ChinaRxiv

AI translation · View original & related papers at
chinarxiv.org/items/chinaxiv-202304.00898

Interannual Variations of Extreme Temperature Events in Shanxi Province over the Past 60 Years and Their Response to Regional Warming: Postprint

Authors: Li Na, Wu Yongli, Zhao Guixiang, Qian Jinxia, Li Fen, Zhao Haiying, Han Pu, Wu Yongli

Date: 2023-04-07T16:37:59+00:00

Abstract

Based on daily maximum temperature, minimum temperature, and mean temperature data from 70 meteorological stations within Shanxi Province, this study analyzed the variation characteristics of extreme temperature events during the nearly 60-year period from 1960 to 2019 using eight different extreme temperature indices, and examined their response to climate warming. The results indicate: (1) Summer days, tropical nights, the maximum value of daily minimum temperature, and the minimum value of daily minimum temperature all exhibited significant increasing trends, while ice days and frost days exhibited significant decreasing trends. (2) Both the maximum and minimum values of extreme maximum (minimum) temperature increased, and in most regions, the warming magnitude of the minimum values of extreme temperature was greater. (3) The mean temperature in Shanxi Province showed a significant warming trend, increasing at an average rate of 0.26 ℃ per 10 years, with the spatial pattern of temperature increase gradually intensifying from southeast to northwest. Various extreme temperature indices exhibited good responses to climate warming, among which frost days showed the most significant response to regional warming in Shanxi Province, followed by the maximum value of daily minimum temperature. (4) In the semi-arid regions of Shanxi Province, the minimum and maximum values of daily minimum temperature warmed faster, and ice days decreased more rapidly; in semi-humid regions, tropical nights increased more rapidly, and frost days decreased more rapidly.

ChinaRxiv

Full Text

Interannual Variations of Extreme Air Temperature Events and Their Response to Regional Warming in Shanxi Province in Recent 60 Years

LI Na[1], WU Yongli[1], ZHAO Guixiang[1], QIAN Jinxia[1], LI Fen[2], ZHAO Haiying[1], HAN Pu[1]

[1]Shanxi Meteorological Observatory, Taiyuan 030006, Shanxi, China
[2]Meteorological Disaster Prevention Technology Center of Shanxi Province, Taiyuan 030032, Shanxi, China

Abstract: Based on daily maximum temperature, minimum temperature, and mean temperature data from 70 meteorological stations in Shanxi Province, this study analyzes eight extreme temperature indices recommended by the World Meteorological Organization to investigate the spatiotemporal characteristics of extreme temperature events and their response to regional warming from 1960 to 2019. The results show that: (1) Summer days, tropical nights, annual maximum daily minimum temperature, and annual minimum daily minimum temperature exhibited significant increasing trends, while ice days and frost days showed significant decreasing trends. (2) Both the maximum and minimum values of extreme high (low) temperatures increased, with the minimum values showing larger warming magnitudes in most regions. (3) The annual mean temperature in Shanxi Province increased significantly at a rate of 0.26 ℃·$(10a)^{-1}$, with a spatial pattern of increasing warming from southeast to northwest. All extreme temperature indices responded well to climate warming, with frost days showing the most significant response, followed by the annual maximum daily minimum temperature. (4) In semi-arid regions of Shanxi, the annual minimum and maximum daily minimum temperatures warmed faster and ice days decreased more rapidly; in semi-humid regions, tropical nights increased faster and frost days decreased more rapidly.

Keywords: extreme temperature indices; spatiotemporal variation; climate change; Shanxi Province

1. Study Area Overview

Shanxi Province is located in the eastern part of the Loess Plateau and west of the North China Plain, situated between the Taihang Mountains and the middle reaches of the Yellow River gorge. It is a mountainous plateau with significant relief, known as the Shanxi Plateau. The province spans 110°15 –114°32 E and 34°35 –40°45 N, with plains, hills, and mountainous areas accounting for 19.7%, 40.0%, and 40.3% of the total area, respectively. The terrain shows substantial variation, resulting in pronounced north-south and vertical climate gradients. The region north of the Hengshan Mountains and the inner Great Wall belongs to the temperate semi-arid climate zone; the area between the inner Great Wall and the Xiyang–Taiyue Mountains–Hejin line falls within the warm temperate semi-arid climate zone; and the region south of this line is classified as warm temperate semi-humid climate. Based on these climatic divisions, Shanxi can be broadly divided into three regions: northern Shanxi (temperate semi-arid zone), central Shanxi (warm temperate semi-arid zone), and southern Shanxi (warm temperate semi-humid zone) [Figure 1: see original paper].

---

2. Data and Methods

2.1 Data Sources

This study utilized daily maximum temperature, minimum temperature, and mean temperature data from 1960 to 2019 at 70 uniformly distributed and spatially representative basic meteorological stations across Shanxi Province [Figure 1: see original paper]. The data were obtained from the Shanxi Meteorological Information Center and had passed the Standard Normal Homogeneity Test validation.

2.2 Research Methods

Eight extreme temperature indices recommended by the World Meteorological Organization's "Expert Team on Climate Change Detection and Indices" were selected for analysis. Following the classification method of Zhou Yaqing et al. [15], these indices were categorized into two types : warm indices (four indices) and cold indices (four indices). Linear trend fitting and correlation analysis methods were employed for data analysis [23].

---

3. Results and Analysis

3.1 Warm Extreme Temperature Indices

3.1.1 Temporal Variation Characteristics From 1960 to 2019, the multi-year mean values of summer days, tropical nights, annual maximum daily maximum temperature (TXx), and annual maximum daily minimum temperature (TNx) in Shanxi Province were 105.60 $d \cdot a^{-1}$, 17.50 $d \cdot a^{-1}$, 35.58 ℃ $\cdot a^{-1}$, and 22.74 ℃ $\cdot a^{-1}$, respectively. All warm indices showed increasing trends [Figure 2: see original paper], with climate tendency rates of 1.40 $d \cdot (10a)^{-1}$, 3.10 $d \cdot (10a)^{-1}$, 0.16 ℃ $\cdot (10a)^{-1}$, and 0.20 ℃ $\cdot (10a)^{-1}$, respectively. The increasing trends of summer days, tropical nights, and TNx were extremely significant ($P < 0.001$), while the trend of TXx was significant ($P < 0.05$). Notably, the growth rate of summer days exceeded that of tropical nights, and the growth rate of TNx exceeded that of TXx.

Examined by decade, summer days decreased briefly in the 1960s, increased slowly in the 1970s, showed the most pronounced upward trend in the 1980s, and continued to rise slowly thereafter. Tropical nights remained relatively stable in the 1960s–1970s, decreased noticeably in the 1980s, and increased significantly after the 1990s. TNx exhibited a turning point around the 1990s, with a clear upward trend since the 2000s. TXx showed little variation before the 1990s, then increased slowly, transitioning from cooling to warming.

3.1.2 Spatial Variation Characteristics During 1960–2019, the spatial distribution of summer days, tropical nights, TXx, and TNx in different regions of Shanxi showed a pattern of higher values in the south and lower values in the north. Over the past 60 years, these indices increased across all regions, though the magnitude varied substantially. Summer days increased by more than 3.79 d$\cdot$(10a)$^{-1}$ in most areas, with smaller increases (<1.22 d$\cdot$(10a)$^{-1}$) in the eastern part of central and southern Shanxi. A total of 57 stations showed statistically significant increases ($P < 0.05$) in summer days. High-increase areas for tropical nights appeared in southern Linfen City and northern Yuncheng City, with increases exceeding 2.73 d$\cdot$(10a)$^{-1}$, while most northern areas and parts of Yangquan, Jinzhong, and Changzhi showed smaller increases (<1.22 d$\cdot$(10a)$^{-1}$). Tropical nights increased significantly ($P < 0.05$) at 45 stations.

High-increase areas for TXx were located in southern Lüliang City, northern Linfen City, followed by the Yellow River basin areas of Xinzhou and Lüliang, and southern Taiyuan and western Jinzhong, with increases exceeding 0.22 ℃$\cdot$(10a)$^{-1}$. Datong, Shuozhou, Xinzhou, and Yuncheng were low-increase areas (<0.10 ℃$\cdot$(10a)$^{-1}$). TXx increased significantly ($P < 0.05$) at 36 stations, mainly in high-value zones with increases exceeding 0.16 ℃$\cdot$(10a)$^{-1}$. High-increase areas for TNx were found in eastern Datong, eastern Shuozhou, northern Yangquan, most of Taiyuan, western Jinzhong, eastern Lüliang, and northern Linfen, with increases exceeding 0.20 ℃$\cdot$(10a)$^{-1}$. Western Xinzhou and Yuncheng were low-increase areas (<0.16 ℃$\cdot$(10a)$^{-1}$). TNx increased significantly ($P < 0.05$) at 62 stations, mostly in areas with increases exceeding 0.16 ℃$\cdot$(10a)$^{-1}$.

Comparing the semi-arid region (north-central Shanxi) with the semi-humid region (southern Shanxi), TNx warmed faster in the semi-arid region, while tropical nights increased more rapidly in the semi-humid region.

3.2 Cold Extreme Temperature Indices

3.2.1 Temporal Variation Characteristics From 1960 to 2019, the multi-year mean values of ice days, frost days, annual minimum daily maximum temperature (TXn), and annual minimum daily minimum temperature (TNn) in Shanxi Province were 31.02 d$\cdot$a^{-1}, 141.48 d$\cdot$a^{-1}, -7.93 ℃$\cdot$a^{-1}, and -20.22 ℃$\cdot$a^{-1}, respectively. Ice days and frost days showed decreasing trends of varying magnitudes, while TXn and TNn showed increasing trends [Figure 4: see original paper]. The climate tendency rates were -2.70 d$\cdot$(10a)$^{-1}$, -9.43 d$\cdot$(10a)$^{-1}$, 0.25 ℃ · $(10a)^{-1}$, and 0.38 ℃ · $(10a)^{-1}$, respectively. Both ice days and frost days decreased extremely significantly ($P < 0.001$). TNn increased significantly ($P < 0.01$), while the increasing trend of TXn was not significant ($P > 0.05$). The decreasing rates of ice days and frost days were similar. The growth rates of TNn, TXn, TNx, and TXx decreased sequentially (0.38 ℃ · $(10a)^{-1}$, 0.25 ℃ · $(10a)^{-1}$, 0.20 ℃ · $(10a)^{-1}$, 0.16 ℃ · $(10a)^{-1}$), indicating that TNn warmed faster and climate change had a greater impact on minimum temperature extremes.

Examined by decade, ice days showed a brief increase in the 1960s before transitioning to a decreasing trend, reaching the lowest values in the 2010s. Frost days remained relatively stable in the 1960s–1970s, then decreased gradually. TXn fluctuated considerably after the 1990s, with two high-value periods. TNn showed an overall increasing trend decade by decade.

3.2.2 Spatial Variation Characteristics During 1960–2019, ice days and frost days in different regions of Shanxi showed a north-high, south-low distribution pattern and a consistent decreasing trend. TXn and TNn showed a south-high, north-low distribution pattern and a consistent increasing trend. However, the changing trends varied significantly across regions.

The largest decrease in ice days occurred in the Yellow River basin areas of western Xinzhou, western Lüliang, and northwestern Linfen, with decreases exceeding 3.71 d · $(10a)^{-1}$, while Yuncheng showed the smallest decrease (<1.43 d · $(10a)^{-1}$). Ice days decreased significantly ($P < 0.05$) at 57 stations. The largest decrease in frost days occurred in Yuncheng, southern Linfen, and western Taiyuan, with decreases exceeding 9.43 d · $(10a)^{-1}$, while Datong, western Xinzhou, western Lüliang, Changzhi, and southern Yangquan showed the smallest decreases. Frost days decreased significantly ($P < 0.05$) at 68 stations.

High-increase areas for TXn were mainly located in western and northeastern Xinzhou, western Linfen, and eastern Datong, with increases exceeding 0.33 ℃ · $(10a)^{-1}$. Taiyuan, Jinzhong, Yangquan, and most of Jincheng were low-increase areas (<0.20 ℃ · $(10a)^{-1}$). TXn increased significantly ($P < 0.05$) at 36 stations, mainly in high-value zones with increases exceeding 0.16 ℃ · $(10a)^{-1}$. High-increase areas for TNn were mainly located in most of Shuozhou, central Xinzhou, and western Taiyuan, with increases exceeding 0.48 ℃ · $(10a)^{-1}$, while southwestern Lüliang and eastern Linfen were low-increase areas (<0.31 ℃ · $(10a)^{-1}$). TNn increased significantly ($P < 0.05$) at 62 stations.

Comparing the spatial patterns of TXx, TXn, TNx, and TNn, both maximum and minimum values of extreme temperatures increased, with minimum values showing larger warming magnitudes in most areas. Specifically, TNn increases exceeded TNx increases at 62 stations, and TXn increases exceeded TXx increases at 36 stations. Comparing the semi-arid and semi-humid regions, the semi-arid region showed faster decreases in ice days and larger increases in TNn, while the semi-humid region showed faster decreases in frost days.

3.3 Mean Temperature Variation Characteristics

To investigate the response of extreme temperature events to climate warming, we first analyzed the variation characteristics of annual mean temperature. From 1960 to 2019, the annual mean temperature in Shanxi Province was 9.6 ℃, with the highest value (10.8 ℃) in 2019 and the lowest value (8.3 ℃) in 1967. The temperature showed a significant warming trend with a climate tendency rate of 0.26 ℃·$(10a)^{-1}$ ($P < 0.001$). The 1960s–1980s had relatively low mean temperatures, with the 1990s serving as a turning point from cooling to warming. Using cumulative anomaly analysis, the inflection point of temperature change was identified as 1996 [Figure 7: see original paper]. Comparing the mean temperatures of the two periods (1960–1996 vs. 1997–2019), t-test results indicated extremely significant differences ($P < 0.01$), with mean temperatures of 9.2 ℃ and 10.2 ℃, respectively.

The multi-year mean temperature across different regions of Shanxi ranged from 4.2 to 14.0 ℃, generally showing a south-high, north-low pattern. Areas with temperatures above 12.0 ℃ were centered in Yuncheng, southern Linfen, and southwestern Jincheng, forming high-value centers, while temperatures in the northwestern region were below 7.0 ℃, forming low-value centers. Spatially, the annual mean temperature showed a consistent warming trend across the province, with 63 stations exhibiting significant warming trends ($P < 0.05$). The warming magnitude gradually increased from southeast to northwest. The larger warming areas were located in the Yellow River basin of western Shanxi, particularly in western Shuozhou, western Lüliang, and northern Linfen, with an average increase of 0.39 ℃·$(10a)^{-1}$. The smaller warming areas were in the Hai River basin of eastern Shanxi, particularly in eastern Jincheng, eastern Changzhi, and eastern Jinzhong, with an average increase of 0.20 ℃·$(10a)^{-1}$. Comparing the semi-arid and semi-humid regions, the semi-arid region showed a larger warming magnitude.

3.4 Response of Extreme Temperature Indices to Regional Warming

To examine the relationship between extreme temperature indices and regional warming in Shanxi, we calculated correlation coefficients between each index and mean temperature . Summer days, tropical nights, TXx, TNx, TXn, and TNn were significantly positively correlated with mean temperature ($P < 0.01$), while ice days and frost days were significantly negatively correlated ($P < 0.01$). All correlations passed the 0.01 significance level, indicating that extreme temperature indices respond well to climate warming. Frost days showed the highest correlation coefficient, indicating the most significant response to regional warming in Shanxi, followed by TNx. As mean temperature rises, summer days, tropical nights, TXx, TNx, TXn, and TNn increase significantly, while ice days and frost days decrease significantly.

Using 1996 as the inflection point, we calculated differences in extreme temperature indices between the two periods . As mean temperature increased by 1.0 ℃, summer days and tropical nights increased by 5.67 d and 12.35 d, respectively, while ice days and frost days decreased by 11.34 d and 8.01 d, respectively. TNx, TXx, TNn, and TXn increased by 0.94 ℃, 0.87 ℃, 0.68 ℃, and 0.21 ℃, respectively, suggesting that the study area faces greater potential risks from high temperature and heat waves under future warming.

3.5 Correlation Analysis Between Extreme Temperature Indices and Geographical Factors

To assess the influence of geographical factors on extreme temperature indices, we analyzed linear correlation coefficients between each index and longitude, latitude, and elevation . Summer days, tropical nights, TXx, TNx, TXn, and TNn were all significantly negatively correlated with longitude, latitude, and elevation ($P < 0.05$), while ice days and frost days were significantly positively correlated ($P < 0.05$). This indicates that as longitude, latitude, or elevation increases, warm indices decrease significantly while cold indices increase significantly. Among warm indices, summer days, tropical nights, TXx, and TNx showed the strongest correlations with elevation. Among cold indices, ice days, frost days, TXn, and TNn showed strong correlations with both latitude and elevation.

---

4. Discussion

The trends of warm and cold indices identified in this study are generally consistent with previous research on extreme temperature events across China [15,16,18,21,22,24,25,27,28,31]. However, Shanxi Province exhibited faster decreases in ice days and slower increases in TXn and TNn. The study indicates that as mean temperature rises, the study area faces greater potential risks from heat waves, consistent with findings by Wang Dai et al. [16] for China. Analysis of different climate zones revealed that in Shanxi's semi-arid region, TNn and TNx warmed faster and ice days decreased more rapidly, while in the semi-humid region, tropical nights increased faster and frost days decreased more rapidly. This differs from Ji Lin et al.'s [27] findings for the Wei River Basin, where both warm and cold indices showed greater warming in semi-arid regions compared to semi-humid regions, suggesting that Shanxi's complex geography and transitional climate characteristics make extreme temperature responses more complex. Overall, the magnitude of change in extreme temperature indices in Shanxi was greater than in the Wei River Basin but lower than the average level in the Loess Plateau region [28,31].

The Paris Agreement aims to limit global temperature rise to within 2 ℃ of pre-industrial levels [3]. Under this target, studying extreme temperature event trends is crucial for effective climate policy formulation. The differential responses of extreme temperature indices to regional warming identified in this study can provide references for predicting and assessing future impacts under climate change scenarios. However, factors influencing extreme temperature changes are extremely complex, including large-scale atmospheric circulation [6,7], urbanization [8,9], and land cover changes [10], which require further in-depth investigation.

---

5. Conclusions

This study analyzed the variation characteristics of extreme temperature events and their response to regional warming in Shanxi Province from 1960 to 2019, yielding the following main conclusions:

1) **Temporal and spatial variation of extreme temperature indices:** Temporally, summer days, tropical nights, and TNx among warm indices increased significantly, while ice days and frost days among cold indices decreased significantly, and TNn increased significantly. Spatially, all regions of Shanxi showed increasing trends for summer days, tropical nights, TXx, TNx, TXn, and TNn, and decreasing trends for ice days and frost days.

2) **Comparison of extreme temperature maxima and minima:** Both maximum and minimum values of extreme temperatures increased, with minimum values showing larger warming magnitudes in most regions.

3) **Response to regional warming:** The annual mean temperature in Shanxi increased significantly at 0.26 $℃ \cdot (10a)^{-1}$, with warming magnitudes increasing from southeast to northwest. All extreme temperature indices responded well to climate warming, with frost days showing the most significant response, followed by TNx.

4) **Relationships with geographical factors:** Among warm indices, summer days, tropical nights, TXx, and TNx showed the strongest correlations with elevation. Among cold indices, ice days, frost days, TXn, and TNn showed strong correlations with both latitude and elevation.

5) **Regional differences:** In Shanxi's semi-arid region, TNn and TNx warmed faster and ice days decreased more rapidly; in the semi-humid region, tropical nights increased faster and frost days decreased more rapidly.

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

Source: ChinaXiv — Machine translation. Verify with original.