

High Temperature Variations in Xinjiang and Their Relationships with Atmospheric Circulation and Sea Surface Temperature, 1961-2018 (Postprint)

Authors: Zhang Taixi

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Abstract

Utilizing observed daily maximum temperature data from Xinjiang meteorological stations, NCEP reanalysis data, and Atlantic sea surface temperature data for the period April-September 1961-2018, this study analyzes the spatiotemporal variation characteristics of high-temperature ($\geq 35^{\circ}\text{C}$) days, including their onset and cessation dates, intensity, and their relationships with upper-level circulation and Atlantic sea surface temperature in the Xinjiang region. The results demonstrate that the number of high-temperature days in Xinjiang has increased significantly. Concurrently, the extremity of high-temperature days ($T_{\max} \geq 40^{\circ}\text{C}$) and a declining trend in the proportion of moderate high-temperature days ($37^{\circ}\text{C} > T_{\max} \geq 35^{\circ}\text{C}$). The number of stations recording extreme high temperatures has increased, with the affected area expanding northward to the Altay region in northern Xinjiang. The onset date of high-temperature days across Xinjiang exhibits a trend of advancement, while the cessation date shows a postponement trend, with increased high-temperature days during spring and early autumn emerging as salient features of high-temperature changes. The increasing trend of high-temperature days in Xinjiang is closely associated with anomalous upper-level circulation patterns; elevated equatorial Atlantic sea surface temperatures favor the dominance of the South Asian high over the region from Balkhash Lake to Mongolia, thereby contributing to an increased number of high-temperature days in Xinjiang.

Full Text

Heatwave Changes and Their Relationship with Atmospheric Circulation and Sea Surface Temperature in Xinjiang from 1961 to 2018

ZHANG Taixi, FAN Jing, LI Yuanpeng, YU Xingjie
Xinjiang Climate Center, Urumqi 830002, Xinjiang, China

Abstract

Using daily maximum temperature data from meteorological stations across Xinjiang, NCEP reanalysis data, and Atlantic sea surface temperature (SST) observations, this study analyzes the spatiotemporal characteristics of heatwaves in Xinjiang from 1961 to 2018 and explores their relationships with upper-level circulation patterns and Atlantic SST anomalies. The results indicate that against the background of regional warming and wetting, the number of heatwave days in Xinjiang has increased significantly. This increase is accompanied by a strengthening of extreme heat events, evidenced by a rising proportion of extreme high temperature days ($T_{\max} \geq 40\text{ }^{\circ}\text{C}$) and a declining proportion of moderate high temperature days ($35\text{ }^{\circ}\text{C} \leq T_{\max} < 37\text{ }^{\circ}\text{C}$). The spatial extent of extreme heat has expanded northward to the Altay region in northern Xinjiang. The first heatwave day has advanced while the last heatwave day has delayed, with notable increases in heatwave occurrences during spring and early autumn. The increasing trend in heatwave days is closely associated with anomalous upper-level circulation patterns. When equatorial Atlantic SST is above normal, it favors the establishment of a South Asian High over the region from Balkhash Lake to Mongolia, resulting in more heatwave days across Xinjiang.

Keywords: heatwave days; heatwave intensity grade; first heatwave day; last heatwave day; atmospheric circulation; Atlantic SST; Xinjiang

Introduction

Global climate change, characterized by sustained increases in surface mean temperature, has intensified since the 1980s, with most land areas experiencing significant rises in extreme maximum temperatures and increasing frequency of heatwaves. This warming trend is projected to continue throughout the 21st century. Xinjiang, with its vast territory and complex topography of “three mountains surrounding two basins,” exhibits strong regional climate characteristics controlled by both vertical and latitudinal zonation. Previous studies have documented significant increases in heatwave frequency and intensity since the mid-1980s in regions such as Hami and Shanshan, with the Turpan area recording extreme temperatures reaching $49.0\text{ }^{\circ}\text{C}$ and the Tuyugou scenic area automatic station observing $50.5\text{ }^{\circ}\text{C}$, setting new national records.

Under the background of climate warming, heatwave events in China have become more frequent and persistent, with the maximum affected area of regional heatwave processes showing a clear expansion trend. Research indicates that the frequency of extreme high temperature events in Northwest China exhibits a significant increasing trend, positively correlated with regional warming. The causes of extreme high temperatures have been extensively studied, with findings suggesting that low-frequency variations of extreme heat in the Northern Hemisphere are closely related to the Atlantic Multidecadal Oscillation. Studies have also identified teleconnections between North Atlantic SST anomalies in winter and spring and summer high temperatures in northern China, as well as the influence of the South Asian High on extreme heat events. When the South Asian High intensifies and shifts northward, it favors increased summer heatwave days in Xinjiang.

Previous research has primarily focused on summer heatwave processes, atmospheric circulation anomalies, and external forcing factors such as SST. However, few studies have examined the abrupt changes in heatwave days, intensity variations, and changes in the timing of first and last heatwave days in Xinjiang from a climate change perspective, nor have they thoroughly investigated the relationship between these changes and Atlantic SST. This paper addresses these gaps to further reveal the patterns of heatwave changes under climate warming and provide a theoretical basis for climate adaptation.

1.1 Data

This study utilizes daily maximum temperature data from national meteorological observation stations in Xinjiang, provided by the Xinjiang Meteorological Information Center. After quality control for missing data and station relocations, 98 stations with reliable data were selected for analysis. Climatological normals are based on the 1981-2010 average. Upper-level geopotential height data at 200 hPa were obtained from NCEP reanalysis with a horizontal resolution of $2.5^{\circ} \times 2.5^{\circ}$, covering the region $10^{\circ} - 70^{\circ} N$, $40^{\circ} W - 160^{\circ} E$ for the period 1961-2018. Atlantic SST data were obtained from [//cmdp.ncc-cma.net/cn/index.htm](http://cmdp.ncc-cma.net/cn/index.htm) with a resolution of $2.5^{\circ} \times 2.5^{\circ}$, covering $100^{\circ} W - 20^{\circ} E$, $20^{\circ} S - 60^{\circ} N$.

1.2 Methods

A heatwave day is defined as a day with maximum temperature $\geq 35^{\circ} C$. Following the standard QX/T 228-2014 for regional high temperature processes, heatwave intensity is classified into three grades: moderate ($35^{\circ} C \leq T_{max} < 37^{\circ} C$), strong ($37^{\circ} C \leq T_{max} < 40^{\circ} C$), and extreme ($T_{max} \geq 40^{\circ} C$). The first heatwave day is defined as the initial date each year when $T_{max} \geq 35^{\circ} C$ occurs, and the last heatwave day is the final such date.

The comprehensive heatwave intensity index (SI) is calculated by summing the annual days of each intensity grade for each county, creating a matrix $X_{m \times n}$ (where $m = 3$ intensity grades, $n =$ number of counties). After dimensionless

processing, the normalized matrix is obtained. The annual heatwave days are then sorted, and percentile methods are used to determine thresholds: 95th-100th percentile for extreme, 85th-95th percentile for strong, and 60th-85th percentile for moderate heatwaves.

Linear trend analysis is applied to annual heatwave days and mean temperature. The Mann-Kendall test is used for abrupt change detection. Correlation analysis between 200 hPa geopotential height, Atlantic SST, and Xinjiang heatwave days follows standard statistical methods.

To analyze the relationship between 200 hPa geopotential height and Xinjiang heatwave days, we first calculate the anomaly matrix $I_{m \times n}$ of monthly mean geopotential height, then correlate it with concurrent Xinjiang heatwave days. The region with highest correlation (Balkhash Lake to northern Xinjiang, 40°-50°N, 70°-90°E) is selected to construct the Balkhash Index:

$$I_{\text{BK}} = \sum_{i,j} \frac{(H_{i,j} - \bar{H}_{\text{mean}})}{\text{STD}}$$

where $H_{i,j}$ represents grid point values, \bar{H}_{mean} is the regional mean, and STD is standard deviation.

Similarly, the Atlantic SST index is constructed from the region showing strongest correlation with the Balkhash Index (0°-10°N, 10°-40°W):

$$I_{\text{ATL}} = \sum_{i,j} \frac{(T_{i,j} - \bar{T})}{\text{STD}}$$

2.1.1 Temporal Variation Characteristics

Xinjiang's annual heatwave days show a significant increasing trend of 0.76 days per decade ($p < 0.05$). Before 1997, the maximum annual heatwave days did not exceed 21 days, with 63.9% of years below the climatological normal. After 1997, 85.7% of years exceeded the normal, with the maximum reaching 45.9 days in 2015. The correlation coefficient between annual heatwave days and mean temperature is 0.76 ($p < 0.05$), while correlation with precipitation is insignificant, confirming that increasing heatwave days are closely linked to regional warming.

2.1.2 Spatial Variation Characteristics

All stations show increasing trends, with greater amplification in southern Xinjiang than northern Xinjiang. The Turpan-Hami region and areas around the Tarim Basin exhibit the highest heatwave frequencies, with Gaochang District recording 102 days/year, Toksun 97 days/year, and Shanshan 74 days/year. Stations in northern Xinjiang along the Tianshan Mountains and the Ili River Valley

show 11–30 days/year, while northernmost areas show fewer than 11 days/year. The relationship between heatwave days and elevation follows a significant exponential function: $y = 1350.2e^{-0.001x}$ ($R^2 = 0.71$, $p < 0.05$), indicating that heatwave days increase exponentially with decreasing altitude.

2.1.3 Abrupt Change Analysis

Mann-Kendall mutation tests reveal that 46.8% of stations show significant increasing trends, with abrupt transitions occurring as a gradual process. Before the 1990s, mutations primarily occurred in northern Xinjiang; after the 2000s, they shifted to southern Xinjiang, particularly in the Turpan-Hami Basin. The most significant increases are found at Naomaohu Town in Yiwu County (5.0 days/decade) and Qiemo County (4.9 days/decade). Some stations show decreasing trends, possibly related to local environmental changes from vegetation restoration, requiring further investigation.

2.2.1 Trends in First and Last Heatwave Days

Given the differences before and after 1997, we analyze two periods. Probability density functions show consistent summer peaks for first heatwave days, but with new peaks emerging in mid-April after 1997, indicating more spring heatwaves. For last heatwave days, the peak shifted from late August to mid-September after 1997, with higher probability density extending to late September, showing increased early autumn heatwaves.

Trend analysis reveals that 58.8% of stations show earlier first heatwave days, with the largest advance at Hejing station (11.4 days/decade). Meanwhile, 41.6% of stations show delayed last heatwave days, with the greatest delay at Qinghe County (21.6 days/decade). Only 13.6% of stations simultaneously show both earlier first days and later last days, with few passing significance tests, indicating substantial uncertainty.

2.2.2 Spatial Distribution of Earliest First and Latest Last Heatwave Days

Before 1997, the earliest first heatwave days occurred only in mid-April at Gaochang and Toksun in Turpan. After 1997, Shanshan, Naomaohu in Hami, Ruoqiang in Bayingolin, and Yuepuhu-Jiashi in Kashgar joined this early occurrence pattern. Most stations around the Tarim Basin and along the northern Tianshan Mountains now see first heatwave days in mid-April, compared to late April to early May before 1997.

The latest last heatwave days have shifted from late August to early September in most areas, with some northern Tianshan stations extending to mid-September. Notably, some high-latitude northern stations like Altay have recorded $T_{max} \geq 40$ °C events, indicating a northward expansion of extreme heat.

2.3.1 Interannual Variation of Different Heatwave Grades

Analysis of different intensity grades shows that moderate heatwave days have decreased proportionally despite absolute increases, while extreme heatwave days ($T_{\max} \geq 40$ °C) have increased significantly, especially after 1997 when their proportion reached 15.6%—about 2.5 times the normal value. The spatial extent of extreme heat has expanded northward to the Altay region. The 2015 extreme heat event saw 16 stations break historical records, with Toksun reaching 48.8 °C and Turpan 49.0 °C.

2.3.2 Spatial Distribution of Heatwave Intensity

The intensity grade distribution reveals that regions with $T_{\max} \geq 40$ °C have expanded significantly. Before 1997, only 18 stations experienced such extreme heat, concentrated in the Turpan-Hami Basin and southern Tarim Basin. After 1997, 46 stations recorded extreme heat, with the northern boundary extending to Altay. The intensity grades have increased markedly in Hami and southeastern Bayingolin, reflecting enhanced extreme heat characteristics.

2.4.1 Correlation with Upper-Level Height Field and Construction of Balkhash Index

Extreme events are closely associated with anomalous atmospheric circulation. Correlation analysis between Xinjiang heatwave days and 200 hPa geopotential height reveals a significant southwest-northeast oriented positive correlation zone from the Atlantic (10°-40°N) to the Far East (40°-60°N), with maximum correlation over the Balkhash Lake region (40°-50°N, 70°-90°E). The Balkhash Index constructed from this region correlates significantly with heatwave days ($r = 0.58$, $p < 0.05$), indicating that higher geopotential height over Balkhash Lake corresponds to more heatwave days in Xinjiang.

2.4.2 Relationship Between Balkhash Index and Atlantic SST

The Balkhash Index shows significant positive correlation with SST anomalies in the equatorial Atlantic (0°-10°N, 10°-40°W). The Atlantic SST index, constructed from this region, correlates with the Balkhash Index at $r = 0.55$ ($p < 0.01$). Since 1997, both indices have been predominantly positive, suggesting that warm equatorial Atlantic SST anomalies favor the development of a South Asian High over Balkhash Lake to Mongolia, leading to increased heatwave days in Xinjiang.

3 Conclusions and Discussion

Under the background of climate warming and wetting in Xinjiang, heatwave days have increased significantly at a rate of 0.76 days per decade, with a marked acceleration after 1997. The increase is more pronounced in southern Xinjiang,

particularly in the Turpan-Hami Basin and eastern Tarim Basin. The first heatwave day has advanced to mid-April while the last has delayed to mid-September, lengthening the heatwave season. The proportion of extreme heatwave days ($T_{\max} \geq 40\text{ }^{\circ}\text{C}$) has increased substantially, with the spatial extent expanding northward to the Altay region.

The increasing trend in heatwave days is closely linked to anomalous upper-level circulation. A significant positive correlation exists between heatwave days and 200 hPa geopotential height over the Balkhash Lake region, which in turn is teleconnected with equatorial Atlantic SST anomalies. When Atlantic SST is warmer than normal, it favors a westward and northward shift of the South Asian High, resulting in more heatwave days across Xinjiang.

Some uncertainties remain regarding stations with decreasing heatwave days and the precise mechanisms of Atlantic SST influence, warranting further investigation. The complex causes of heatwave intensification in Xinjiang require additional research to improve understanding and inform climate adaptation strategies.

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Figure Captions

[Figure 1: see original paper] Changes of heatwave days (daily maximum temperature ≥ 35 °C), mean temperature (a) and precipitation (b) in Xinjiang from 1961 to 2018

[Figure 2: see original paper] Spatial distribution of mean annual high temperature days (a) and trend of high temperature days (b) in Xinjiang region from 1961 to 2018

[Figure 3: see original paper] Spatial distribution of abrupt transition years of heatwave days in Xinjiang

[Figure 4: see original paper] Probability density function distribution of the first (a) and last (b) days of high temperature in Xinjiang during 1961-2018

[Figure 5: see original paper] Distribution chart of the first and last high temperature day at various stations in Xinjiang

[Figure 6: see original paper] Portion changes of moderate, strong and extreme heatwaves in Xinjiang from 1961 to 2018

[Figure 7: see original paper] Spatial distribution of high temperature weather (≥ 40 °C) intensity grades in Xinjiang

[Figure 8: see original paper] The spatial distribution of correlation coefficient between heatwave days in Xinjiang (maximum temperature ≥ 35 °C) and the geopotential height at 200 hPa

[Figure 9: see original paper] Changes of Balkhash index with heatwave days (a) and Atlantic SST index (b) from 1961 to 2018

[Figure 10: see original paper] The spatial distribution of correlation coefficient between Balkhash index and SST anomalies

Number of stations with abrupt changes in the number of high temperature days in different decadal periods in Xinjiang

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

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