A review of recent studies on extreme heat in China

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ABSTRACT
This paper reviews recent studies on extreme high temperatures in China during summer. The focus is on the variation in extreme heat and tropical nights (i.e. high temperature at night), and the factors of influence. Potential research topics in the future are also discussed.

In addition, hot weather has a significant impact on social and economic activities, affecting the consumption of electricity and water, and inducing forest fires and crop losses (Valor, Meneu, and Caselles 2001; Zhang and Wang 2002; Peng et al. 2004; Coumou and Rahmstorf 2012). Against the background of global warming in particular, high temperature weather such as hot days, hot nights, and heat waves has become more frequent on the global scale (IPCC 2013). According to the World Meteorological Organization (WMO 2013), during the most recent decade (2001–2010), the number of deaths due to heat waves (136,000) increased markedly (by 2300%) compared to the number (6000) in the decade before (1991–2000). Even after excluding the mega European heat wave of 2003 (~70,000 deaths) and the Russian heat wave of 2010 (~11,000 deaths), the increase in deaths was still 800% – much larger than the overall increase of 20% due to various extreme weather events including heat, cold, drought, storms, and floods (Figure 1).

Therefore, extreme heat events have become an important public concern, and are thus receiving an increasing amount of attention in the literature. In this paper, we review previous studies on the variation in extreme heat events in China and the meteorological conditions responsible for these events, focusing in particular on extreme high temperatures during the summer season. For other seasons and other climate extremes, there are review
papers already available in the existing literature to which readers may refer. For instance, Wang et al. (2012) comprehensively reviewed various climate extremes in China, including temperature, extreme precipitation events, dust weather, tropical cyclone activity, intense snowfall, cold surge activity, floods, and droughts.

2. Variation in extreme heat

As well as other regions in the world, China has also experienced a significant warming trend in recent decades, as indicated by various observational studies (Zhai and Ren 1997; Liu et al. 2004; Tang, Zhai, and Wang 2005; Qi and Wang 2012). There have been many previous studies on the variation in extreme heat (Zhai and Pan 2003; Gong, Pan, and Wang 2004; Wei, Yang, and Sun 2004; Wei and Chen 2009, 2011; Ding, Qian, and Yan 2010; Huang, Qian, and Zhu 2010; Ding and Qian 2011; Qian et al. 2011; Sun, Wang, and Yuan 2011; Wang and Fu 2013). In general, these studies, especially recent ones, suggest that extreme heat has increased over most parts of China. The details of the extreme heat trend, however, show a complex structure, with the trend being dependent on the study period and the latitude of stations. For instance, for the period 1958–2008, the frequency of extreme heat shows an increasing trend in southern and northwestern China and a decreasing trend in central China (Figure 2a). However, the distributions are quite different for the first and second half of this period: For the first half (1958–1983), a strong decreasing trend is apparent in central China, northern China, and the middle and lower reaches of the Yangtze River (Figure 2b), while for the second half (1984–2008), an overall increasing trend can be seen across China, with a stronger increase over southern and northwestern China (Figure 2c). In addition, the altitude of observational stations seems also to have an effect on local temperature trends, with larger increasing trends in daily maximum temperature for stations at higher altitude (Dong and Huang 2015; Feng, Liu, and Yan 2015).

In addition to the warming trend, some studies have indicated that the frequency of extreme heat shows a decadal variation. Wei and Chen (2009, 2011) indicated that there was an abrupt increase in the number of days with high temperature around the mid-1990s. Ding and Qian (2011) suggested that the frequency of wet heatwave events, which are defined considering both air temperature and relative humidity, were relatively low in the 1980s and increased remarkably since the 1990s. Wang and Gong (2010), considering both surface air temperature and humidity, found that ‘sultry weather’ occurred less frequently in the 1990s than in the 1940s. They argued that this phenomenon was due to the ‘urban dry island’ effect induced by the urbanization in Beijing during recent decades.

3. Factors affecting extreme heat

Large-scale circulation anomalies are considered as a major factor affecting temperature. Previous studies have focused on case studies (e.g. Wei and Sun 2007), and generally suggest that anticyclonic circulations induce extreme heat. However, some recent studies have indicated that high temperature weather in particular regions can result from various types of circulation anomaly (Cassou, Terray, and Phillips 2005; Harpaz et al. 2014; Takane, Kusaka, and Kondo 2014). In addition, the circulation affecting nearby sites (e.g. Madrid, Spain and Lisbon, Portugal) can be quite different (García-Herrera et al. 2005). Therefore, the diversity and regional features should be emphasized when studying the circulations associated with high temperature weather.

Chen and Lu (2015) recently investigated the synoptic circulation anomalies associated with extreme heat in eastern China, and categorized them into three patterns:
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A number of other studies have investigated the large-scale circulations associated with the interannual and decadal variations of extreme heat in China. Sun, Wang, and Yuan (2011) suggested that the circulation anomalies affecting the interannual and decadal variability of extreme heat in China are similar. According to their results, the variations in extreme heat in northern China are associated with anticyclonic/cyclonic anomalies in the mid-upper troposphere, while those in central and southern China are additionally associated with lower-tropospheric meridional wind anomalies.

Regarding the decadal variation of extreme heat, Wei and Chen (2011) argued that the increase in extreme heat over most areas of China after the mid-1990s was contributed to by the anticyclonic anomaly over northern China and Mongolia, and the related weakened East Asian monsoonal flow. The reason for this anticyclonic anomaly or temperature increase after the mid-1990s, however, is still not clear. Zhu et al. (2012) emphasized the role of greenhouse gas forcing on the temperature increase and the weakening of summer monsoon over northern East Asia, while other studies suggest that more precipitation in South China may have induced the anticyclonic anomaly over northern China and Mongolia (Kwon, Jhun, and Ha 2007; Chen and Lu 2014a).

Besides the impact of local atmospheric general circulation, remote factors also contribute to variation in air temperature. Sun (2012) indicated that the North Atlantic Oscillation can affect extreme heat in northern China, through a zonal wave train along the westerly jet. In addition, a number of studies have indicated that extreme heat may be affected by remote SST anomalies or heating forces. Hu et al. (2012) suggested that Indian Ocean SST anomalies affect the high temperature extremes over South China during late summer. Liu et al. (2015) suggested that precipitation anomalies over India and the South China Sea, as tropical heating anomalies, may affect the mean temperature and long-lasting high temperature events over the Yangtze River valley.

Meanwhile, other studies have focused on the influence of the underlying land surface. Wu, Zhang, and Dong (2011) revealed that vegetation exerts positive feedback on air temperature over many areas of China (except the ecological transition zone of northern China and some other isolated areas), contributing to 10%–30% of the total variance in temperature. Zhang, Liu, and Chen (2015) indicated that heat wave frequency and duration are negatively correlated with soil moisture, and that decreased soil

Figure 2. Linear trends in the number of extreme heat days (with maximum temperature greater than 35 °C) for the years from (a) 1958 to 2008, (b) 1958 to 1983, and (c) 1984 to 2008. The marks are proportional to the values of the trend, with red dots for positive values and green dots for negative values. Only the stations with a significant trend level above 95% are displayed. Units: d/10 yr. Source: Wei and Chen (2009).
4. Tropical nights

High temperature weather can be classified into two types: extreme heat, which denotes very high maximum
temperatures; and ‘tropical nights’, which means very high minimum temperatures. These two types may be quite different in terms of their occurrence and underlying mechanisms. Wei and Sun (2007) analyzed the occurrence frequency of these two kinds of hot weather over several major cities in North China, and showed that coastal cities like Qingdao usually suffer from tropical nights, but rarely from extreme heat. Meanwhile, in Taiyuan, a city on the Loess Plateau, tropical nights never occur, but extreme heat occurs occasionally. Even in the same city, extreme heat and tropical nights may exhibit different occurrence characteristics. For instance, in Beijing, extreme heat happens frequently in early summer, while tropical nights occur mainly in late summer (Wang, Ge, and Tao 2003; Park et al. 2012). Therefore, extreme heat and tropical nights might be caused by different physical processes, and it is necessary to study them separately. However, studies thus far have paid relatively less attention to tropical nights, in comparison with extreme heat.

Although the frequency of both warm days and warm nights has generally risen, warm nights have been found to show a more obvious increasing trend than warm days (Qian and Lin 2004; Zhou and Ren 2011), with a decreasing tendency of diurnal temperature range (Hua, Ma, and Zeng 2006; Huang et al. 2015). Actually, tropical nights have tended to occur more frequently in North China during the past several decades. For example, Wei and Sun (2007) reported that tropical nights have occurred more frequently in this region since the 1980s. In addition, Park et al. (2012) indicated that the frequency of tropical night occurrence during 1994–2008 was almost three times as large as that during 1960–1993, while the increase in extreme heat around the mid-1990s was not so clear.

Tropical nights have a significant impact on sleep comfort and inhibit a person’s recovery from heat experienced during the daytime, thus increasing the threat to human health of high temperature weather (Argaud et al. 2007). Therefore, it is important to have a detailed understanding of the variation in tropical nights, as well as extreme heat.

Park et al. (2012) analyzed the large-scale circulation associated with the interannual variation in tropical night occurrence in Beijing, and found that anticyclonic anomalies are responsible for more frequent tropical nights. However, in essence, tropical nights are related to synoptic processes and occur only occasionally in North China. For instance, in Beijing, tropical nights only account for 7.7% of the total days in July and August (Park et al. 2012), or 5.3% of the days in June, July, and August (Wang, Ge, and Tao 2003). Therefore, the synoptic weather processes associated with tropical nights should be emphasized.

Wei and Sun (2007) examined the circulation during a persistent tropical night period in North China, and demonstrated that the western Pacific subtropical high played an important role. More recently, Chen and Lu (2014b) investigated the large-scale circulation anomalies associated with tropical nights in Beijing, and compared them with those associated with extreme heat, based on extreme cases during 1979–2008. They found that Beijing tropical nights are associated with an upper-tropospheric anticyclonic anomaly to the northwest of Beijing and a lower-tropospheric anticyclonic anomaly to the southeast of Beijing (Figure 3(a) and (b)). These circulation anomalies are distinct from those associated with extreme heat, which are manifested by a cyclonic anomaly to the northeast of North China in both the upper and lower troposphere (Figure 3(c) and (d)). The difference in circulation between tropical nights and extreme heat leads to significantly different humidity anomalies, which are crucial for the difference between tropical nights and extreme heat.

Most tropical nights occur under wetter air conditions, and extreme heat days occur under drier air conditions. However, Chen and Lu (2014c) identified that atypical phenomena exist, i.e. dry tropical nights (30% of all tropical nights) and wet extreme heat (20% of all extreme heat days), during July and August in Beijing. They found that, in addition to meteorological conditions, temperature persistence between the day and night contributes greatly to these atypical phenomena: The maximum daytime temperature (minimum nighttime temperature) prior to a dry tropical night (wet extreme heat) is obviously higher than that prior to a wet tropical night (dry extreme heat) (Figure 4), suggesting a complicated mechanism for inducing tropical nights and extreme heat.

5. Future research

Two predominant trends mean that China will experience greater challenges in the coming several decades. First, the aging of China’s population is set to continue in the next three decades, meaning the number of vulnerable Chinese aged 65 and older will continue to grow. In addition, urbanization will continue in the coming decades, and the number of people living in cities will increase, exposing more vulnerable individuals to the ‘urban heat island’ effect in the future. Therefore, a better understanding of extreme weather and its impacts on human health is of particular significance for China. This provides a basis for higher levels of heat awareness and the implementation of a heat warning system. In addition, China’s development strategy should involve improvements in living conditions, such as the increased use of air conditioning, larger living areas, and increased urban green space, to deal with the potentially increasing crises of hot weather (Tan et al. 2007).

However, far less attention has been paid to temperature extremes than precipitation extremes in China, which
is possibly due to the long history of China as a traditional agricultural country. Even the extreme high temperature event in summer 2013 triggered relatively little investigation (Sun et al. 2014; Zhang et al. 2014; Zhou, Ma, and Zou 2014; Wang et al. 2016). Certainly, this special case should be studied comprehensively, similar to the extreme heat event that took place across Europe in 2003. In summary, more studies on temperature extremes, particularly on high temperature extremes under global warming, will be necessary in the future.

On the other hand, most studies on high temperature extremes have focused on extreme heat weather, while tropical nights have been somewhat ignored. This review indicates clearly that the meteorological conditions for extreme heat and tropical nights are considerably different. In addition, it is reasonable to assume that warmer nights might have increasingly greater effects in comparison with warmer days under global warming. Thus, more studies on the variation in, and formation of, tropical nights should be encouraged.

There have only been a few studies that have discussed the reasons for regional features of projected change in heat extremes under global warming. Li, Feng, and Zhou (2011) suggested that high temperature extremes would occur more frequently under global warming (doubling of CO₂) in China, but with regional differences that may be due to the differences in moist convection. In addition, Xu et al. (2015) also found regional differences in projected warming under global warming scenarios, based on CMIP5 (Coupled Model Intercomparison Project, Phase 5) output. Therefore, a better understanding of the impacts of large-scale circulation and SST on extreme heat in China may also be helpful for more reliable projections of the regional features of the warming trend. Actually, changes in regional circulation patterns may affect long-term changes in heat extremes over some regions (Horton et al. 2015). To project the future changes in temperature extremes more reliably at the regional scale, it is necessary for models to reliably project regional circulation changes and capture the relationship between regional circulation and surface air temperature.

Currently, seasonal forecasts generally focus on rainfall anomalies in China. We suggest that attention should also be paid to temperature anomalies. Severe temperature anomalies also have a significant impact on human health and social and economic activities. In addition, although drought occurrence is mainly controlled by rainfall amounts, high temperatures can greatly exacerbate the drought severity (Chen and Sun 2015). For this reason, it is necessary to improve our understanding of the impacts of large-scale circulation and tropical SST on temperature anomalies in China.

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