Recent increase in heat wave frequency around Mongolia: role of atmospheric forcing and possible influence of soil moisture deficit

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Abstract

A 30-year meteorological station and reanalysis datasets revealed that the frequency and intensity of hot extremes have increased dramatically around Mongolia since the late 1990s. Many recent heat waves (HWs) were triggered by atmospheric forcing with a mid-tropospheric ridge pattern which appears frequently around Mongolia in 2000s. An observational data analysis for each HW event indicates that the rate of temperature increase at the beginning stage of HW is sensitive to the soil moisture condition. Therefore, it is suggested that the recent drier soil conditions played a role in enhancing the frequency and intensity of HWs and localization around Mongolia.

Keywords: heat wave, soil moisture–atmosphere interaction, Mongolia

1. Introduction

The Intergovernmental Panel on Climate Change 5th Assessment Report documents a warming trend of 0.85ºC (1880–2012) in the global average combined land and ocean surface temperature (Hartmann *et al*., 2013). The frequency and intensity of extreme weather events have also increased since the 1950s (Hartmann *et al*., 2013). Heat wave (HW) frequency has increased since the mid 20th century, particularly over the middle–high latitude regions, such as Europe, North Asia, and Australia (Easterling *et al*., 2000).

Europe experienced its most extreme HW event in 2003, which led to a number of serious impacts including many deaths, economic losses, and wildfires (Fischer *et al*., 2007a, b; Stott *et al*., 2004; Weisheimer *et al*., 2011). This HW has been identified as the hottest recorded over the last 500 years (Luterbacher *et al*., 2004). However, the majority of atmosphere-ocean global circulation model experiments that incorporate enhanced anthropogenic greenhouse gas concentrations suggest that in the second half of the 21st century HW events similar to those in Europe in 2003 and Chicago in 1995 will occur more frequently and last for longer (Beniston, 2004; Meehl and Tebaldi, 2004; Schär *et al*., 2004).

According to the instrumental record, global mean temperatures in the 1980s, 1990s, and 2000s have been successively warmer than all previous decades (Hartmann *et al*., 2013). However, the rate of warming depends on location, with particularly strong warming in southern Brazil, central Russia (Siberia), and Mongolia (Hartmann *et al*., 2013). In Mongolia, the target region in this study, the annual mean air temperature increased at the rapid rate of 0.4ºC/decade over the period 1951–1990, whereas the rate of change in summer was negligible before the 1990s (Yatagai and Yasunari, 1994). Furthermore, a recent study based on 25 weather stations over the period 1961–2001 found that there was a statistically significant increase of 8–18 days in the annual number of HW days, with a more pronounced change in high mountain areas than in the Gobi desert (Batima *et al*., 2005). Similarly, Nandintsetseg *et al*. (2007) found an increase of 5–7 days in hot extremes, along with a decreasing number of cold extremes, in the northern Mongolia during the period 1963–2002. Despite these studies, the characteristics of hot extremes in Mongolia remain unclear, at least in the following respects: (1) whether the spatial extent of the rapid increase in hot events is restricted to Mongolia or spreads more widely over the surrounding areas, and (2) the physical mechanisms behind the sudden increase in hot extremes.

Schubert *et al*. (2014) examined HWs in the northern Eurasia and summarized the associated physical mechanisms. They suggested key parameters connected to the development of a HW, including atmospheric features such as a persistent anticyclone and atmospheric blocking as a driver of the HW, and land surface parameters such as soil moisture (SM) as environmental conditions. In this study, we first demonstrate the spatial and temporal variation of hot extremes around Mongolia using local observations and reanalysis data. A mechanism controlling the recent increase in HW is then discussed from the perspective of atmospheric forcing and possible roles of land surface processes. Although low SM may enhance the possibility of HW by limiting evapotranspiration (Hirschi *et al*., 2011; Jung *et al*., 2010), a strong HW also leads to a low SM condition because of a positive feedback process which often makes difficult to diagnose the role of SM. In Section 4 we will examine a potential influence of SM deficit to the HW development through a context of observational data analysis.

2. Data, definitions, and method

2.1 Data

In this study, we used surface meteorological observations and reanalysis data for the 30 years from 1981 to 2010. Mongolia is located in the transitional zone between the Taiga forest and the Gobi desert. We analysed 70 stations covering all of the climate regimes of Mongolia (Fig. 1a). The observational dataset provided by the National Agency for Meteorology and Environment Monitoring (NAMEM) of Mongolia contains daily maximum surface air temperatures, daily precipitation, and SM (10cm) for June to August (JJA). To investigate the spatial extent of hot extremes outside Mongolia and to study the mechanisms responsible, we used the daily mean air temperature at a height of 2 m, the 500-hPa geopotential height, and the surface (0–10 cm) SM provided by the NCEP/NCAR Reanalysis 1 (Kalnay *et al*., 1996) on a 2.5° mesh grid.

2.2 Definitions and method

The HW was identified based on the World Meteorological Organization standard, which requires that at each station the daily maximum air temperature is 5 ºC higher than the daily climatology (1981-2010), for four or more consecutive days. We also allowed a one-day discontinuity, preceded or followed by three consecutive days if above criteria is satisfied. We applied the same methodology to the reanalysis data to determine the horizontal extent of HWs outside Mongolia.

To examine the interannual variation of the synoptic circulation pattern associated with the HW, the middle tropospheric circulation pattern was analysed together with other surface parameters, which is discussed in Section 4.

3. Results

This section examines the interannual variability of hot extremes by using HW indices to show how they have changed in recent decades. Figure 1a displays the climatological (1981–2010) distribution of HW frequency around Mongolia derived from the reanalysis data. There are three separate regions with high HW frequency in the northern Russia (Siberia), the northern Pakistan, and Mongolia. The northern Pakistan region is isolated from the other two and has a smaller spatial extent. In contrast, the high HW frequency areas around Siberia (4–10 days) and Mongolia (2–6 days) have wide spatial extent.

Figure 1b illustrates the interannual variation of HW frequency averaged over 70 stations (see Fig. 1a) in Mongolia. Fewer HW events were observed during JJA in the 1980s with 0.6 days on average, which increased to 4.2 days in the 1990s, and reached 9.4 days in the 2000s. HW frequency derived from the reanalysis data indicates a similar trend (not shown). The maximum was reached in 2002 with 22.2 days. Indeed, HW frequency was persistently high from 1999 to 2002, corresponding to the intensive drought during which many water sources dried up, including 683 rivers and 760 lakes (Davaa *et al*., 2007). In addition, HWs tend to occur nationwide in the 2000s as indicated by the widespread HWs which are assigned when more than half of the 70 stations simultaneously observed HW (Fig. 1b). The recent increase in HW frequency is in good agreement with daily maximum air temperature, which indicates a significant ($p = 0.05$) warming during the 1980s and 1990s (23.0°C in the 1980s and 24.1°C in the 1990s) followed by a rapid increase to 25.5°C in the 2000s (Fig. 1b).

Figure 2 illustrates the location where the HW change was significant (95% confidence level of the Student's t-test) over the decades using the NCEP/NCAR Reanalysis 1 data. Significant change in HW frequency occurred in the eastern Europe and Mongolia between the 1980s and 1990s, and in the eastern Russia and the northwestern Mongolia between the 1990s and 2000s. In the northwestern Mongolia, the HW increase is significant for all decades, which is a unique feature of the northern Eurasia. The similar results were confirmed for ERA-interim reanalysis. This persistent HW increase supports the analysis of Batima *et al*. (2005), who pointed out the higher rate of increase of HWs in mountains than in deserts in Mongolia. Further analysis on the mechanism of this rapid change is presented in the next section.

4. Possible mechanisms of HW increase

We analysed synoptic-scale circulation patterns to investigate the contribution of atmospheric forcing to HW. JJA-mean geopotential height anomaly at 500 hPa represents that the high pressure anomaly centered around the northern Mongolia and Europe are intensified in the

2000s (Fig. 3) consistently with the localized recent increase in HW frequency around Mongolia. This suggests a ridge around Mongolia is associated with continental-scale wave train in middle latitude (Iwao and Takahashi, 2006). A composite of 500-hPa geopotential height during the widespread HW (Fig. 3d) exhibits a ridge structure around Mongolia whose geographical location matches well with high pressure anomaly in the JJA mean field in the 2000s (Fig. 3c), confirming the importance of large-scale atmospheric circulation as a driver of Mongolian HW (Horton *et al.*, 2015). The similar results were confirmed for ERA-interim (not shown).

A new index reflecting the strength of the middle tropospheric atmospheric circulation forcing (ACF) is introduced to diagnose the role of atmospheric forcing on the temporal variation of HW. The ACF is designed to capture the typical circulation patterns around Mongolia during the widespread HW events (Fig. 3d), and is defined as the number of days per year when the geopotential height difference at 500 hPa between the Taklimakan Desert (40°N, 80°E) and the area around Lake Khovsgol (50°N, 100°E) (hereinafter ΔgZ) is equal or less than 50 m (mean is 111m in JJA) over more than 3 consecutive days. In Fig. 4, the interannual variation of ACF indicates a weak increase over the study period, with anomalously high values in the 2000s. The JJA mean ACF was 5.0 days in the 1980s, 10.5 days in the 1990s, and 17.9 days in the 2000s. The maximum ACF (30 days) occurred in JJA of 2002. This suggests the possible contribution of changes in atmospheric circulation pattern to the increase in HWs. However, the response of HW to ACF seems to vary over time. In the 1980s and 1990s, HW frequency was relatively low, even in high ACF years (e.g., 1981, 1991, and 1992), leading to the weak sensitivity of HW to ACF (Fig. 4). In contrast, in the 2000s the high ACF affects the high HW frequency, especially during the multi-year drought period from 1999 to 2002 (Fig. 4). The different responses of HW frequency to the ACF suggest that atmospheric forcing alone is insufficient to explain the increase of HW in the 2000s.

Previous studies have suggested that SM might have had a role in intensifying the

European HW event in 2003 (e.g., Fischer *et al.*, 2007b). To assess the influence of land surface processes on the relationship between ACF and HW, we examined surface variables in Fig. 4. The 70-station-averaged standardized precipitation index (SPI; blue bar in Fig. 4) calibrated for one month was relatively high, with positive values before 1998. But, it shifted to negative values after 1999, which corresponds with the timing of the multi-year drought (1999–2002). This precipitation variability is in good agreement with SM both in reanalysis and in-situ observation (averaged over a framed area in Fig. 1a) which became very low in the 2000s (Fig. 4). A similar declining trend in deeper (5-100cm) SM is found in reanalysis and observation (not shown). These results suggest a hypothesis that land surface condition is associated with extreme temperature events.

To verify this hypothesis, a scatter plot of ACF and HW frequency is shown in Fig. 5a. In general, HW frequency is proportional to ACF (r = 0.74); i.e., atmospheric forcing is a key driver of HW. A regression coefficient between HW and ACF is 0.174 for years when reanalysis SM is above climatology (SM > 0.249 m^3 m^{-3}). In contrast, for dry years when the SM is less than the climatology, the coefficient becomes 0.519, which is significantly higher than wet years tested by jackknife cross validation while the coefficient for dry year is not significantly higher than that for all years. This suggests in previous decades positive feedback between atmosphere and SM was dampened by wetter SM.

There are exceptional years, such as 1992 and 2003, in which the HW is not high even under high ACF and low SM conditions. Since low SM and high ACF can occur simultaneously as a result of positive feedback between SM and atmosphere, it is difficult to conclude that whether low SM in 2000s was the cause or the result of high HW. To discuss the potential effect of low SM, daily-based HW development in 2000s was investigated for atmospheric forcing events. To ensure significant temperature response, strong atmospheric forcing is focused. Figure 5b displays a lag composite of daily temperature anomaly at 21 stations (See Fig.1a) relative to the day when ΔgZ satisfies $\Delta gZ \leq 0$ or $\Delta gZ \leq -30$ (day=0). The mean duration required for reaching $\Delta gZ \leq 0$ and

$\Delta gZ \leq$–30 from climatological condition is 5-day and 7-day, respectively. To examine the temperature response under the different initial SM conditions, we adopted 10-day interval observed SM before day=0. For both temperature and SM, anomalies from climatology at corresponding day are calculated for each station. For dry SM condition, the temperature increasing rate is higher (3.3 °C/5day) than wet initial (2.1 °C/5day) for moderate atmospheric forcing ($\Delta gZ \leq$0). Furthermore, the rate for dry SM (4.1 °C/5day) and wet SM (2.7 °C/5day) are obviously different under strong atmospheric forcing ($\Delta gZ \leq$–30). The difference becomes statistically significant (95%) after day=–2 for both moderate and strong atmospheric forcing ($\Delta gZ \leq$0). Although lack of spatial and temporal resolution of the dataset in Mongolia, this suggests a precursor SM deficit helps amplify the temperature response to given ACF, similar to modelling studies in other regions which evaluated the role of low SM for intensifying HWs (e.g., Fischer *et al.*, 2007b).

Finally, we examined the spatial distribution of land surface changes with respect to the location of HW change. The decadal change in SM anomaly shows positive in the 1980s (Fig. S1a) and small difference in the 1990s (not shown), followed by a pronounced depletion in the northern Mongolia and the northeastern China in the 2000s, which is also evident in the northern Pakistan and the eastern Afghanistan (Fig. S1b). The centre of change in SM around the northern Mongolia, located to the southwest of Lake Baikal, corresponds closely to the region of HW increase (Fig. 2), suggesting that local SM reduction is associated with the localized HW increase in the northern Mongolia. As Mongolia is situated in the ecotone where high levels of vegetation activity and SM in the Taiga forest in the northern Mongolia meet the low levels in the southern Mongolian Gobi desert region, land surface condition is highly sensitive to climate change.

This study has revealed the spatial distribution of the local HW increase in Mongolia, which is associated with changes in atmospheric circulation and local land surface conditions that have occurred simultaneously since the late 1990s. To evaluate the role of SM in enhancing the probability of a strong HW, a sensitivity experiment controlling the SM in an atmosphere–land coupled model (e.g., Fischer *et al*., 2007a, b) will be necessary in future research. In addition, more detailed analysis of the moisture and surface energy budgets (e.g., Miyazaki *et al*., 2004) would be valuable to explain the unexpectedly high HW frequency in wet years, by taking account of intraseasonal variation of precipitation and SM.

5. Conclusions

This study investigated the interannual variation of extreme hot events in Mongolia. The frequency and duration of extreme events have increased since the late 1990s, which seems to associate with a middle tropospheric ridge pattern around Mongolia, indicating that synoptic-scale circulation has contributed to the recent increase in HW. This intensification represents localization in Mongolia, isolated from the surrounding regions in the northern Eurasia. The regression coefficient between monthly-based ACF and HW become high when the soil is dry. Furthermore, the daily-based temperature increasing rate is significantly larger for low soil moisture condition, suggesting that SM regulates the magnitude of temperature response to a given atmospheric forcing. Therefore, it is suggested that the recent drier soil conditions played a role in enhancing the frequency and intensity of HWs and localization around Mongolia. Further studies probably by the numerical modelling are necessary to quantitatively discuss the SM effect to the localized HW increase and its mechanism.

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Supporting information

The following supporting information is available:

Figure S1. Horizontal distribution of reanalysis SM.

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