by Zhenghong Chen\textsuperscript{1, 2} and Guifang Yang\textsuperscript{3}

Analysis of historical meteorological drought and flood hazards in the area of Shanghai City, China, in the context of climatic change

Most Chinese metropolitan regions have experienced rapid urbanization. Cities lying in coastal areas are prone to severe weather events. The meteorological hazards expose greater numbers of developed areas a variety of inhabitants to increased risk. This paper attempts to characterize how urbanization process, as well as monsoon climatic oscillations, affects Shanghai’s vulnerability to severe weather conditions. To assess how regional urbanization may impact vulnerability to droughts and floods, an analysis examining potential rhythmic variations was implemented. Our results indicated that the centennial scale metrological droughts and floods were a function of monsoon climate, while the decadal metrological oscillations in recent one and half centuries were primarily modified by the anthropogenic behaviors and resulting hydrologic characteristics. In view of the wide distribution, the meteorological droughts and floods are key issues for long-term social-economic harmonization in Shanghai. This study can assist in prioritizing disaster mitigation measures and ensuring regional sustainable development in the study area.

Introduction

Meteorological drought is considered to be a period of abnormally dry weather sufficiently prolonged for the lack of water to cause serious hydrologic imbalance in the affected area (Academy of Meteorological Sciences, China Central Meteorological Bureau, 1981). Flood, on the other hand, is caused by extreme excesses of precipitation or the sudden release of a surfeit of water from storage, such as a reservoir or snowpack (Academy of Meteorological Sciences, China Central Meteorological Bureau, 1981). Meteorological droughts and floods are among the world’s most dangerous and costly of all natural disasters and have caused enormous economic damage and human suffering (Easterling et al., 2000; Wilhite, 2000; Milly and Wetherald, 2002; Ge, 2011; Chen and Yang, 2013a). Statistics from the United Nations indicates that during 1970-2005 over 30% of natural disasters were floods and nearly 15% were droughts or drought-related (wild fires and extreme high temperatures) (Easterling et al., 2000; China Meteorological Administration, 2010). In China, although it is argued whether the number of meteorological droughts and floods has significantly increased, the intensity of extreme events and associated economic losses seem to be rising (Yin and Li, 2001; Yu et al., 2009; China Meteorological Administration, 2010). For instance, extreme droughts (category 4 and 5 droughts, also classified as very dry and extreme dry periods based on China’s national criteria of droughts, usually initiating certain or serious effects on agriculture, industries and anthropogenic activities: see Academy of Meteorological Sciences, China Central Meteorological Bureau, 1981) in China are likely to have been accelerating nationwide in recent decades, posing significant challenges for humanity (Ye and Huang, 1990; Li et al., 2000; Qin et al., 2005; Ding, 2008; Chen and Gao, 2010; China Meteorological Administration, 2010; Ge, 2011; Chen and Yang, 2013a). Thus, China, as one of the top meteorological-hazard countries in the world, has long attracted the attention of numerous geologists and meteorologists (Clegg and Wigley, 1984; Qin and Duan, 1992; Bordi et al., 2004).

Shanghai is situated at 31º14’N, 121º29’E, at the east of Yangtze River Delta, with the East China Sea lying on the east, the Hangzhou Bay neighboring on the south and Jiangsu and Zhejiang provinces bounding on the west (Fig. 1). Located in a relatively moist region and characterized by seasonal monsoon rainfall, and as one of the richest cities in eastern China with GDP per capita of 82,560 Chinese yuan (US $12,784; Wang and Ma, 2013), Shanghai is especially vulnerable to droughts and floods leading to significant adverse effects on ecological systems and socioeconomic implications (Wang, 1962; Bordi et al., 2004; Zhang et al., 2009). Understanding how to characterize meteorological droughts and floods over a long time scale (decadal or centennial scale for instance), therefore, is essential for mitigation of meteorological hazards.

Shanghai city has good records of meteorological observations spanning 140 years (1873-2013) and long term continuous documentation over 1762 years (251 A.D. to present), offering significant materials for the climatic research in this region (Xu, 2006; Zhang et al., 2009; Ge, 2011). For decades, various studies have addressed the annual or interannual meteorological fluctuations of dry and wet conditions or single extreme events including rainstorm and big flood occurred in Shanghai over the past one and half centuries (Wang et al., 1981; Qin and Duan, 1992; Jiang et al., 1997; Tan, 1998; Chen and Zong, 2000; Easterling et al., 2000; Zhou and Yang, 2010). Their efforts have indicated that the centennial scale metrological droughts and floods are key issues for the decadal or centennial scale droughts (category 4 and 5 droughts, also classified as very dry and extreme dry periods based on China’s national criteria of droughts, usually initiating certain or serious effects on agriculture, industries and anthropogenic activities: see Academy of Meteorological Sciences, China Central Meteorological Bureau, 1981) in China are likely to have been accelerating nationwide in recent decades, posing significant challenges for humanity (Ye and Huang, 1990; Li et al., 2000; Qin et al., 2005; Ding, 2008; Chen and Gao, 2010; China Meteorological Administration, 2010; Ge, 2011; Chen and Yang, 2013a). Thus, China, as one of the top meteorological-hazard countries in the world, has long attracted the attention of numerous geologists and meteorologists (Clegg and Wigley, 1984; Qin and Duan, 1992; Bordi et al., 2004).

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Those studies, however, do not fully cover the longer term duration extending to hundreds or thousands of years. Also, it is often difficult to determine the regularity of commencement of droughts and floods over the longer term scale (decadal to centennial timescale) in a given area due to the high recurrence rate and vulnerability to damage. As a result, very little scientific literature can be found regarding long-term meteorological droughts and floods, potential natural/anthropogenic controlling factors, and coupling effects with economic and social development. How to associate the long-term meteorological sequence with its underlying natural and anthropogenic factors is, thus, the key to reducing the meteorological hazard vulnerability of the city and promoting local sustainable development.

In this paper, we first examined the temporal pattern of selected droughts and floods in the study area. Based on this record, we then reconstructed and assessed the historical changes of natural and anthropogenic factors that underlie the droughts and floods in the area. To conclude, a systematic and integrated multi-weather hazard mitigation system framework has been proposed.

Data and Methods

Database setting

One way to test the nature of meteorological droughts and floods in Shanghai is to determine overall temporal risk levels since 1873, or possibly as far back as 1470 A.D., with respect to the given data available: meteorological hazard frequency and intensity; population growth or economic development patterns; urban hydrologic variations; and possibly urbanization. The primary source of data used for this study is the Best Track Dataset from China Meteorological Administration (CMA) spanning 1873-2013. These data were originally released by China Central Meteorological Bureau (CCMB) during 1873-1979, and have been maintained and updated by CMA and some meteorologists (Zhang and Wu, 1999; Zhang et al., 2003). In this paper, annual precipitation data relative to the mean value from 1873-2013 were used (Zhou and Yang, 2001; China Meteorological Administration, 2010). In order to meet the primary goals of our present study, we collected yearly measurements of droughts and floods during 1470-2000 from various references and reports (Academy of Meteorological Sciences, China Central Meteorological Bureau, 1981; Zhang and Liu, 1993; Zhang and Wu, 1999; Zhang et al., 2003). We also incorporated the published database in recent decades from previous and ongoing studies to ensure a comprehensive and reliable dataset (Qin and Duan, 1992; Jiang et al., 2005; Qin and Zhao, 2006; Xu, 2006; Cao et al., 2008; Ma, 2008; Yun et al., 2009; Zhang et al., 2009; Shen et al., 2011; Shi and Cui, 2012).

Drought-flood classification and Methods

In this paper, meteorological floods and droughts are classified into five levels in terms of major flood, flood, medium, drought, and extreme drought (assigned as 1, 2, 3, 4, and 5, respectively; Fig. 2) based on anomalies in the actual measured precipitation or described occurrence frequency as well as area intensity (as shown in Fig. 2; Academy of Meteorological Sciences, China Central Meteorological Bureau, 1981). To facilitate a comprehensive study, the temporal patterns of droughts and floods were further compared with the precipitation-based drought anomaly maps over the past 140 years from four or five meteorological stations located in both urban and suburban areas of Shanghai. The drought process at the stations and the drought events of different periods during the past 500 years then can be determined. The processing analysis performed for drought classification can be found in Academy of Meteorological Sciences, China Central Meteorological Bureau (1981), Zhang and Wu (1999), and Zhang et al. (2003).

Continuous wavelet transforms (CWTs; see Yang et al., 2005) and functional spectral analysis (Yang et al., 2003) were used to identify the temporal variability of droughts and floods in Shanghai over time. Wavelet spectrum analysis was employed to show the variations in the dominant frequency since the 1470s. With these approaches, effective countermeasures can be developed for...
alleviating environmental vulnerability while mitigating the management of resource protection and human activities.

**Temporal Characteristics of Historical Droughts and Floods**

Given its sensitive eco-geological environment, unique climatic and hydrological patterns, and increasing anthropogenic activities, Shanghai is subject to droughts and floods that have negatively impacted on resource utilization, regional planning, and local economic sustainable development (Shanghai Bureau of Geology and Mineral Resources, 1988; Qin et al., 2005; Xu, 2006; Ge, 2011). Many areas, the Pudong, and Minhang districts in particular, frequently suffer from droughts and floods (China Meteorological Administration, 2010). The issue of meteorological hazards and associated eco-environmental degradation has been one of the major problems in this region.

Over the last thousand years, the recurrence intervals of meteorological droughts and floods in Shanghai has been gradually shortening (Zhang et al., 2011; Shi and Cui, 2012; Table 1). For example, between 251 A.D. and 899 A.D. (primarily from Sanguo to Figure 2. Time sequence of drought-flood occurring in Shanghai during 1470-2000 (drawn from dataset of previous studies (referring to Academy of Meteorological Sciences, China Central Meteorological Bureau, 1981; Zhang and Liu, 1993; Zhang et al., 2003)) and its correlation with sunspot activity (Solanki et al., 2004), city evolution, hydrological pattern, economic development, and urbanization processes (modified from Qin and Zhao 2006; Ma 2008).

| Table 1 | Meteorological droughts and floods during recent decades in Shanghai (Qin and Duan 1992; Xu, 2006) |
|---------|----------------------------------|
| Duration (A.D.) | Total number | Flood | Drought |
| 251-299 | 1 | 1 | 1 |
| 300-399 | 2 | 1 | 1 |
| 400-499 | 5 | 5 | 1 |
| 500-599 | 2 | 1 | 1 |
| 600-699 | 2 | 1 | 1 |
| 700-799 | 2 | 1 | 1 |
| 800-899 | 12 | 8 | 4 |
| 900-999 | 3 | 1 | 2 |
| 1000-1099 | 12 | 8 | 4 |
| 1100-1199 | 30 | 14 | 16 |
| 1200-1299 | 17 | 11 | 6 |
| 1300-1399 | 26 | 17 | 9 |
| 1400-1499 | 30 | 20 | 10 |
| 1500-1599 | 46 | 25 | 21 |
| 1600-1699 | 59 | 31 | 28 |
| 1700-1799 | 46 | 24 | 22 |
| 1800-1899 | 45 | 22 | 23 |
| 1900-1999 | 52 | 24 | 28 |
| Total number | 392 | 214 | 177 |
| 1873-2000 Total number | 125 | 34 | 37 |
| Annual number | 0.56 | 0.27 | 0.29 |
Tang Dynasty), the meteorological drought and flood recurrence interval in Shanghai was about 24.9 years, but shortened to 5.1 years during 900-1499 A.D. (from Wudai to Yuan Dynasty), and was 1.6 years from 1500 to 1999 A.D. (After Ming Dynasty) (Xu 2006; China Meteorological Administration 2010; Table 1). In the 20th century, on average, the recurrence interval was around 1 year (Ding, 2008; China Meteorological Administration 2010).

At the decadal scale, droughts and floods in Shanghai have changed dramatically, as evidently indicated by oscillations with approximate 40 year rhythm since mid 19th century (Fig. 2). The oscillations were most clearly displayed in a plot showing high values of drought occurrence in circa 1898, 1935, and 1972 (or low values of floods in 1882, 1919, 1954, and 1987, respectively, Fig. 2). Lower drought frequency occurred from 1470 to early 19th century, suggesting distinct centennial-scale climatic cycles (as represented in Fig. 2). In general, the number of droughts and floods in Shanghai reveals an increasing trend during 1470-2000 from an average recurrence interval from 3-5 years to 2-3 years, with 19th and 20th centuries showing an accelerated recurrence (Fig. 2). The droughts and floods during these above-mentioned centuries were quite remarkable and affected most districts of the city (China Meteorological Administration, 2010).

Discussion

Monsoonal variations in relation to centennial scale droughts and floods

Shanghai is located in the easternmost of Yangtze River Delta and is characterized by relatively flat terrain and a typical marine monsoon climate, with cold and dry winter and hot and moist summer (Shanghai Bureau of Geology and Mineral Resources, 1988; Qin and Zhao, 2006; Cao et al., 2008; Liang et al., 2011). The monsoonal instability in recent centuries makes Shanghai highly vulnerable to meteorological drought and flood hazards (Shanghai Bureau of Geology and Mineral Resources, 1988). The centennial scale oscillations in drought and flood variability during 1470-1800 are most clearly depicted in Figure 2 which shows three successive high values of drought frequency and low values of flood frequency (Fig. 2). Given the interannual variations in the dataset, it appears that the prominent drying processes occurred during early-middle periods of 16th, 17th, and 18th centuries. Three unusual strengthenings of the winter monsoon signals during these periods were generally similar to the palaeoclimatic changes in the eastern China (Shen et al., 2006; Ge, 2011; Liang et al., 2011).

Situated in a typical monsoon area, this region is likely to be affected by variations of monsoonal climate. When the winter monsoon is enhanced, the drought occurrence frequency should increase significantly and vice versa. In particular, extensive evidence is emerging that Earth’s climate has been sensitive to small changes in solar output at centennial time scale during the Holocene (Balachandran et al., 1999; Shindell et al., 1999; Landscheidt, 2003; Solanki et al., 2004; Xiao et al., 2006). In the year of solar maximum, during which sunspot activity is significantly amplified, the abnormality of the East Asian monsoon would lead to the shifting of rainfall belt. Therefore, the probability for convergence of bodies of cold and warm air would be largely decreased, seemingly causing the regional droughts that dominate the study area. We thus further believe that the consistent centennial cyclicity of climate might imply that the climates of East China were closely linked to, and potentially controlled by, the sunspot activity cycle and monsoon climate, as well as global change (Qin et al., 2005; Ge, 2011; Shen et al., 2011; Fig. 2). The drought and flood variations presented here, therefore, give new insight about regional or even global climatic changes occurring over the last 500 years.

Urbanization process affecting decadal scale droughts and floods

Also, our results are of interest in the context of decadal drought and flood events occurring after the middle of 19th century. This period is, however, synchronous with distinct urbanization variations due to the overall opening up policy in Shanghai (Ma, 2008; Fig. 2). As noted, unlike some other Chinese metropolis, Shanghai has always been at the forefront of the urban topographical evolution and river-system changes in the international and national economic context. In 1840s there was great commercial development in this city due to the initial opening of Shanghai to western countries (Ma, 2008). Shanghai began to serve as “modern town” and received much commercial attention (Fig. 2). In line with this trend, the population increased in Shanghai sharply from <8‰ of growth rate on average before the commercial

| Stage | Year | Population/Million | Arithmetic average growth rate (GR)/‰ |
|-------|------|--------------------|---------------------------------------|
| I     | 1412 | 0.38               | <8                                   |
|       | 1435 | 0.33               |                                       |
|       | 1445 | 0.32               |                                       |
|       | 1452 | 0.31               |                                       |
|       | 1462 | 0.27               |                                       |
|       | 1472 | 0.26               |                                       |
|       | 1482 | 0.26               |                                       |
|       | 1492 | 0.26               |                                       |
|       | 1502 | 0.26               |                                       |
|       | 1522 | 0.25               |                                       |
|       | 1810 | 0.53               |                                       |
|       | 1811 | 0.53               |                                       |
|       | 1816 | 0.53               |                                       |
|       | 1852 | 0.54               |                                       |
|       | 1865 | 0.69               |                                       |
| II    | 1910 | 1.29               | −31                                   |
|       | 1915 | 2.01               |                                       |
|       | 1927 | 2.64               |                                       |
|       | 1931 | 3.32               |                                       |
|       | 1932 | 3.13               |                                       |
|       | 1935 | 3.70               |                                       |
|       | 1937 | 3.85               |                                       |
|       | 1942 | 3.92               |                                       |
|       | 1945 | 3.37               |                                       |
|       | 1946 | 3.83               |                                       |
|       | 1947 | 4.49               |                                       |
|       | 1948 | 5.41               |                                       |
|       | 1949 | 5.46               |                                       |
|       | 1953 | 6.20               |                                       |
| III   | 1964 | 10.82              | −44                                   |
|       | 1982 | 11.86              |                                       |
|       | 1990 | 13.34              |                                       |
|       | 2000 | 16.74              |                                       |
|       | 2010 | 23.02              |                                       |
|       | 2012 | 23.80              |                                       |
opening-up (Stage I) to an average of 31‰ in the early 20th century (Stage II), and then 44‰ after the foundation of new China (Stage III) (Fig. 3 and Table 2; Hou, 1995; Shanghai Place Names Committee, 1998). The associated intensifying urbanization process largely altered the nature of the underlying surface and geomorphic configuration in the city (Cao et al., 2008; Ma, 2008; Quan et al., 2010; Liang et al., 2011). More than 300 rivers in the central urban area of Shanghai had disappeared between 1860 to 2003, amounting to a total of 520 km in channel length (Cheng et al., 2009; Fig. 4). The dense distribution of water systems in the suburban area also largely shrank from 12% in the mid 20th century to 6% recently (Cao et al., 2008).

Consequently, the changes in the river distribution of the city were potentially accelerating the recurrence of urban meteorological disasters (Fig. 2). This was reflected by the uneven spatial distribution of drought and flood recurrence variability, with densely-developed riverine areas showing pronounced vulnerability to both floods and droughts in past decades (Yan and Xu, 1996; Liang et al., 2011; Fig. 5). The induced disruption of water circulation and energy exchange remodeled the local climate and ecological system and led to a more fragile landscape environment and complex disaster-causing process, as revealed by the rain island (or heavy rain centre) scattering in the city (Cao et al., 2008; Quan et al., 2010; Chen and Yang, 2013b; as shown in Table 3).

Also, the permeability of the ground to natural surface water in Shanghai has, since the 1840s, decreased dramatically (Quan et al.,

Table 3. Urbanization-induced rain island effect revealing by the incremental percentage induced from precipitation difference between urban and suburb areas over time (modified from Zhou and Yang, 2001; Cao et al., 2008).

| Year      | Rainfall of suburb(SR)/mm | Rainfall of urban(UR)/mm | Incremental percentage/‰ |
|-----------|---------------------------|---------------------------|---------------------------|
| 1959-1968 | 10326                     | 10500                     | 1.68                      |
| 1969-1978 | 10429                     | 11221                     | 7.59                      |
| 1979-1988 | 11001                     | 11480                     | 4.35                      |
| 1989-1998 | 11673                     | 11699                     | 0.22                      |
| 1999-2007 | 10117                     | 10742                     | 6.18                      |

Here, incremental percentage = \((\frac{UR}{SR}-1)\times100\)

Figure 3. Population growth condition in Shanghai during the last 600 years.

Figure 4. Disappeared rivers in central districts of Shanghai over the last 150 years (a); Number of disappeared rivers in the central Shanghai (b) and length of disappeared rivers in the central Shanghai (c) (modified from Cheng et al., 2009).
As a commercial centre, Shanghai made significant steps forward in city construction and road building, following the effects that economic development exerted on the city (Ma, 2008; Liang et al., 2011; Figs. 2 and 6). Poor building layouts and decrease of permeability made the city more vulnerable to meteorological droughts and floods (Figs. 2 and 6; Cao et al., 2008; Quan et al., 2010; Liang et al., 2011). Therefore, the rapid population acceleration from 0.6 million to >23 million between 1840s and 2010 (The sixth population census bulletin of Shanghai, 2011; Fig. 3 and Table 2) and accelerated anthropogenic activities also altered the conditions for the surface river system, regional hydrologic conditions, and the meteorological circumstances (Figs. 2 and 4; Cao et al., 2008; Ma, 2008; Cheng et al., 2009; Yun et al., 2009; Ge, 2011; Liang et al., 2011). It seems rational to presume that these behaviors might be closely correlated with drought and flood hazards in the central city, coastal plain, and areas along the Huangpu River (Figs. 2 and 4).

To further validate the data on natural and anthropogenic signals in the meteorological droughts and floods, it is necessary to estimate the potential controlling in hazard recurrence during the past 500 years. For our record, such calibration efforts were largely hampered by the fact that instrumental data are only available for the last 140 years (Shen et al., 2011; Shi and Cui, 2012). Luckily, the climate of the last 1000 years has received considerable attention based on natural records (Wang et al., 2002; Ge, 2011). Thus, several proxy-based climate reconstructions ranging from regional to hemispherical scales are available in literature and a general consensus exists with respect to magnitude and amplitude of major climate deviations (Wang et al., 2002; Ge, 2011). Thus, for the most part of our dataset, evidence for the centennial meteorological droughts and floods suggested that these climate anomalies were driven by larger-scale phenomena, in agreement with previous studies (Wang et al., 2002; Ge, 2011). The precise mechanisms and processes that induced the observed precipitation fluctuations are still uncertain, but several factors including monsoon instability, fluctuations of the thermohaline circulation, and solar activity might be the potential factors over that period.

In spite of the difficulty in establishing the relatively long-period climatic variations, the occurrence of the observed sharp reducing of recurrence in ~40 year cycles should be indicative of a high anthropogenic-induced effect. This is also supported by the appearance of more road-building along the river resulted from urbanization since 1840s (Ma, 2008; Zhang et al., 2009; Shen et al., 2011; Shi and Cui, 2012). Identification of prompt expansion of urban population, extensive reduction of the river system and rapid expansion of transportation system since 1840's is consistence with previous observations (Ma, 2008; Liang et al., 2011; Shen et al., 2011; Shi and Cui, 2012; Figs. 2, 3, and 6). More particularly, information with regard to how human variables evidently contribute to these changes need to be further discussed and verified in our subsequent studies.
Framework for multi-weather hazard prevention and mitigation

Results from this study can be used to guide and prioritize management countermeasures to reduce meteorological hazard vulnerability in Shanghai. Firstly, the meteorological database system should be significantly improved for disaster prevention and mitigation. Localities such as Pudong and Minhang districts, that have higher drought vulnerability, should receive a higher priority for regulations and methods to reduce meteorological hazards. Perfect automatic monitoring systems such as the 3S system (GIS, RS, and GPS) should be adopted in the survey of meteorological disasters. The system for real time survey can be properly established in central urban areas to improve weather forecast accuracy and precision. Secondly, the geological-geomorphological background research for weather events should be substantially enhanced and meteorological disaster monitoring and evaluation should be intensified, particularly examining the weakest aspects for more precise disaster prediction. For the urban construction, human activities should be effectively undertaken and an early warning system and emergency response mechanism should be significantly improved. Hopefully, we should standardize the meteorological disaster prevention system and change the traditional concept of disaster mitigation management, arriving at a Chinese pattern of law-economy-technology-human system.

Conclusion

The temporal variation of meteorological droughts and floods over the past centuries in Shanghai remains a complex current problem. This article has presented a basic analysis of the historical meteorological hazards in Shanghai, with special emphasis on the droughts and floods during the past 500 years. Preliminary data suggest that it is likely that Shanghai, with flat terrain and changeable monsoon circulation, might be particularly vulnerable to many meteorological hazards. Our results indicated that the centennial scale meteorological variations are a function of monsoon climate; other decadal oscillations might be largely modified by hydrological and anthropogenic responses. These effects might have been amplified, in particular, by the rapid urbanization process. To ensure regional sustainable development in Shanghai, some possible disaster mitigation measures for social-economic harmonization have been proposed.

Acknowledgements

This work described in this paper has been supported by National Natural Science Foundation of China (No. 41220001, Z. H. Chen; No. 41172167 and 41320003, GF. Yang). Project funded by China Postdoctoral Science Foundation (General Program No. 2012MS20220 and Special Program No. 2014T70059, Z.H. Chen), Opening Fund from Institute of Urban Meteorology, China Meteorological Administration, Beijing (No. UMR201203, Z.H. Chen), and the Fundamental Research Funds for the Central Universities (No. 2652014058, GF. Yang). Professors P.J. Shi and C.S. Huang are greatly appreciated for their helpful and critical comments. The authors gratefully acknowledge the anonymous referees for their insightful reviews and recommendations.

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Zhonghong Chen is Associate Professor in Climatology at China Meteorological Administration Training Centre. He has obtained his PhD in Philosophy of Science and Technology from Beijing Normal University in 2009 and worked as a postdoctoral research fellow at Atmospheric Science in National Climate Centre of China since 2012. He conducts high-impact research in meteorological hazards and climate change.

Guifang Yang is Associate Professor in Geomorphology and Quaternary Geology at China University of Geosciences, Beijing (CUGB). She got her PhD in Quaternary Geology with a thesis on Paleoclimatic reconstruction at China University of Geosciences, Wuhan (CUG) in 2003. Since 2005, she serves as professional staff at China University of Geosciences, Beijing and coordinator of Chinese projects of Geomorphology and Quaternary Paleoenvironment.