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Variations in start date, end date, frequency and intensity of yearly temperature extremes across China during the period 1961–2017

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Abstract

Frequent temperature extremes due to climate change have had serious effects on human society and the natural environment. Using a 0.25° × 0.25° gridded Tmax (daily maximum temperature) and Tmin (daily minimum temperature) data set and 12 global climate models simulations from the sixth phase of the Coupled Model Intercomparison Project (CMIP6), we investigated variations in yearly temperature extremes in China during the past five decades with respect to four characteristics, namely, their start date, end date, frequency, and intensity. Results showed that the occurrence of nighttime extremes (the cold nights and warm nights) responded strongly to climate change. For 1961–2017, cold extremes started later (3.25 d/decade) and ended earlier (−4.58 d/decade), with decreased frequency (−6.56 d/decade), especially for cold nights, and weakened intensity (0.14 °C/decade). In the same period, warm extremes started earlier (−3.43 d/decade) and ended later (3.15 d/decade) with increased frequency (6.79 d/decade), especially for warm nights, and enhanced intensity (0.09 °C/decade). The spatial pattern of the variations was complex with anomalous regions. Multimodel ensembles (MMEs) from CMIP6 agreed well with observations regarding the average trends of temperature extremes over China, although detailed changes in spatial pattern were not captured adequately. The hazards of temperature extremes deserve close attention in the future due to the complex changes likely to occur across China for various characteristics of these temperature extremes under conditions of climate change.

1. Introduction

Climate change and its impacts on water resources (Miao et al 2016, Gou et al 2020), agricultural production (Piao et al 2010), vegetation growth (Seddon et al 2016) and other areas of importance are major forces that human society will have to cope with in the 21st century (IPCC 2018). Observations show that global average surface temperature has increased about 0.85 °C over the period 1880–2012 (Compo et al 2013), and the continuous emissions of greenhouse gases will cause further warming (IPCC 2013). Changes in the frequency, intensity, spatial extent, duration and timing of weather and climate extremes are more intense compared to changes in average temperatures under this rapid global warming (IPCC 2018). Previous studies have suggested that the number of extreme events has increased approximately in proportion to the rate of the warming trend (WMO 2019), with an increase in both warm and cold extremes and more frequent and severe extreme precipitation events (Bao et al 2017, Han et al 2019, Sun et al 2019, Zheng et al 2019).

On a global scale, previous studies have demonstrated that historical warming over the past century has increased the frequency and intensity of warm extremes, while decreasing the frequency and intensity of cold extremes in most regions of the globe (Coumou and Rahmstorf 2020, Morak et al 2013, Donat et al 2016). Extreme temperature events have exerted more devastating influences on human societies and the natural environment than mean warming trends.
(Schiermeier 2018, Chen et al 2019). However, the pattern of change for extreme temperatures is not spatially uniform at the regional scale due to regional differences in the response of the climate system to increasing radiative forcing and the background noise of climate variability (IPCC 2018). For example, an increase in warm extremes and a decrease in cold extremes have been observed in the Arab region (Donat et al 2014), Australia (Wang et al 2016) and China (Sun et al 2015b); however, a decrease in warm extremes has occurred in the northwest of the contiguous United States (Mutiibwa et al 2015) over the past 50 years. Regionwide warming of extreme minimum temperatures and cooling of extreme maximum temperatures occurred in the southeastern United States during the period 1948–2012, which differed from trends at the global scale (Powell and Keim 2014).

China is susceptible to climate change (Chen and Zhai 2017). It was reported that the frequencies of warm days and warm nights have increased at rates of 0%–3.0% and 0%–4.0% per decade, respectively, in almost the entire region of China for the period 1961–2015 (Shi et al 2018), while the intensities of warm extremes have shown an asymmetric change pattern in China (Zhou et al 2016, Shen et al 2018). Spatially, warm extremes became significantly warmer in South China, northwestern North China, northeastern Northeast China, eastern Northwest China and eastern Southwest China. Cold extremes warmed significantly for most regions of China, with notable increases in Northeast China, northern and southeastern North China, and northwestern and eastern Northwest China (Sun et al 2015a). These previous studies provide substantial information on changes in the frequency and intensity of temperature extremes in China under climate change. However, changes in the start and end dates of periods of temperature extremes are also of special interest, as climate warming has been shown to alter the timing of important developmental stages in birds, plants and amphibians (Fitter and Fitter 2002). Since more frequent and intense temperature extremes are being observed over China under current climate change, it is crucial to understand changes in start and end dates of yearly extreme temperature periods for better projecting yearly economic production and other effects on life instead of focusing only on the interdecadal scale (Founda et al 2019).

Global climate models (GCMs), which have been developed by various modeling groups and are used in support of the coupled model intercomparison project (CMIP), are regarded as the state-of-the-art climate model simulations to study the impacts of past, present and future climate change (Eyring et al 2016). CMIP has evolved over five phases into a major international multi-model research activity that has become a core element of national and international assessments of climate change (Taylor et al 2011, IPCC 2013). Currently, for the purpose of meeting the increasingly broad scientific demands of the climate science community, a new and more federated organizational structure of CMIP—namely CMIP6—has been adopted (Meehl et al 2014, Eyring et al 2016). Compared to the previous phase of CMIP, these latest climate models in CMIP6 have improvements in spatial resolution, physical parameterizations (e.g. the representation of clouds) and inclusion of additional Earth system processes (e.g. nutrient limitations on the terrestrial carbon cycle) and components (Eyring et al 2019). Before using CMIP6 projections for policymaking, it is essential to evaluate the performance of CMIP6 historical simulations of climate change, because they serve as an important benchmark for assessing model performance (Eyring et al 2016, Grose Michael et al 2020). Previous studies have assessed the performance of climate model simulations in CMIP6 for capturing the complex dynamics of Indian summer monsoon rainfall for the period 1951–2005 (Gusain et al 2020) and changes in temperature and rainfall over Australia (Grose Michael et al 2020). They found incremental improvements in the historical mean state in the CMIP6 ensemble compared to CMIP5, although regional biases remain. However, there is a lack of studies evaluating the performance of CMIP6 historical simulations in temperature extremes.

Looking forward, a comprehensive analysis addressing changes in start and end dates, intensity, and frequency of temperature extremes will provide information for decision-making for risk management and other critical sectors. An effective analysis of spatiotemporal changes in extreme temperature across China using CMIP6 historical simulations will also be beneficial for understanding temperature extremes under climate change. Therefore, the purposes of this study are (1) to explore the characteristics of temperature extremes by analyzing start and end dates, frequency, and intensity of extreme temperature indices (looking specifically at warm days, warm nights, cold days and cold nights); and (2) to inspect the ability of available CMIP6 models to capture the changes in temperature extremes.

2. Data and methods

2.1. Data

The observed 0.25° × 0.25° daily maximum and minimum temperatures during the period 1961–2017 are the gridded daily scale data set of CN05.1 provided by the China Meteorological Administration. This homogenized high-resolution data set is based on interpolation from 2416 station observations with quality control measures applied, such as deleting outliers that are far different from the actual climate state and surrounding meteorological stations (Wu and Gao 2013, Zhao and Zhou 2019). In the ‘anomaly
interpolation method used, a gridded climatology is first calculated and then the gridded daily anomalies are added to the climatology (Liu et al 2019). In this approach, the number of archived and easily obtainable station normals is far greater than that of station time series, particularly as one goes back in time, thus maximizing available station data in space and time (New et al 1999, 2000). The data set has been widely used to quantify temperature extremes over China and other regions (Cao et al 2017, Wu et al 2017, Dong et al 2018, Yin and Sun 2018). For the purpose of comparing temperature extremes in different regions of China, we divided the Chinese mainland into eight climate regions based on administrative divisions and the regional characteristics of the monsoon climate of China (Shi and Xu 2007, Mao et al 2010, Miao et al 2019). The resulting regions are Northeast China, North China, Jianghuai (the middle and lower reaches of the Yangtze River and the Huaihe River valley), South China, Southwest China, the Tibetan Plateau, western Northwest China, and eastern Northwest China (figure 1).

We choose output data from 12 GCMs from CMIP6 provided by the World Climate Research Programme to evaluate the simulated daily maximum and minimum temperature data across China (https://esgf-node.llnl.gov/projects/cmip6/). Historical daily maximum and minimum temperature simulations for the period 1961–2014 were processed for the performance analysis. For the purpose of model comparison with observations over China in the present study, we use a bilinear interpolation method to interpolate all of the selected model data into a common grid of 0.25° × 0.25° (Gusain et al 2020). The relevant details of the 12 models are presented in table 1.

2.2. Methods

In this study, we analyze characteristics of temperature extremes using four basic indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI): cold days and cold nights for cold extremes, and warm days and warm nights for warm extremes (http://etccdi.pacificclimate.org/indices_def.shtml). These percentile-based indices are only slightly affected by internal variability, and thus they provide a robust way to analyze the different aspects of temperature extremes. They are also important indicators for impacts on human and natural systems compared to ‘extreme extremes’ (e.g. the coldest day of a year) (Simolo et al 2011, Oudin Åström et al 2013).

We calculate three characteristics (start date, end date and frequency) for each of these four basic indices; we also calculate the mean value of Tmin on cold nights and the mean value of Tmax on warm days as indicators of intensity of temperature extremes. Together, these make up the 14 indices we explore in our analysis (table 2).

We define a one-year period by considering the start and end dates, and the human production habits are also taken into account in this study. Each one-year period starts with 1 April in a given year and ends with 31 March of the next year under this definition, and thus the meteorological data for 1961–2017 will generate a 56 year time series ranging from 1 April 1961, to 31 March 2017. Under the above definition, the year 1961 represents a period starting 1 April 1961, and ending 31 March 1962, on the calendar, while the year 1962 represents a period starting 1 April 1962, and ending 31 March 1963, on the calendar, and the following year (1963, 1964, 1965, …, 2016) can be deduced by analogy. This method is effective for
Table 1. CMIP6 models used in this study.

| Model name       | Resolution: grids in Longitude × Latitude | Source                                                                 |
|------------------|------------------------------------------|------------------------------------------------------------------------|
| AWI-CM-1-1MR     | 384 × 192                                 | Alfred Wegener Institute, Germany                                       |
| BCC-CSM2-MR      | 320 × 160                                 | Beijing Climate Center, China                                           |
| BCC-ESM1         | 128 × 64                                  | Beijing Climate Center, China                                           |
| CanESM5          | 128 × 64                                  | Canadian Center for Climate Modeling and Analysis, Environment and Climate Change Canada, Canada |
| EC-Earth3        | 512 × 256                                 | EC-Earth Consortium, Europe                                            |
| FGOALS-g3        | 180 × 80                                  | LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, China |
| GFDL-ESM4        | 288 × 180                                 | National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, United States |
| GISS-E2-1-G      | 144 × 90                                  | NASA Goddard Institute for Space Studies, United States                |
| IPSL-CM6A-LR     | 144 × 143                                 | Institute Pierre Simon Laplace, France                                 |
| MIROC6           | 256 × 128                                 | Japan Agency for Marine-Earth Science and Technology, Japan            |
| NESM3            | 192 × 96                                  | Earth System Modeling Center, Nanjing University of Information Science and Technology, China |
| NorESM2-LM       | 144 × 96                                  | Bjerknes Center for Climate Research, Norwegian Research Center, Norway |
|                   |                                          |                                                                        |

Table 2. Information about the 14 indices of temperature extremes in this study.

| Category          | Index          | Definition                                                                 | Units         |
|-------------------|----------------|---------------------------------------------------------------------------|---------------|
| Start and end dates| Start date of warm days | Annual start date of days when $T_{\text{max}} > 90$th percentile for 1961–1990 | Julian days  |
|                   | Start date of warm nights | Annual start date of days when $T_{\text{min}} > 90$th percentile for 1961–1990 | Julian days  |
|                   | Start date of cold days | Annual start date of days when $T_{\text{max}} < 10$th percentile for 1961–1990 | Julian days  |
|                   | Start date of cold nights | Annual start date of days when $T_{\text{min}} < 10$th percentile for 1961–1990 | Julian days  |
|                   | End date of warm days | Annual end date of days when $T_{\text{max}} > 90$th percentile for 1961–1990 | Julian days  |
|                   | End date of warm nights | Annual end date of days when $T_{\text{min}} > 90$th percentile for 1961–1990 | Julian days  |
|                   | End date of cold days | Annual end date of days when $T_{\text{max}} < 10$th percentile for 1961–1990 | Julian days  |
|                   | End date of cold nights | Annual end date of days when $T_{\text{min}} < 10$th percentile for 1961–1990 | Julian days  |
| Frequency         | Frequency of warm days | Annual occurrence of days when $T_{\text{max}} > 90$th percentile for 1961–1990 | Days          |
|                   | Frequency of warm nights | Annual occurrence of days when $T_{\text{min}} > 90$th percentile for 1961–1990 | Days          |
|                   | Frequency of cold days | Annual occurrence of days when $T_{\text{max}} < 10$th percentile for 1961–1990 | Days          |
|                   | Frequency of cold nights | Annual occurrence of days when $T_{\text{min}} < 10$th percentile for 1961–1990 | Days          |
| Intensity         | Intensity of warm days | Mean value of $T_{\text{max}} > 90$th percentile for 1961–1990 each year | °C           |
|                   | Intensity of cold days | Mean value of $T_{\text{min}} < 10$th percentile for 1961–1990 each year | °C           |

depicting the characteristics of changes in temperature extremes, as a continuous time series of warm or cold extremes might be interrupted by the habitual division of a year that starts 1 January and ends 31 December (Dong et al 2010). For example, cold nights usually cluster from the end of November to the beginning of the following January. In addition, we apply criteria to eliminate potential bias due to outliers at edges of the time series that we used to identify start and end dates. For the beginning of a cold extreme period, there must be at least three consecutive days with cold extremes. Likewise, for the beginning of a warm period, there must be at least three consecutive days with warm extremes (Chen and Li 2017). Then, we use the ordinary least squares method to determine the linear trends of these extreme temperature indices and estimate the significance of the trends (Founda et al 2019).

Considering the time coverage of the CMIP6 historical experiments, we use observed data during the period 1961–2014 to evaluate the GCMs performance in simulating the temperature extreme.

3. Results and discussion

3.1. Observed change in temperature extremes

3.1.1. Observed start date and end date of periods of temperature extremes

During the period 1961–2017, the cold extremes started later and ended earlier over time across China (figures 2(a), (c), (e) and (g)). Both start date and end date changed significantly faster for cold nights ($p < 0.05$), at rates of 3.25 d/decade and −4.58 d/decade, respectively, as compared to the rates for cold days. The yearly timing of cold extremes showed the opposite trend after 1998 versus the whole period for the start date of cold days and the end dates of cold days and cold nights. The start date of cold nights occurred increasingly later, while the end dates of cold
Figure 2. Spatiotemporal change of the observed yearly timing for periods of (a), (c) cold days, (b), (f) warm days, (c), (g) cold nights, and (d), (h) warm nights in China during the period 1961–2017. The crossed dots on the grids represent the trends that are significant at the level of 0.05. The values on the grids of each map are the regional average trends in eight climate regions of China for 1961–2017 in units of days/decade. Different colored lines in the bottom left corner of each map show the best-fit linear regression lines for different time periods: black for 1961–2017, red for 1961–1998 and blue for 1998–2013. The slope values show the linear trend for the period of 1961–2017 (days/decade), and the p values indicate the trend significance.
days and cold nights occurred incrementally earlier in the year for all eight climate regions from 1961 to 2017 (figures 2(c), (e) and (g)). The start date of cold days was also delayed in most parts of China, except for North China and the coastal areas of South China, where it instead advanced at rates of 0.89 d/decade and over 6 d/decade, respectively (figure 2(a)). A significantly later start date of cold extremes (p < 0.05) occurred mainly in the Tibetan Plateau, with a change of 3.51 d/decade for the start date of cold days and 5.6 d/decade for the start date of cold nights, and in Hainan province (>6 d/decade for cold nights). For the end date of the cold days, areas that experienced an increasingly later end date at a rate of 0–2 d/decade were mainly located in the southern part of Southwest China. By contrast, areas experiencing a notably advancing end date for the cold extremes were mostly concentrated in North China.

For warm extremes, the start date for periods of warm nights advanced significantly faster at ~3.43 d/decade (p < 0.05), as compared to ~2.04 d/decade (p < 0.05) for warm days (figures 2(b) and (d)). The end date of the period of warm nights shifted later in the year by 3.15 d/decade (p < 0.05), which was 0.77 d/decade faster (p < 0.05) than the change in warm days (figures 2(f) and (h)). In contrast to the pattern for cold extremes, the spatial pattern of the start date and end date of warm extremes exhibited a reversed pattern during the period 1961–2017, with an increasingly earlier start date and later end date across most climate regions except for the start date of warm days in North China (0.57 d/decade) and the end date of warm days in Jianghuai (0.12 d/decade). A rapidly advancing start date for warm days can be seen mainly in Southwest China (~3.57 d/decade), while a delayed trend ranging from 0 to 2 d/decade was found mainly in eastern North China and the Tibetan Plateau. Warm nights started increasingly earlier, by a rate of ~3 to ~5 d/decade in most parts of China except for Jianghuai, where the rate was ~1.91 d/decade. The delayed end date of warm extremes was most pronounced in the southern Tibetan Plateau, southern Southwest China and southern South China (>6 d/decade). However, an increasingly earlier end date (0 to ~2 d/decade) for periods of warm days occurred in small areas of northern and southern Jianghuai.

Generally, larger trends are observed in the timing of nighttime extremes compared to daytime extremes during the period 1961–2017, which is consistent with the rates found for other midlatitude regions (Founa et al 2019). Previous studies found an earlier onset of spring ranging from 1 to 1.5 d/decade across most temperate Northern Hemisphere land regions over the 1955–2002 period (Schwartz et al 2006). Our findings suggest that the onset and offset of warm extremes also experienced changes. Cold extremes started later and ended earlier, however warm extremes started earlier and ended later across China between 1961 and 2017. That means the duration of warm extremes was lengthening over China, which is consistent with global trends under climate warming (Dong et al 2010, Perkins et al 2012). Strong and McCabe (2017) noted that atmospheric circulation indices account for 25%–48% of the frost-timing indices, suggesting circulation factors play an important role in the timing of temperature extremes. Previous studies have suggested that the expansion of extreme warm spells is associated with specific atmospheric circulation patterns represented by semi-stationary 500 hPa positive height anomalies that dynamically produce subsidence, clear skies, light winds, warm-air advection and prolonged hot conditions at the surface (Palecki et al 2001, Meehl and Tebaldi 2004). The durations of cold extremes shortened over the course of the whole study period but lengthened in the period 1998–2013, which suggests that cold extremes are more sensitive to temperature change than warm extremes are. In this study, the start and end dates of periods for temperature extremes exhibited more intense change rates over the Tibetan Plateau in contrast to the other regions of China during the period 1961–2017. This may be related to the Tibetan Plateau’s sensitivity to climate change, as evidenced by the fact that a large-amplitude climatic change happened in the Tibetan Plateau with a rapid warming rate that was greater than the rate for the whole world (Chen et al 2013, IPCC 2013).

3.1.2. Observed frequency and intensity of temperature extremes

In general, the frequency of cold nights significantly (p < 0.05) decreased at a rapid rate of ~6.56 d/decade, which was 3.39 d/decade faster than the decrease of cold days (p < 0.05) (figures 3(a) and (c)). However, the frequency of cold extremes increased from 1998 to 2013. Over all eight climate regions of China, the frequency of cold extremes showed a decreasing trend during the period 1961–2017. This decreasing trend was more intense in the Tibetan Plateau, with a change of ~4.38 d/decade for cold days and ~6.92 d/decade for cold nights. Conversely, the frequency of warm extremes showed significant upward trends across China, with a faster rate of change of 6.79 d/decade (p < 0.05) for warm nights and a rate of 5.15 d/decade (p < 0.05) for warm days (figures 3(b) and (d)). The frequency of warm extremes also exhibited increasing trends in all eight climate regions during the period 1961–2017. A rapid upward trend in the frequency of warm nights was concentrated in the southeastern part of western Northwest China, the Tibetan Plateau, the southern part of Southwestern China and South China (>6 d/decade). However, the frequency of warm days decreased at a rate of 0–2 d/decade at the border of North China and Jianghuai.

The intensity of cold extremes increased faster, at 0.14 °C/decade (p < 0.05), than the intensity of warm extremes, which increased by 0.09 °C/decade (p < 0.05) from 1961 to 2017 (figures 3(e) and (f)).
Interestingly, the intensity of cold extremes rapidly decreased from 1998 to 2013, which was the opposite of the trend over the entire period. Nationwide, increasing trends were observed for the intensity of cold extremes, with the maximum value in the Tibetan Plateau (0.16 °C/decade) and the minimum value in eastern Northwest China (0.07 °C/decade) (figure 3(f)). Similarly, figure 3(e) showed nationwide increases in the intensity of warm extremes for most locations, with a strong increasing trend of 0.1–0.2 °C/decade in eastern Northwest China, Southwestern China, eastern Tibetan Plateau and northern Northeast China. However, decreasing trends with a rate of −0.1 to 0 °C/decade were exhibited in central Northeast China and at the border of North China and Jianghuai.

This suggests that warm extremes have become warmer and cold extremes cooler, with significantly increasing frequency over China, during the period 1998–2013, which coincides with previous studies (Li et al 2015, Johnson et al 2018). The amount of solar energy reaching the surface is a major component of the surface energy balance and governs a large number of diverse surface processes, as well as the diurnal and
seasonal course of surface temperatures (Wild 2009). Recent studies have suggested that summer mean maximum temperature is significantly correlated with concurrent increases in solar radiation (Li et al 2015). Under long-term climate warming, the cooling of cold extremes in China may result partly from an atmospheric circulation change, i.e. an increase in winds from the north in accord with atmospheric pressure patterns as shown in the 20th Century Reanalysis Project (Compo et al 2013). Previous studies concluded that the increasing occurrences of cold extremes are associated with an atmospheric circulation pattern resembling the ‘Warm Arctic–Cold Continents’ pattern, and that the increase in warm extremes is tied to a pattern of sea surface temperatures resembling the Atlantic Multidecadal Oscillation (England et al 2014, Horton et al 2015, Johnson et al 2018).

3.2. Simulated historical change in temperature extremes

3.2.1. Simulated historical change in start date and end date of temperature extremes from CMIP6

Overall, the multimodel ensembles (MMEs) could satisfactorily capture the basic spatial pattern features of the trend for yearly timing of temperature extremes over China, with spatial correlation coefficients over 0.99 between MME simulations and observations (figures 4(a)–(h)). However, the MMEs underestimated the trends in magnitude over China generally. For the start date of temperature extremes, the MME agreed well with observations for warm days, with a relative error of 4.87%. For the end date of temperature extremes, the MME captured the trend of warm nights well, with a relative error of $-12.66\%$. In terms of the eight climate regions, the MMEs performed better in Jianghuai for the start date and Northeast China for the end date, with relative errors of 29.66% and 27.74%, respectively. As for individual model outputs, most models captured the general change trends reasonably well, with the exception of the end date of cold days from BCC-CSM2-MR (figures 4(i)–(p)). Generally, EC-Earth3 performed better for the start date and NorESM2-LM behaved better for the end date. The CanESM5 model most substantially overestimated the trends in timing of temperature extremes over China, except for the end date of cold extremes.

Model results in CMIP6 agreed well with observations for the advanced start date and delayed end date of cold extremes, and the advanced end date and delayed start date of warm extremes. This means the length of cold duration was shortening whereas the

![Figure 4. Spatiotemporal change of the simulated yearly timing for periods of warm and cold extremes in China over the period 1961–2014 from CMIP6. Subgraphs (a)–(h) show the spatial pattern of MME-simulated start date and end date for periods of cold days, warm days, cold nights and warm nights. The values on the grids of each map are the regional average trends in eight climate regions of China for 1961–2014. The crossed dots on the grids represent the trends that are significant at the level of 0.05. Bar graphs show the mean trends of start date and end date for periods of cold days, warm days, cold nights and warm nights across China over the period 1961–2014 from the 12 CMIP6 models (white bars), the MME (gray bars) and the observations (red bars). The numbers 1 to 14 in the horizontal axis respectively represent models AWI-CM-1-1MR, BCC-CSM2-MR, BCC-ESM1, CanESM5, EC-Earth3, FGOALS-g3, GFDL-ESM4, GISS-E2-1-C, IPSL-CM6A-LR, MIROC6, NESM3, and NorESM2-LM, the MME and the observations. Asterisks over the bars indicate the trends are significant at the level of 0.05.](image-url)
The length of warm duration was extending between 1961 and 2014. From the perspective of phenology, previous field-based phenological observation of plants and simulations from a dynamic vegetation model also suggested an advancement of phenological events in spring and a delay of phenological events in autumn across North America and Europe (Lucht et al 2002, Fitter and Fitter 2002). The reproductive cycles of plants have changed considerably, as they are primarily controlled by temperature and day length in temperate zones (Menzel 2002). Especially for the spring events in mid-latitude plants (budding, leafing and flowering), several studies have demonstrated the close correlation between spring growth phases and air temperature (Chen et al 2005). Changes in the timing of warm and cold extremes may also have far-reaching consequences for plant and animal ecosystems, because a persistent increase in length of warm extremes may lead to changes in carbon storage and vegetation cover (Cotton 2003, Linderholm 2006).

3.2.2. Simulated historical change in frequency and intensity of temperature extremes from CMIP6

Similarly, the MMEs presented the dominant features of the frequency and intensity of warm and cold extremes (figures 5(a)–(f)). The spatial correlation coefficients between simulations and observations were above 0.998 for each index. Generally, the MMEs underestimated the trends in the frequency and intensity of temperature extremes across China, with biases of $-2$ d/decade and $-0.1$ °C/decade for the frequency and intensity, respectively. For the frequency of temperature extremes, the MME agreed well with observations for warm days across China, with a relative error of $-9.26\%$. As for intensity, the MME performed well in cold extremes, with a relative error of $-1.87\%$ over China. The MME failed to capture the detailed change in some regions, such as the downward trend in frequency of warm days across the border of North China and Jianghuai. Except for the model MIROC6 simulations of the intensity of warm extremes, most individual model results were roughly the same as observations (figures 5(g)–(l)). The models also performed well in warm extremes and cold nights, with a large number of models passing the significance test at level of 0.05. In general, Model NESM3 performed best for the frequency and BCC-CSM2-MR behaved better for the intensity.

Grose Michael et al (2020) found that the multimodel mean of annual maximum value of daily maximum temperature in Australia sits close to the observations, but the coldest night of the year is generally cooler in observations than the multimodel mean of both CMIP6 and CMIP5. Our study suggested that the MMEs of CMIP6 also underestimated the intensity of cold extremes over most parts of China. Most of the models performed better at simulating warm extremes than cold extremes, which is consistent with previous studies in simulation of frequency of warm extremes in CMIP5 (Yang et al 2014, Figure 5. Spatiotemporal change of the simulated frequency and intensity of warm and cold extremes in China over the period 1961–2014 from CMIP6. Subgraphs (a)–(f) show the spatial pattern of the MME-simulated frequency and intensity of cold days, warm days, cold nights and warm nights. The values on the grids of each map are the regional average trends in eight climate regions of China for 1961–2014. The crossed dots on the grids represent the trends that are significant at the level of 0.05. Bar graphs show the mean trends of frequency and intensity of cold days, warm days, cold nights and warm nights across China over the period 1961–2014 from the 12 models of CMIP6 (white bars), the MME (gray bars) and observations (red bars). The numbers 1–14 on the horizontal axis respectively represent models AWI-CM-1-1MR, BCC-CSM2-MR, BCC-ESM1, CanESM5, EC-Earth3, FGOALS-g3, GFDL-ESM4, GISS-E2-1-G, JPSL-CM6A-LR, MIROC6, NESM3, and NorESM2-LM, the multimodel ensemble and the observations. Asterisks over the bars indicate the trends are significant at the level of 0.05.
You et al. 2014, 2018). The decreasing frequency of cold extremes and increasing frequency of warm extremes was also demonstrated in regional climate models (RCMs) (Yu et al. 2015). For detailed changes of spatial pattern, the simulations’ abilities in CMIP6 are still less satisfactory and need to be improved. The coarse resolution of the GCMs may be a potential factor that limits the models’ performance in resolving the regional-to-local-scale atmospheric circulation, thus affecting the accuracy of model simulations (Liu et al. 2013, Yu 2013).

Taking into consideration of changes to start date, end date, frequency and intensity of temperature extremes, both observations and historical simulations in CMIP6 showed that the temperature extremes exhibited warming trends, which for cold extremes features later start dates, earlier end dates and decreased frequencies; and for warm extremes features earlier start dates, later end dates and increased frequencies. The nighttime extremes had a more intense response to the warming trend than the daytime extremes during the global warming period (Xu et al. 2011), while the ‘extreme’ temperature extremes (cold nights and warm days) responded strongly to the climate change, suggesting by the opposite trends between the whole study period (1961–2017) and the hiatus period (1998–2013) in China. Spatially, the anomalous cooling of warm extremes observed in central China during the period 1961–2017, also termed a ‘warming hole’ in China (Zhang et al. 2017), was exactly the region where anomalous later start dates and decreased frequency of warm days exist (figures 2(b), 3(b) and (e)). This homogeneous response in both time and space may also imply that the downward trend in intensity of warm extremes potentially contributes to the anomalous changes in the timing of warm extremes. Similarly, for the conterminous United States, locations with advancing end dates for the frost-free periods correspond to the US ‘warming hole’ previously identified in temperature records (Kumar et al. 2012, McCabe et al. 2015). Previous studies suggested that the US ‘warming hole’ existing in the central and south-central United States during the 20th century can be attributed mainly to shortwave cloud forcing due to aerosols with offsets from the greenhouse effect of precipitable water vapor (Partridge et al. 2018). The long-term phase changes in the North Atlantic Oscillation and the Pacific Decadal Oscillation also contribute significantly to southern US cooling (Mascioli et al. 2017).

4. Conclusions

In this study, we analyzed the variations in start and end dates, frequency, and intensity of annual cold and warm extremes across China in observations and model simulations from CMIP6. During the period 1961–2017, the annual start date for cold nights shifted later in the year by 3.25 d/decade ($p < 0.05$), while the end date for cold nights advanced by 4.58 d/decade ($p < 0.05$). For the same period, the annual start date for warm extremes, in particular for warm nights, started earlier over time, changing at a rate of $−3.43$ d/decade ($p < 0.05$), and ended later, delaying by 3.15 d/decade ($p < 0.05$). The frequency of cold nights decreased rapidly by 6.56 d/decade ($p < 0.05$) and the frequency of warm nights increased strongly by 6.79 d/decade ($p < 0.05$). Cold extremes warmed at a rate of $0.14$ °C/decade, which was $0.05$ °C/decade faster than warm extremes. MMEs from CMIP6 agreed well with observations in the average trends of temperature extremes over China, although detailed changes in spatial pattern were not captured adequately.

To sum up, over the past five decades, annual cold extremes across China had increasingly later start dates, increasingly earlier end dates, decreased frequency and weakened intensity; warm extremes showed increasingly earlier start dates, increasingly later end dates, increased frequency and enhanced intensity. The results also suggest that nighttime extremes have had a more intense response to global warming than daytime extremes for all of the characteristics, exhibiting larger rates of change. These findings suggest that adaptation to temperature extremes will need further attention in the future, because widespread changes in timing, frequency, and intensity of temperature extremes in response to climate change might pose challenges to the sustainability of human society and ecosystems across all of China.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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