, and Anyang are −52.1% (the third lowest value), −55.9% (the minimum), −44.9% (the second lowest value), −47% (the second lowest value), and −57.9% (the minimum) respectively, indicating a great intensity of drought. Additionally, springs in Jinan, the city in eastern China famous for its springs, stopped flowing in 1640 and 1641, corresponding to the desiccation of the Yellow River. Such events happened twice in Chinese history, the other was in 1073 and 1074 in the Song Dynasty. The most recent one appeared in 2002, when Jinan experienced a severe drought, receiving only 159 mm of summer rainfall (the second lowest value in the observational record of 1951–2003) with a departure of −52% from the normal. As population and development of industry and agriculture has increased, the need for water supplies in the last several decades has risen dramatically in eastern China. This implies that the same hydrological event would happen more easily now than during historical times, in other words, the drought conditions during such events would have had to be more severe in historical times than the present. Thus, the exceptional drought event in 1638–1641 appears to have surpassed the most recent one in intensity too.

3.3 1965–1966 event

3.3.1 Spatial pattern and intensity

The contemporary case has the least spatial extent and duration among three events (Fig. 3). In 1965, the areas under very wet, wet, normal, dry, and very dry for the whole eastern China are 4.9, 10.9, 23.4, 26.7, and 34.1%, respectively, with the latter two covering the NC (the drought center), the lower Yangtze River Valley, and the southwestern part of the SEC. The pattern in 1966 indicates that the drought center moved southward to the MLYRV, and the total area under very dry conditions reached 842,200 km^2 (40.8%). On the other hand, the northern and southern parts, a combined total of 29.6%, were in normal and wet to very wet conditions. From 1965 to 1966, the drought center moved from the NC to the MLYRV, and more area was in very dry conditions.

It is evident from Fig. 2 that the most recent exceptional drought identified here was the most extensive and persistent drought during 1950–2000, although high area percentages in very dry conditions were also observed in several extreme drought years such as 1972, 1978, 1991, and 1997. Moreover, its intensity, determined by observational data, was the greatest. Observational data from 1950 to 2000 indicates that the whole of eastern China recorded the least summer precipitation of the late 20th century in 1966 and the fourth lowest value in 1965. Less than 50% of the climatological mean summer rainfall was recorded in 1966 at the drought center. The minimum values of monthly rainfalls were observed in May, August, and September of 1966. Eastern China as a whole received normal monthly rainfalls in June and July of 1966 (Fig. 4). However, their spatial distributions are not even, exhibiting a three-belts-like pattern. The MLYRV received less rainfall, whereas the northern and southern parts of eastern China received more than normal. Thus, the 1965–1966 event is the most severe drought of the 20th century in eastern China in terms of drought intensity, duration, and spatial coverage.

3.3.2 Circulation statistics

Figure 4a–e shows the spatial patterns of monthly rainfall anomalies from May to September in 1966. It is evident that summer rainfall in the exceptional drought year over eastern China did not follow the general pattern mentioned above in Section 2.2. Heavy rainfall in the SEC normally arriving in May did not appear until June, and a “void” Meiyu occurred from June to July in the MLYRV. Rainfall in August and September declined more than 50% in the most parts of eastern China, except for the northern part of the NC in August and the coastal regions in September.

This rainfall anomaly is mainly attributed to a weak summer monsoon, and the position of the subtropical high. As shown in Fig. 5, a marked decrease in total column moisture (TCM) was observed over eastern China during the monsoon season of 1966. The negative anomalies of monthly TCM occurred in May, June, August, and September. The total TCM from May to September decreased by more than 15% in most parts of eastern China apart from its northernmost part, where a small positive anomaly was observed. The monthly rainfall anomalies, shown in Fig. 4, match closely with the monthly TCM anomalies, which implies that the rainfall reduction in 1966 was caused by a significant decrease of water

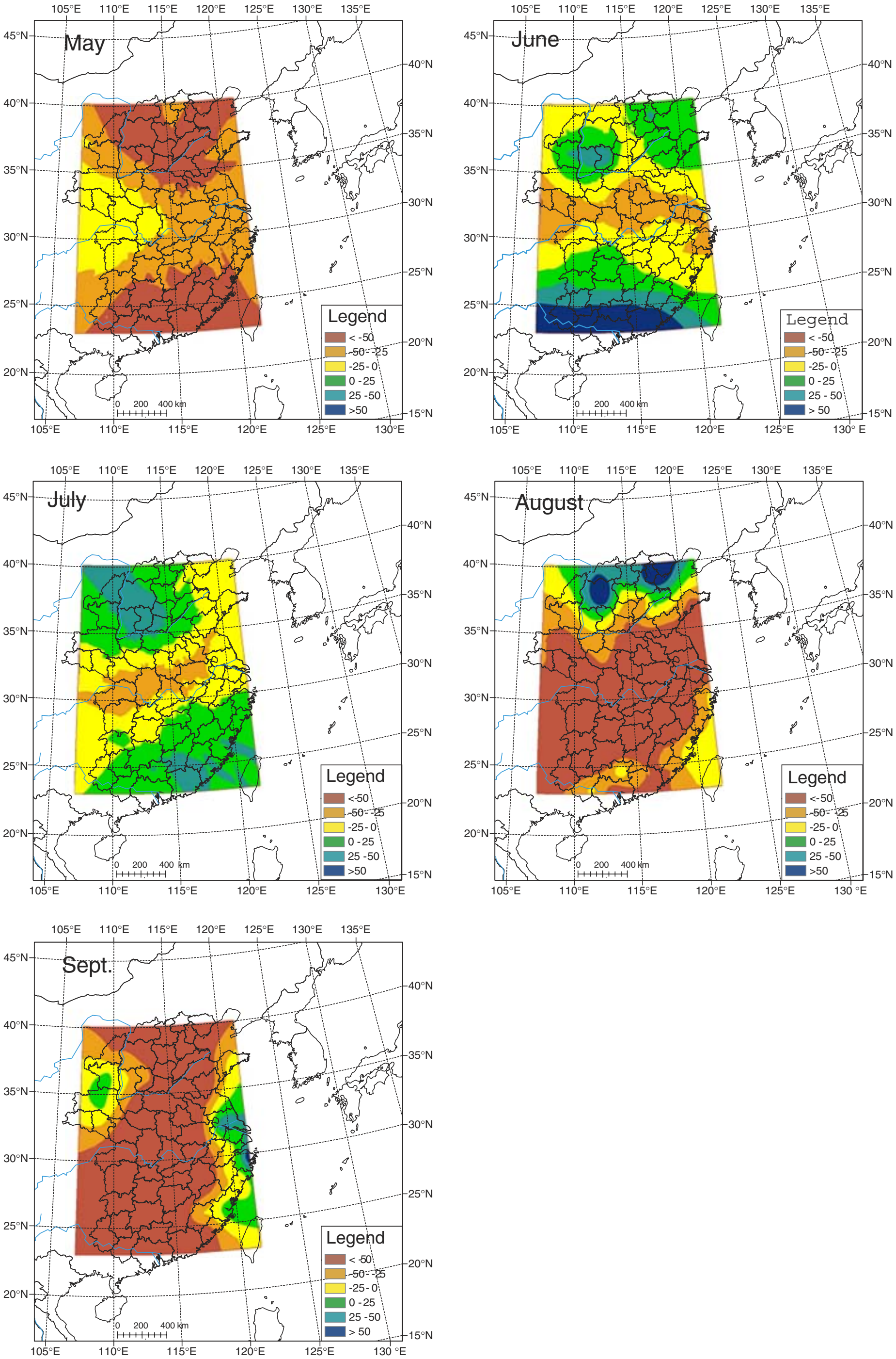

Fig. 4 Spatial pattern of monthly rainfall anomalies (%) from May to September in the exceptional drought year of 1966 over eastern China, derived from monthly precipitation data of 64 meteorological stations in these regions. Anomalies are with respect to the period of 1951–2000

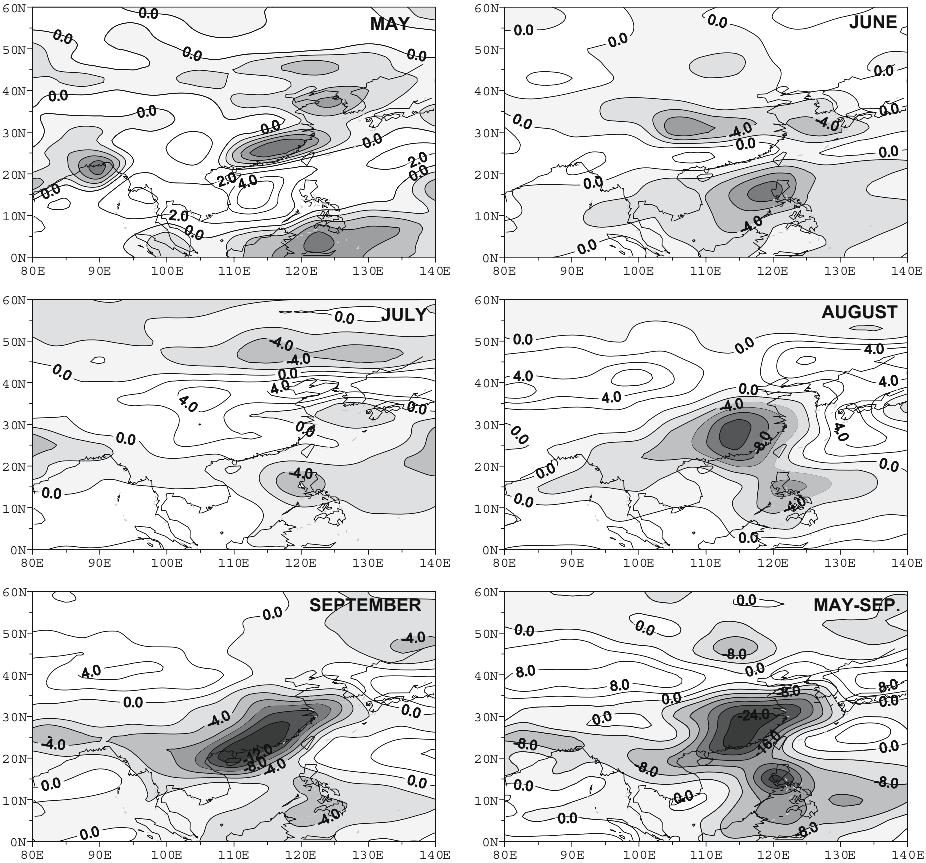

Fig. 5 Monthly and total TCM anomalies (%) from May to September in 1966, showing a marked decrease of TCM in exceptional drought year. Anomalies are with respect to the period of 1951–2000

vapor into eastern China related to a weak monsoon, as suggested by the Indian monsoon index, the western North Pacific summer monsoon index, and the East Asia summer monsoon Index (Wang et al. 2001b; Zhang et al. 2003b). The small positive anomaly of TCM in the northernmost part of eastern China is probably attributed to the midlatitude westerlies, since this part is under the influence of the midlatitude westerlies, which is another contributor of moisture transport to the NC except for the Asian summer monsoon (ASM, Simmonds et al. 1999).

On the other hand, the "void" Meiyu in the MLYRV during June and July of 1966 was associated with the position of the subtropical high. The 500 hPa heights, shown in Fig. 6a, indicate that the subtropical high was farther to the south and west than normal in June. This position caused the occurrence of heavy rainfall over the high's northwestern flank, i.e., Meiyu front over the SEC rather than the MLYRV (Figs. 6c and 4b). In July, the enhanced subtropical high shifted northward and westward (Fig. 6b). The more westward and northward extension of the high enabled it to control the MLYRV, resulting in a northward shift of Meiyu front to the NC, thus a "void" Meiyu over the MLYRV (Figs. 6d and 4c). Such circulation pattern causing "void" Meiyu over the MLYRV was also observed in the extreme drought year of 1978 (Tao et al. 1988). In the other extreme drought years

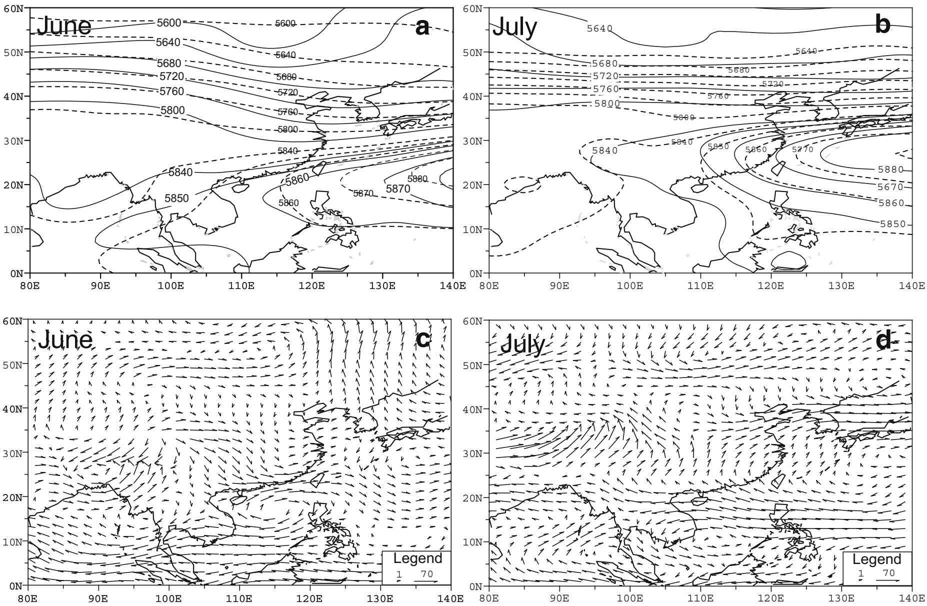

Fig. 6 Five hundred hectopascal geopotential height in June and July of 1966 (solid) and of 1951–2000 (*dashed*) (**a**, **b**), and anomalies (departure from averages of 1951–2000) of 850 hPa water vapor flux (10^{-3} kg m^{-2} Pa^{-1} s^{-1}) vectors in June and July of 1966 (**c**, **d**), showing the atmospheric circulation in the exceptional drought year. The water vapor flux vectors are computed from the specific humidity (q) and wind components (u- and v-wind) (Phillips and McGregor 2001)

such as 1972 and 1997 when the spatial patterns of drought condition were different from that in 1966 and 1978 and their drought centers were located in the NC instead of the MLYRV, the subtropical high was weak and shifted eastward.

4 Discussion and conclusions

In China, the economic damages attributed to drought have escalated in response to development of economy in recent decades. For example, the drought in 2001 caused temporary shortages in drinking water for 33 million rural people and 22 million head of livestock in China, and China lost US$6.4 billion in crops during the drought. However, the prolonged and extensive extreme and exceptional droughts in twentieth century and historical times have greater socioeconomic impacts than those in recent decades. In 20th century, two 2-year major droughts in 1928–1929 and 1965–1966 resulted in more than one million deaths in China and India (http://www.gesource.ac.uk/hazards/drughts-timeline.html). In historical times, the first two exceptional droughts in eastern China happened at the end of the Ming Dynasty. Many reasons have been cited for the collapse of the Ming Dynasty, including political corruption, economic breakdown, peasant rebellions, the invasion of the Manchu, and bad climatic conditions. The last is one of the direct reasons (Rodzinski 1979). As shown in Fig. 2, China experienced a series of severe, extreme, and exceptional droughts from 1500 to 1600, which greatly worsened the economic condition of the late Ming Dynasty. In 1627, severe drought and ensuing famine in Shanxi Province triggered the longest peasant rebellion in Chinese history (Parson 1970). Eleven years later, the most extensive and intensive exceptional drought began. Following this exceptional drought, the Ming Dynasty collapsed in 1644. Between 1585 and 1645, the population of China seems to have declined by as much as 40%, partly due to economic distress, warfare, and the collapse of law and order, and partly due to droughts and floods and ensuing famine and disease (Wakeman 1985; Temple 2002). It is evident that the exceptional droughts caused great economic, societal, and life losses, although their occurrence was very rare. Therefore, understanding the causes of exceptional droughts is vital to assessing the likelihood of similar events in the future.

Eastern China experienced a series of severe, extreme, and exceptional droughts over the last five centuries. Relatively high frequency of severe drought occurred in 16th–17th, 19th and 20th centuries, and the 18th century saw less severe droughts. Three intervals with relatively frequent severe droughts coincide with two cold periods (16th–17th centuries and 19th centuries) and one warm period (20th century) of North Hemisphere (NH), whereas the temperatures in relatively norm 18th century were higher than that of these cold periods but lower than that of 20th century (Mann et al. 1998; Wang et al. 2001a; Jones and Mann 2004). Among three identified exceptional drought events, the most recent one occurred in the warmest 20th century, whereas the other two, more persistent and extensive, appeared in the first cold period. The question here is what causes these exceptional drought events with long periods of time, great intensity, and extensive coverage since they happened in different climatic background. As shown in Fig. 3 and illustrated in Sections 3.1, 3.2, and 3.3, these three exceptional drought events seem similar to each other in their general features of spatial and temporal patterns, although there are some differences in their intensity, duration, and spatial coverage. The drought first developed in the NC. It then moved southward to the MLYRV and expanded to reach its maximum spatial coverage in 1586–1589 and 1965–1966 cases. The slight difference between 1638–1641 case and the others is that the drought condition in the former simply extended southward to take over most areas of eastern China after its early developing stage. The fact that all three exceptional drought events originated in the same region probably implies that the same climatic forcing would have triggered them, whereas the differences in their intensity, duration, and spatial coverage of drought may indicate variations of forcing strength and/or fluctuations in drought-producing atmospheric circulations.

On the other hand, the exceptional drought events identified here are not regional events. The most recent exceptional drought event is consistent with a major drought in India from 1965 to 1966 (Das 2000; Fig. 7a) and an extreme drought in 1962–1966 over the northeastern U.S. (Cook et al. 1992). High dust and chloride concentrations around 1590 and 1640, documented in a high-resolution ice core record from Dasuopu, Tibet, indicate serious Indian monsoon failures and ensuing droughts in the Indian monsoon domain (Thompson et al. 2000). Tree-ring records show that the drought persisting from 1587 to 1589 is the driest 3-year episode over the last 800 years in the southeastern U. S. (Stahle et al. 1998). Therefore, the mechanisms that caused these exceptional drought events must be variations in external forcing and/or internal fluctuations either within or outside the monsoon system.

The analysis of the meteorological data shows that the most recent exceptional drought was induced by the summer monsoon weakening and anomalous position of the subtropical high. The influence of summer monsoon strength on droughts over eastern China has long been recognized (e.g., Zhu 1934), and has been studied extensively (e.g., Shen and Zhu 1982; Guo 1985, 1994; Tan et al. 2003). In general, strong summer monsoon results in drought in the MLYRV and flood in both the NC and the SEC, and normal summer monsoon causes inverse climate conditions in these three regions, whereas droughts can occur during the years with weak summer monsoon in the most part of eastern China,

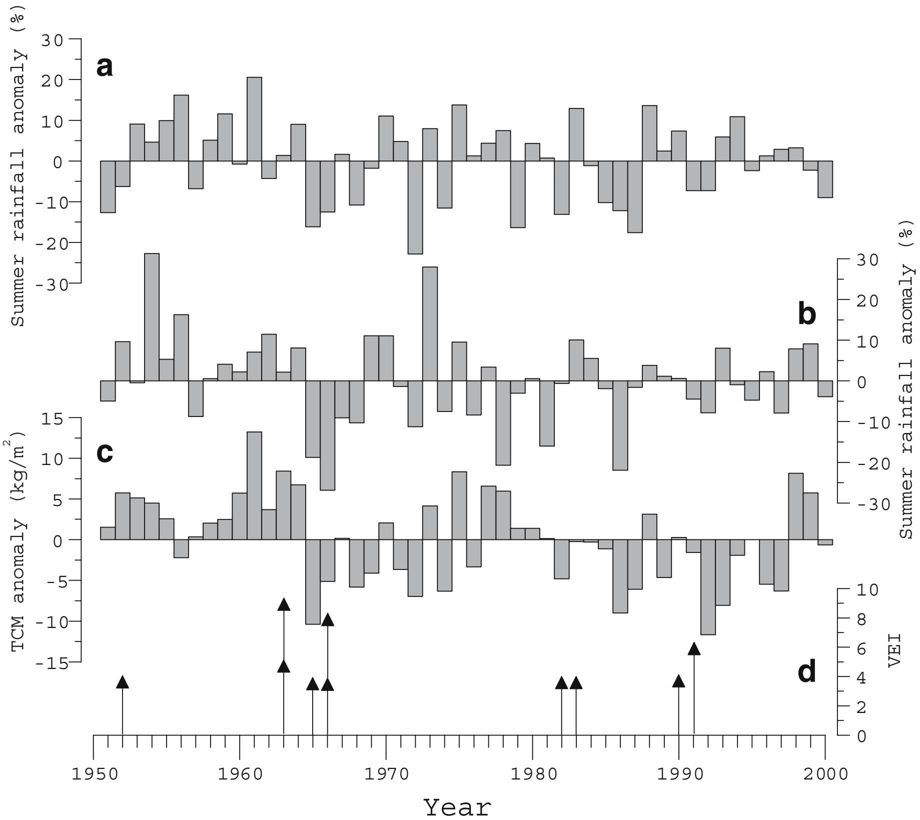

Fig. 7 **a** Time series of summer (June–August) monsoon rainfall anomaly (percentage) over all India (Parthasarathy et al. 1995). **b** Time series of summer (May–September) monsoon rainfall anomaly (percentage) over eastern China. **c** Time series of the TCM anomaly (kg/m^2, departure from average of 1951–2000) over East Asian monsoon domain (20–45°N, 110–140°E). **d** Volcanic eruptions with a VEI of 4 or larger in tropical Asian monsoon region (source: http://www.volcano.si.edu/world/largeeruptions.cfm)

especially in the NC and the MLYRV due to significant decrease of moisture brought by summer monsoon into these regions (Guo 1994). In the most recent exceptional drought event, both 1965 and 1966 experienced weak summer monsoons as shown by Fig. 7 and indicated by the monsoon indices (Wang et al. 2001b). The spatial patterns of drought in these 2 years tend to confirm the results of previous studies. However, the area affected by severe drought or worse was more extensive in 1966 than 1965, although the TCM reduced more significantly in 1965 than 1966 (Fig. 7). This implies the influence of the anomalous westward extension and northward movement of the subtropical high on extensive drought in the exceptional drought year is also important. It has been demonstrated that droughts (flood) generally occur over the NC (the MLYRV) when the position of the subtropical high is farther east and/or south than normal (Bi 1990; Ding 1991; Wang et al. 2000b). For example, the westernmost border of the subtropical high was about 40° farther east than normal in the extreme drought year of 1972, when drought center was located in the NC. Our analysis on circulation in Section 3.3.2 indicates that an inverse relationship is also true, as suggested by Tao et al. (1988). Therefore, it seems reasonable to conclude that the extensive drought in the exceptional drought year over eastern China was caused by the weak summer monsoon in combination with the anomalous westward and northward displacement of the western Pacific subtropical high.

Then, the next question will be the causes for a weak summer monsoon and an anomalous position of the subtropical high. The variability of summer monsoon strength and the position of the subtropical high have been found to be associated with the internal variability of the coupled ocean–atmosphere systems such as ENSO and PDO. Many previous studies indicate that a weak (strong) ASM is associated with the warm (cold) phase of the ENSO (e.g., Fu and Teng 1988; Zhao et al. 1989, Philander 1990; Chen and Yen 1994; Meehl and Arblaster 1998; Torrence and Webster 1999; Chang et al. 2000). The PDO, a long-lived ENSO-like pattern of decadal variability in sea surface temperature of the extratropical North Pacific has impacts on both the summer monsoon and the subtropical high. During warm phases, the summer monsoon is weak, and the strong subtropical high is located far to the south and west (Zhou and Huang 2003; Guo et al. 2004). The ENSO-ASM relationship may also be modulated by the PDO (Wu and Wang 2002). However, more than half of the major anomalies in the ASM are not related to ENSO (Lau et al. 2000). In our identified three exceptional droughts, only 1589, 1640, 1641, and 1965, were in-phase with El Niño episodes (Quinn and Neal 1995). And the first and the most recent cases were in cold phases of the PDO, whereas the second in warm phase (Shen et al. 2006). These two facts imply that the exceptional droughts persisting for several years cannot be explained by the internal climate variability alone, and other factors must be involved in causes.

A possible external forcing responsible for exceptional drought events in eastern China is volcanic eruption. It is well known that large volcanic eruptions have a significant impact on surface land and ocean temperatures (Robock 2000; Church et al. 2005). Volcanic eruptions inject massive amounts of dust and gases into the stratosphere. The resulting volcanic aerosols affect both shortwave and longwave radiation. This disturbance to the radiation balance of the Earth affects surface temperatures through direct radiative effects as well as through indirect effects on the atmospheric circulation (Robock and Mao 1995; Robock 2000). Although the volcanic signal in precipitation records is not as obvious as temperature records (Mass and Portman 1989), some recent studies of observed and simulated global precipitation indicate that the volcanic signal is detectable, especially these colossal volcanic eruptions as ranked with the volcanic explosivity index (VEI) of 4 or larger (Allen and Ingram 2002; Gillett et al. 2004; Lambert et al. 2005). These studies show that global precipitation significantly reduced in several years after four largest volcanic eruptions in the 20th century (i.e., Agung 1963, VEI=5; Mount St. Helens 1980, VEI=5; El Chichón, 1982, VEI=5; and Mount Pinatubo, VEI=6 1991). Xu (1986) investigated the impacts of three colossal volcanic eruptions (Agung 1963, Fuego 1974, VEI=4; and Mount St. Helens 1980) on summer rainfall in China. He found that significant reductions of shortwave radiation in the NC and the MLYRV occurred in summers of 1965, 1975 and 1980, when the NC experienced moderate (1975) to severe droughts (1965 and 1980), and the MLYRV saw floods. He attributed this anomaly summer rainfall to the southward shift of the subtropical high and the monsoon rainfall belt due to the anomaly decline of shortwave radiation. Our analysis shows that the TCM in the East Asian monsoon region declined significantly after a colossal volcanic eruption in the tropical region (Fig. 7), although there probably was a one or 2-year lag in the response of the summer monsoon to the eruption in some cases. An interesting fact is that the dipole pattern of anomaly summer rainfall, i.e., drought in the NC and flood in the MLYRV, is also observed in 1991. And moderate to severe drought conditions occurred in both the NC and the MLYRV in 1992. The spatial patterns and temporal evolution of drought in these 2 years are very similar to those of the 1965–1966 case, although the drought intensity in 1991–1992 was not as great as that in 1965–1966.

All three exceptional drought events started in a year witnessing a large-volume explosive eruption as ranked with the VEI of 4 or larger (Table 3). Moreover, one or more colossal volcanic eruptions occurred in one or 2 years before the starting years of the exceptional drought events such as 1586–1589 case and 1965–1966 case, and during the events such as 1640, 1641, and 1966. Additionally, the exceptional and extreme drought years of 1589, 1640, 1641, and 1965, were in El Niño episodes (Quinn and Neal 1995). Adams et al. (2003) linked the ENSO phenomenon with forcing from explosive volcanism. Although this hypotheses is still in debate, it seems clear that both ENSO events and volcanic eruptions influence the drought-producing atmospheric circulation patterns such as weak summer monsoon and the anomalous position of the subtropical high, directly or indirectly (Xu 1986; Tang 1988; Slingo 1999; Chang et al. 2000; Wang et al. 2000a). Volcanic eruptions also cause cool summers (Robock and Mao 1995) and more snow cover on the Eurasian continent (Robock 2002), weakening the strength of the summer monsoon (Hahn and Schukla 1976; Tao et al. 1988; Liu and Yanai 2002; Fasullo 2004). Lower temperatures in summer may enhance the high ridge or blocking situation over East Siberia, which makes the subtropical high shift farther south (Ding 1991). It seems reasonable to conclude that explosive volcanism plays a role as trigger in causing the exceptional drought events in eastern China. Drought conditions during these events were then amplified by "cluster" eruptions since more than one eruptions happened during the events. The most extensive drought years of 1589, 1640, and 1642 are coincident with El Niño events, indicating that ENSO may play a role as amplifier too. The temporal evolution of the events shows that droughts moved southward over multiple years. It may indicate that the drought conditions might have been amplified by some local feedbacks such as changes in land cover and soil moisture, but more evidences, such as simulation results of regional climate models, are needed to support this hypothesis. We note that not each explosive eruption results in an exceptional drought event. One possible explanation is that the volcanic effects were not amplified or even subdued by other factors. An alternative is that the climatological mechanism for exceptional drought events is more complex than those we discuss here.

Table 3 Volcanic eruptions during three exceptional drought events

No.	Volcano name	Eruption start date	VEI
1	Colima, Mexico	1585 Jan. 10	4
2	Kelut, Indonesia	1586	5?
3	Raung, Indonesia	1638	4
4	Llaima, Chile	1640 Feb.	4
5	Komaga-Take, Japan	1640 Jul. 31	5
6	Kelut, Indonesia	1641	4?
7	Parker, Philippines	1641 Jan.	5?
8	Agung, Indonesia	1963 Mar. 17	5
9	Agung, Indonesia	1963 May 16	4
10	Shiveluch, Kamchatka Peninsula	1964 Nov. 12	4
11	Taal, Philippines	1965 Sept. 28	4
12	Kelut, Indonesia	1966 Apr. 26	4
13	Awu, Indonesia	1966 Aug. 12	4

Source: http://www.volcano.si.edu/world/largeeruptions.cfm

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