Changing Characteristics of Extreme Warm Events in Xinjiang from 1961 to 2017 and Future Scenario Projections: Postprint

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Date: 2021-12-12T00:00:00+00:00

Abstract

Investigating extreme warm events holds significant theoretical value and practical implications for addressing climate change and formulating disaster prevention and mitigation policies. Utilizing the 1961–2017 China daily surface air temperature gridded dataset and 1961–2050 CMIP6 climate model data, models with better simulation performance were selected through simulation accuracy validation for multi-model ensemble averaging. The climate tendency rate and inverse distance weighting (IDW) method were applied to investigate the spatiotemporal variations of extreme warm event days, frequency, and intensity in Xinjiang during June–September for both the past and future periods. Results indicate that over the past 57 years, extreme warm event days, frequency, and intensity in Xinjiang exhibited increasing trends, with tendency rates of 0.2 d · (10a)^-1, 0.02 times · (10a)^-1, and 0.04 ℃ · (10a)^-1, respectively. The spatial distribution of extreme warm event days and frequency was characterized by higher values in southern Xinjiang than in northern Xinjiang, with high-incidence areas located in western southern Xinjiang, while intensity exhibited a north-high-south-low spatial distribution pattern, with high-value areas distributed in northern Xinjiang. In the next 33 years, under the SSP245 and SSP585 scenarios, extreme warm event days, frequency, and intensity in Xinjiang all exhibited significant increasing trends. Relative to the 1961-2017 mean, extreme warm event days increase by 21 d and 28 d, extreme warm event frequency increases by 1.6 times and 1.8 times, and extreme warm event intensity increases by 1.2 ℃ and 1.3 ℃, respectively, with more pronounced increases under the SSP585 scenario. High-incidence areas for extreme warm event days and frequency are located in central southern Xinjiang, while high-intensity areas remain in northern Xinjiang; the increases in extreme warm event days, frequency, and intensity are all greater in southern Xinjiang than in northern Xinjiang. Changes in the position of the Iranian subtropical high and the western Pacific subtropical high, along with soil moisture variations, influence the intensity of extreme warm events in Xinjiang. Keywords: extreme warm events; multi-model ensemble; spatiotemporal variation; scenario projection; Xinjiang

Full Text

Abstract

Studying extreme warm events holds important theoretical value and practical significance for addressing climate change and formulating disaster prevention and mitigation policies. Using the China daily surface temperature gridded dataset from 1961 to 2017 and CMIP6 climate model data, this study selected better-performing models through simulation accuracy verification for multi-model ensemble averaging. Employing climate tendency rates and the inverse distance weighting method, we investigated the spatiotemporal variations in the number of days, frequency, and intensity of extreme warm events in Xinjiang from June to September in both the past and future. The results show that over the past 57 years, the number of days, frequency, and intensity of extreme warm events in Xinjiang exhibited increasing trends, with tendency rates of 0.2 $d \cdot (10a)^{-1}$, 0.02 $times \cdot (10a)^{-1}$, and 0.04 $℃ \cdot (10a)^{-1}$, respectively. The spatial distribution of extreme warm event days and frequency featured higher values in southern Xinjiang than in northern Xinjiang, with high-incidence areas in western southern Xinjiang, while intensity showed a north-high, south-low spatial distribution pattern, with high-value areas in northern Xinjiang. Under future SSP245 and SSP585 scenarios, the number of days, frequency, and intensity of extreme warm events in Xinjiang all showed significant increasing trends. Compared with the 1961-2017 average, the annual average number of extreme warm event days increased by 21 days and 28 days, the average frequency increased by 1.6 and 1.8 times, and the average intensity increased by 1.2 ℃ and 1.3 ℃ under SSP245 and SSP585 scenarios, respectively, with more significant increases under SSP585. High-incidence areas for extreme warm event days and frequency were located in central southern Xinjiang, while the high-incidence area for intensity remained in northern Xinjiang. The increases in the number of days, frequency, and intensity of extreme warm events in southern Xinjiang were all greater than those in northern Xinjiang. Changes in the position of the Iran subtropical high and the western Pacific subtropical high, along with soil moisture variations, can influence the occurrence of extreme warm events in Xinjiang.

Keywords: extreme warm events; multi-model ensemble; temporal-spatial change; scenario projections; Xinjiang

1.1 Study Area Overview

Xinjiang is located in the northwestern border of China, between 73°40 ~96°18 E and 34°25 ~48°10 N, covering an area of 1.66$×10^{6}$ km^2. The terrain features "three mountains surrounding two basins," dominated by basins and mountains. The Tianshan Mountains run across central Xinjiang, dividing it into northern and southern Xinjiang. The region has a typical temperate continental climate, with an average annual temperature of 9-12 ℃, annual precipitation of 145 mm, annual evaporation of 2000-4000 mm, and annual sunshine duration of 2600-3600 h. Summer temperatures in southern Xinjiang are hotter than in northern Xinjiang, while precipitation is more abundant in northern Xinjiang than in southern Xinjiang. The region has numerous river systems, mainly replenished by glacier and perennial snowmelt. The main soil types are aeolian sandy soil, brown desert soil, and brown calcic soil, with primary vegetation types including *Populus euphratica*, *Tamarix chinensis*, and *Haloxylon ammodendron*.

[Figure 1: see original paper]

1.2 Data Sources

Meteorological data were obtained from the China Meteorological Data Center (http://data.cma.cn/), which provides China' s daily surface temperature gridded dataset at 0.5°$×0.5°resolution.Climatesimulationdatawerederivedfrom14globalclimatemodelsprovided
//esgf−node.llnl.gov/search/cmip6/)undertwoSharedSocioeconomicPathway(SSP)scenarios(SSP245and
SSP245combinesamediumsocioeconomicdevelopmentpathwaywithmediumradiativeforcingbasedonRCP4.5
fuelintensivedevelopmentpathwaywithhighradiativeforcingbasedonRCP8.5.The500hPageopotentialheight
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RangeWeatherForecasts(ECMWF)ERA5monthlylandreanalysisdataat0.1°×$0.1°
resolution.

1.3 Research Methods

Currently, research on climate extreme changes generally employs either absolute threshold methods or relative threshold methods to define extreme value thresholds. Absolute threshold methods fail to account for local topography and climate differences and are only suitable for regions with small spatial variability. Relative threshold methods can better eliminate regional and seasonal factors. This study follows the standard practice of examining climate events using a 30-year climate baseline period, adopting the 90th percentile calculated from the baseline period as the daily high-temperature threshold for extreme warm days. The specific definitions and formulas are as follows.

Daily high-temperature threshold: For a given day j, using the daily maximum temperature data $P(y,d)$ within the 30-day window centered on day j during the climate baseline period Y (1981-2010), the 90th percentile is taken as the threshold temperature for day j.

Extreme warm day: A day when the daily maximum temperature exceeds the high-temperature threshold for that day.

Extreme warm event: When at least three consecutive days have maximum temperatures not lower than the daily high-temperature threshold, with intervals not exceeding one day, this is defined as one extreme warm event.

Frequency: The number of extreme warm events occurring each year and their total duration in days.

Intensity: The cumulative average of the difference between daily temperature during extreme warm events and the average temperature during the climate baseline period, representing the temperature anomaly state.

The formulas are:

- Daily threshold temperature: $T_{90}(j)$ = 90th percentile of $P(y,d)$
- Extreme warm event intensity: $I = (1/n)\ [T(t) - T\ (j)]$ from t to t_{1}
- Root Mean Square Error: RMSE = $\sqrt{[(1/N)\ (x - \hat{x})^2]}$
- Relative Error: RE = $(1/N)\ |x - \hat{x}|/|\hat{x}| \times 100\%$
- Correlation Coefficient: Corr = $[\ (x - \bar{x})(\hat{x} - \bar{\hat{x}})]\ /\ [\sqrt{\ (x - \bar{x})^2}\ \sqrt{\ (\hat{x} - \bar{\hat{x}})^2}]$

2.1.1 Temporal Variation of Extreme Warm Events in Xinjiang

From the perspective of interannual variation (Figure 2), the number of extreme warm event days in Xinjiang showed an increasing trend from 1961 to 2017, with a tendency rate of 0.2 d·$(10a)^{-1}$ ($P \leq 0.05$), averaging 10.1 d annually, with a maximum of 10.3 d in 2015. The frequency of extreme warm events in Xinjiang showed a slight increasing trend, with a tendency rate of 0.02 times·$(10a)^{-1}$ ($P \leq 0.05$). The year 2015 had the highest frequency of extreme warm events, occurring 2.3 times, followed by 2008 with 2.2 times, while other years had at least one event. The intensity of extreme warm events showed a similar slight increasing trend to frequency (Figure 2c), with a tendency rate of 0.04 ℃·$(10a)^{-1}$ ($P \leq 0.05$), averaging 5.4 ℃ annually, with a maximum intensity of 6.3 ℃ in 2015.

[Figure 2: see original paper]

2.1.2 Spatial Variation of Extreme Warm Events in Xinjiang

Using inverse distance weighting interpolation suitable for uniformly distributed sample points, we interpolated the 0.5°$×0.5° gridded data to obtain the spatial distribution and linear trends of ext
value areas mainly located in Taxkorgan Tajik Autonomous County in western southern Xinjiang (6–18d), consistent with Kong Feng's research on high–value areas of extreme warm event duration. Areas with incre
(10a)^{-1}) accounted for 85.3{-1}$ ($P \leq 0.05$). The spatial distribution of extreme warm event frequency was consistent with that of days, with frequencies higher than 1.8 times in high-value areas. The frequency increased in areas ranging from -0.3 to 0.2 times·$(10a)^{-1}$, with the fastest increase in Minfeng Oasis in southern Xinjiang at 0.2 times·$(10a)^{-1}$ ($P \leq 0.05$). The intensity of extreme warm events showed a spatial pattern increasing from south to north (Figure 3f), with high-value areas concentrated in the Gurbantunggut Desert and surrounding oases in northern Xinjiang (6.3-7.5 ℃). Intensity increased in areas ranging from -0.2 to 0.2 ℃·$(10a)^{-1}$, with the highest increase rates in Yutian, Minfeng, and Qiemo oases at 0.2 ℃·$(10a)^{-1}$ ($P \leq 0.05$).

[Figure 3: see original paper]

2.2.1 Influence of Atmospheric Circulation Anomalies

Atmospheric circulation is often the dominant factor causing various weather processes, so extreme warm events in Xinjiang must be closely related to atmospheric circulation. Using years when extreme warm event days were more (less) than 1.5 times the standard deviation above (below) the multi-year average as the criterion for anomalously strong (weak) years, we identified 2008, 2010, and 2015 as strong years and 1962, 1968, and 1984 as weak years. Analysis of the 500 hPa geopotential height field showed that during strong extreme warm event years (Figure 4a), the Iran subtropical high and western Pacific subtropical high extended eastward-northward and westward-northward respectively, with the 5720-5840 gpm contour shifting significantly northward and high-pressure intensity strengthening. The positive anomaly center over western Xinjiang (Figure 4b) indicated that the high-pressure system controlling Xinjiang strengthened, with enhanced anticyclonic activity and prevailing subsidence, leading to temperature increases and frequent extreme warm events. During weak extreme warm event years (Figure 4c), the Iran subtropical high and western Pacific subtropical high retreated westward-southward and eastward-southward respectively, with the 5720 gpm contour shifting southward and high-pressure intensity weakening. The negative anomaly over Xinjiang (Figure 4d) indicated that the controlling high-pressure system weakened, with enhanced cyclonic activity and prevailing upward motion, reducing extreme warm event activity.

[Figure 4: see original paper]

2.2.2 Influence of Soil Moisture on Extreme Warm Events

Recent research has increasingly highlighted the impact of land-atmosphere interactions on extreme warm events, with soil moisture changes receiving growing attention in the causes and prediction of extreme warm events. Spatial correlation analysis between summer shallow soil moisture and extreme warm events in Xinjiang (Figure 5) showed that except for northeastern Xinjiang, where extreme warm event days and frequency were positively correlated with soil moisture, most regions showed negative correlations, with correlation coefficients mainly ranging from -0.6 to 0. The most significant negative correlation occurred in western southern Xinjiang (Figure 5a, 5b), with correlation coefficients of -0.6 to 0 ($P \leq 0.05$), overlapping with previous high-value areas of extreme warm event days and frequency. The spatial correlation distribution between intensity and soil moisture increased from northeast to southwest (Figure 5c), with negative correlations in most areas, reaching -0.6 to -0.3 in central-southern southern Xinjiang ($P \leq 0.05$). In summary, extreme warm events in Xinjiang are mainly negatively correlated with soil moisture, indicating that as soil moisture decreases, extreme warm events become more frequent.

[Figure 5: see original paper]

2.3 Future Projection Analysis of Extreme Warm Events in Xinjiang

We evaluated the simulation capabilities of 14 CMIP6 climate models. Since the spatial resolution of each model' s grid data was not uniform, we used linear interpolation in Matlab to unify all model data to a 0.5°$×$0.5° grid for comparison and extraction of high-temperature data. Using formulas (1)-(3), we calculated the RMSE, RE, and Corr for each model' s simulation results compared with Xinjiang surface temperature grid data from June-September 1961-2014. The results showed that most models had RMSE within 2.5-3.5 ℃, RE within 5%-8%, and Corr within 0.85-0.95, all passing significance tests. Multi-model ensemble (MME) results showed RMSE of 2.1 ℃, RE of 4.5%, and Corr of 0.93, with errors smaller than most individual models and closer to actual temperature grid data. Previous studies indicate that current climate simulation effects influence future climate change projections, and multi-model ensemble of better-performing models yields projections closer to reality. Therefore, we selected 6 models (EC-Earth3-Veg, MPI-ESM1-2-LR, INM-CM5-0, CanESM5, EC-Earth3, and NorESM2-LM) for MME to project future extreme warm events in Xinjiang.

[Figure 6: see original paper]

2.3.1 Temporal Simulation Characteristics of Extreme Warm Events in Xinjiang From the interannual variation perspective (Figure 7), extreme warm event days in Xinjiang showed fluctuating upward trends under both SSP245 and SSP585 scenarios, with tendency rates of 9.9 d $\cdot$ $(10a)^{-1}$ ($P \leq 0.01$) and 16.1 d $\cdot$ $(10a)^{-1}$ ($P \leq 0.01$), respectively. The increase rate under SSP585 was significantly higher than under SSP245, with extreme warm event days reaching a maximum of 42.1 d. The frequency of extreme warm events also showed significant increasing trends under both scenarios, with tendency rates of 0.9 times $\cdot$ $(10a)^{-1}$ ($P \leq 0.01$) and 1.5 times $\cdot$ $(10a)^{-1}$ ($P \leq 0.01$), respectively. The intensity of extreme warm events showed similar increasing trends, with tendency rates of 0.15 ℃ $\cdot$ $(10a)^{-1}$ ($P \leq 0.05$) and 0.3 ℃ $\cdot$ $(10a)^{-1}$ ($P \leq 0.05$) under SSP245 and SSP585, respectively, with average intensities of 6.6 ℃ and 6.7 ℃.

[Figure 7: see original paper]

2.3.2 Spatial Simulation Characteristics of Extreme Warm Events in Xinjiang Under SSP245 and SSP585 scenarios, the spatial distribution of extreme warm event indicators in Xinjiang showed similar patterns to 1961-2017, but with significantly expanded high-value areas (Figure 8). The spatial distribution of extreme warm event days showed higher values in southern Xinjiang than northern Xinjiang, with high-value areas in the Taklamakan Desert and surrounding oases in central-southern southern Xinjiang, reaching 28-34 d under SSP245 and 34-42 d under SSP585. The spatial distribution of frequency was similar to that of days, with high-incidence areas in southern Xinjiang oases, increasing from 2.5-3.0 times under SSP245 to 3-3.5 times under SSP585. The spatial distribution of intensity showed an increasing trend from south to north, consistent with the 1961-2017 pattern but with significantly increased intensity, reaching 7.7 ℃ in the Gurbantunggut Desert and surrounding oases in northern Xinjiang.

Analysis of changes relative to the 1961-2017 average (Figure 9) showed that under both scenarios, extreme warm event days in Xinjiang would increase, with increases of 8-34 d under SSP245 and 8-42 d under SSP585, with the largest increases in central-southern southern Xinjiang. The spatial distribution of frequency changes was similar to that of days, with greater increases in southern Xinjiang than northern Xinjiang, increasing by 1.0-1.5 times $\cdot$ year^{-1} under SSP245 and 1.5-2.0 times $\cdot$ year^{-1} under SSP585. The intensity changes showed a spatial distribution pattern increasing from north to south, with increases of 0.3-0.9 ℃ under SSP245 and 0.3-1.2 ℃ under SSP585, with increases up to 1.2 ℃ in southern Xinjiang.

[Figure 8: see original paper]

[Figure 9: see original paper]

3 Discussion

This study investigated the spatiotemporal variations in the number of days, frequency, and intensity of extreme warm events in Xinjiang from June to September in both the past and future. The results are generally consistent with previous research, but differ in spatial distribution, primarily because this study used the relative threshold method to define extreme warm events, emphasizing the impact of temperature variation amplitude on local ecological environments rather than background temperature. This approach includes extreme warm events in low-temperature regions, whereas previous studies generally used absolute thresholds (35 ℃) to define extreme warm events, ignoring the fact that extreme warm events can also occur in regions with lower temperatures. In reality, even in perennially cold regions, temperature variations can be large relative to normal conditions, constituting extreme warm events that affect local ecosystems. Related studies have shown that even polar regions experience extreme warm events that impact their ecosystems. Regarding influencing factors, this study demonstrates that extreme warm events are closely related to atmospheric circulation and soil moisture. When the Iran subtropical high and western Pacific subtropical high extend eastward-northward and westward-northward, respectively, anticyclonic activity strengthens, causing temperature increases and frequent extreme warm events in Xinjiang. Meanwhile, extreme warm events in Xinjiang are mainly negatively correlated with soil moisture. When soil moisture is low, reduced latent heat flux and increased sensible heat flux from soil to atmosphere favor temperature increases, leading to more frequent extreme warm events. Using CMIP6 multi-model ensemble projections, the results show that under both scenarios, extreme warm events in Xinjiang will continue to increase at rates far exceeding current levels, with high-incidence areas mainly in southern Xinjiang, consistent with previous studies. However, this study only analyzed atmospheric circulation and soil moisture separately without integrating these factors, which will be addressed in future research using numerical models. Additionally, although we used internationally recognized multi-model ensemble averaging, uncertainties remain due to inconsistent spatial resolutions among models, and future work will employ dynamical downscaling to improve projection accuracy.

4 Conclusions

(1) From 1961 to 2017, the number of days, frequency, and intensity of extreme warm events in Xinjiang showed increasing trends, with tendency rates of 0.2 d $\cdot$ $(10a)^{-1}$, 0.02 times $\cdot$ $(10a)^{-1}$, and 0.04 ℃ $\cdot$ $(10a)^{-1}$, respectively ($P \leq 0.05$). The spatial distribution of extreme warm event frequency and days showed a pattern of higher values in southern Xinjiang than northern Xinjiang, with high-value areas in western southern Xinjiang, while intensity showed a north-high, south-low distribution, with high-value areas in northern Xinjiang oases.

(2) Under SSP245 and SSP585 scenarios, the number of days, frequency, and intensity of future extreme warm events in Xinjiang all showed highly significant increasing trends, with tendency rates of 9.9 d $\cdot$ $(10a)^{-1}$, 0.9 times $\cdot$ $(10a)^{-1}$, and 0.15 ℃ $\cdot$ $(10a)^{-1}$ under SSP245, and 16.1 d $\cdot$ $(10a)^{-1}$, 1.5 times $\cdot$ $(10a)^{-1}$, and 0.3 ℃ $\cdot$ $(10a)^{-1}$ under SSP585, all passing significance tests. The increase rates under SSP585 were faster than under SSP245. The spatial distribution patterns of future extreme warm event days, frequency, and intensity were basically consistent with those from 1961-2017, but the high-value areas expanded significantly. High-value areas for days and frequency were distributed in the Taklamakan Desert and surrounding oases in southern Xinjiang, while high-value areas for intensity were located in northern Xinjiang oases. The increases in days, frequency, and intensity in southern Xinjiang were greater than those in northern Xinjiang.

(3) The occurrence of extreme warm events is mainly negatively correlated with soil moisture, while the intensity of extreme warm events is closely related to changes in the position of the Iran subtropical high and western Pacific subtropical high.

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Note: Figure translations are in progress. See original paper for figures.