Temperature Changes and Urban Heat Island Effect in Nur-Sultan, 1973-2015: Postprint

Authors: Ekber Askar

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Abstract

Based on daily temperature data from Nur-Sultan city and Akol town during 1973-2015, as well as urban development data for Nur-Sultan from 2000-2015, this study investigated the variation characteristics and causes of temperature and urban heat island intensity in the region using analytical methods such as regression analysis, seven-point quadratic smoothing, Mann-Kendall abrupt change test, and moving T-test. The results indicate that: (1) Against the backdrop of significant temperature increases in the Northern Hemisphere and Central Asia during the same period, the annual mean temperature in Nur-Sultan showed no significant change, with the impact of global change on temperature mainly manifested as intensified polarization; (2) Due to the weakening of winter heat island intensity, the annual mean heat island intensity in Nur-Sultan exhibited a significant weakening trend. The weakening of winter heat island intensity was primarily influenced by winter temperature changes at the contrast station, and secondarily associated with urban development in Nur-Sultan.

Full Text

Temperature Variation and Urban Heat Island Effect in Nur-Sultan during 1973-2015

Akida ASKAR[1,2], Talgat ABZHANOV[3], WANG Yongdong[1], ZHAO Yongcheng[1], LEI Jiaqiang[1]

[1]Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Saken Seifullin Kazakh Agrotechnical University, Nur-Sultan 010000, Kazakhstan

Abstract: Based on daily temperature data from Nur-Sultan City and Akkol Town from 1973-2015, together with urban development data for Nur-Sultan, this study employs regression analysis, seven-point quadratic smoothing, Mann-Kendall mutation test, sliding T-test, and other analytical methods to investigate the characteristics and driving factors of regional temperature changes and urban heat island intensity. The results indicate that: (1) Against the backdrop of significant warming in the Northern Hemisphere and Central Asia during the same period, Nur-Sultan' s annual mean temperature showed no significant trend, with the primary manifestation of global change being increased polarization of temperature extremes; (2) Influenced by weakening winter heat island intensity, Nur-Sultan' s annual mean heat island intensity exhibited a significant decreasing trend, with the winter weakening mainly attributable to temperature changes at the comparison station, though also partially associated with urban development in Nur-Sultan.

Keywords: arid land; temperature change trend; heat island intensity; cold island effect; Nur-Sultan

The latter half of the 20th century represents both the most rapid period of industrialization in human history and the warmest century on record. Research demonstrates that human activities constitute the primary driver of climate warming. Against this backdrop of climate change, the global climate system is undergoing profound transformations, with global warming leading to more intense and frequent extreme weather events. Climate change exhibits strong local characteristics, and regional climate variations represent the response of climate fluctuations at regional or urban scales, closely linked to urbanization. The urban heat island effect represents the most significant impact of urbanization on urban temperatures. Urban construction intensifies the spatiotemporal heterogeneity of regional temperatures and urban heat island effects, increasing uncertainty in regional responses to extreme climate change and making the interdecadal variation patterns and causes of regional climate a focal research area within global change studies.

Arid regions are among the most sensitive areas to climate change and human activities. Kazakhstan's arid zone covers a vast area, and its capital, Nur-Sultan, is situated in the arid and semi-arid climatic zone of Central Asia. Following its designation as the capital, Nur-Sultan has experienced rapid development, transforming from a small town with fewer than 40,000 residents into a city exceeding one million inhabitants, with a development speed ranking first in Kazakhstan and across Central Asia. The impact of Nur-Sultan' s urbanization on regional climate change can serve as a typical case study for exploring how urbanization affects climate in arid zone cities. However, existing research primarily treats Central Asia or Kazakhstan as integrated study areas to investigate climate change or national development status, or examines climate change patterns in the former capital, Almaty, with few studies focusing on Nur-Sultan' s temperature changes and urban heat island effects. Therefore, based on Nur-Sultan' s daily temperature data and related urban development data, this paper elucidates the temperature and urban heat island intensity patterns in Nur-Sultan over the past 43 years and explores their potential influencing factors, providing a scientific basis for future urban construction and climate adaptation strategies in Nur-Sultan.

1 Study Area Overview

Nur-Sultan (51.00°-51.30°N, 71.22°-71.74°E), formerly known as Akmola and Astana, is located on the vast Kazakh steppe at an elevation of 347 m. The city experiences a typical temperate continental climate with an annual mean temperature of 1.8°C and multi-year average precipitation of 290 mm. Characterized by long, cold winters with frequent snowstorms and short, hot, humid summers, Nur-Sultan is considered one of the world' s coldest capitals. Since becoming Kazakhstan' s capital in 1997, Nur-Sultan has developed rapidly, with its population growing from 83,300 to over one million and its urban area expanding from 70.2 km^2 to 185.9 km^2, making it Kazakhstan' s second-largest city after Almaty.

2 Data and Methods

2.1 Data Sources

This study primarily utilizes meteorological data and urban development data (total resident population, fuel and energy consumption, motor vehicle maintenance service sales, etc.). The meteorological data, obtained from the National Oceanic and Atmospheric Administration (NOAA) Global Climate Station dataset (https://www.climate.gov), consist of daily temperature records from 1973-2015 for Nur-Sultan Station (the city' s oldest and most complete meteorological station) and Akkol Station (the heat island comparison station). With a data missing rate below 1.5%, missing values were linearly interpolated to ensure data quality and accuracy. After processing, monthly, seasonal, and annual temperature data and diurnal temperature ranges were obtained. Northern Hemisphere and Central Asian temperature data were derived from the CRU TS 3.24.01 global monthly temperature dataset (0.5°$×$0.5° resolution) from the University of East Anglia' s Climatic Research Unit, which has been validated for applicability in Central Asia. Urban development data were obtained from the Statistics Committee of Kazakhstan' s Ministry of National Economy (https://taldau.stat.gov.kz).

2.2 Comparison Station Selection

To investigate urbanization impacts on urban climate, suburban stations near the city with similar natural conditions and minimal urban influence are typically selected for comparative analysis. This study selected Akkol Town Station as the comparison site due to its proximity to Nur-Sultan (98.5 km), complete data record, and similar latitude, longitude, elevation, and background climate. Akkol is a township with fewer than 10,000 residents, representing an area minimally affected by urbanization compared to the capital.

Correlation and periodic analyses of annual mean temperatures between the two locations yielded a correlation coefficient exceeding 0.99 at the 99.9% confidence level, with Akkol' s annual mean temperature sharing the same primary and secondary periodicities as Nur-Sultan during 1973–2015. This synchrony confirms that Akkol' s meteorological data can serve as background climate information for studying Nur-Sultan' s urban climate.

2.3 Research Methods

We employed univariate linear regression and seven-point quadratic smoothing to analyze overall temperature trends. The Mann-Kendall (M-K) mutation test and sliding T-test were combined to identify abrupt change onset times and locations. Morlet wavelet analysis was used to comprehensively examine multi-scale periodic variations in temperature series and their temporal distribution. All analyses were conducted using Matlab.

3 Results

3.1 Interannual Temperature Variation Characteristics

Figure 1 illustrates the interannual variation of annual mean temperature in Nur-Sultan, Central Asia, and the Northern Hemisphere from 1973–2015. During the mid-1980s, Nur-Sultan' s annual mean temperature exhibited a "W-shaped" pattern, broadly consistent with trends in Central Asia and the Northern Hemisphere. However, while Central Asia showed a fluctuating upward trend and the Northern Hemisphere displayed continuous warming, Nur-Sultan' s annual mean temperature remained relatively stable overall. Linear fitting revealed a weak warming trend of $0.07°C \cdot (10a)^{-1}$, far below the $0.32°C \cdot (10a)^{-1}$ and $0.35°C \cdot (10a)^{-1}$ warming rates in Central Asia and the Northern Hemisphere, respectively.

Although Nur-Sultan' s annual mean temperature showed no significant trend, its annual mean maximum temperature, annual mean minimum temperature, and diurnal temperature range changed significantly ($p < 0.05$). As shown in Figure 3, the annual mean maximum temperature increased at $0.42°C \cdot (10a)^{-1}$, with a trend similar to Central Asia and the Northern Hemisphere. Conversely, the annual mean minimum temperature decreased at $0.30°C \cdot (10a)^{-1}$, while the diurnal temperature range increased at $0.73°C \cdot (10a)^{-1}$. These findings indicate that under global change, Nur-Sultan experienced increased polarization between rising maximum temperatures and falling minimum temperatures.

The M-K test detected multiple intersections of statistical curves within critical bounds but no exceedances, preventing definitive identification of mutation points. Combining this with sliding T-test results (Figure 2) revealed that the t-statistic for 1993 passed significance tests, indicating an abrupt temperature change in Nur-Sultan that year; other M-K intersections were false mutation points. Wavelet analysis identified three periodic fluctuations controlling temperature changes over the past 43 years: 28-year, 11-year, and 6-year cycles, though these periodicities were localized and did not dominate the entire study period.

3.2 Seasonal Temperature Variation Characteristics

Analysis of seasonal temperature data derived from daily observations shows distinct patterns across seasons (Figure 4). Spring mean temperature increased significantly at 0.36°C·$(10a)^{-1}$, with spring mean maximum temperature rising at 0.74°C·$(10a)^{-1}$ and peaking after 1998; spring mean minimum temperature showed no significant trend. Summer mean temperature and maximum temperature exhibited no significant changes, while summer mean minimum temperature decreased significantly at 0.41°C·$(10a)^{-1}$ after 1998. Autumn mean temperature and minimum temperature showed non-significant changes, though autumn mean maximum temperature increased at 0.59°C·$(10a)^{-1}$. Winter mean temperature and minimum temperature both decreased significantly, reaching minima of -26.3°C and -20.7°C in 2012, respectively, while winter mean maximum temperature increased.

3.3 Urban Heat (Cold) Island Effect

The urban heat island effect describes significantly higher urban temperatures compared to suburbs, while the cold island effect refers to lower urban temperatures. Heat island intensity is typically expressed as the temperature difference between urban and suburban areas. Using the monthly mean temperature difference between Nur-Sultan and Akkol, Figure 7 shows Nur-Sultan' s annual mean heat island intensity first strengthened then weakened. The linear trend reveals a significant weakening at 0.14°C·$(10a)^{-1}$. Heat island intensity began strengthening in the late 1970s, peaking around 1987 (significant at $p < 0.05$), with the enhancement trend becoming insignificant by the late 1990s. An abrupt change occurred around 1998, after which intensity weakened, reaching statistical significance ($p < 0.05$) after 2000.

Seasonal analysis demonstrates that all four seasons exhibited fluctuating decreasing trends in heat island intensity (Figure 8). Summer, spring, and autumn trends were non-significant, while winter showed a highly significant weakening trend of 0.29°C·$(10a)^{-1}$, with cold island effects occurring multiple times after 1998. Correlation analysis reveals extremely strong linkage between winter heat island intensity and annual mean heat island intensity, indicating that the significant weakening of Nur-Sultan' s urban heat island intensity is primarily driven by winter weakening.

To examine relationships with urban development, we collected Nur-Sultan' s total population data from 1997–2015 and analyzed correlations with heat island intensity (Figure 9). Only winter mean heat island intensity showed significant negative correlation with population. Population growth mutation tests indicate significant increases after 1998 ($p < 0.05$) and extremely significant growth after 2000 ($p < 0.01$). Considering the lagged environmental impacts of population growth, Nur-Sultan' s winter cold island effect is partially associated with urban development.

4 Discussion

Cold island formation is influenced by weather processes, urban emissions, smoke, and urban greening. Human alteration of global climate primarily occurs through atmospheric composition changes that disrupt natural energy flows. Population growth inevitably leads to rapid energy consumption and increased vehicles, affecting urban atmospheric conditions. Nur-Sultan' s heating period lasts seven months, with coal as the primary fuel for power generation and heating. From 2000–2015, urban fuel and energy consumption increased nearly six-fold, while motor vehicle maintenance service sales increased nearly ten-fold, both showing significant negative correlations with winter mean heat island intensity.

Research indicates that when urban forest area exceeds 100 hm^2, cooling effects strengthen with increasing green space, with forests larger than 12 hm^2 showing enhanced cooling. Since Kazakhstan relocated its capital to Nur-Sultan in 1997, the city has vigorously implemented the "Capital Green Belt Project,"expanding planted vegetation to 28.8 million m^2 by 2015 with planned annual expansion. This greening cannot be excluded as a factor in weakening heat island intensity, though further verification is needed.

Additionally, Nur-Sultan's total suspended particulate (TSP) concentrations exceed national standards, with winter concentrations higher than other seasons due to low temperatures and frequent temperature inversions that trap pollutants and reduce solar radiation reaching the surface. We therefore hypothesize that worsening air pollution from urban development may also contribute to winter cold island effects.

5 Conclusions

(1) Against the backdrop of significant warming in the Northern Hemisphere and Central Asia, Nur-Sultan' s annual mean temperature showed no significant change. However, significant changes in annual mean maximum temperature, minimum temperature, and diurnal temperature range indicate that global change impacts manifest primarily through increased temperature polarization.

(2) Nur-Sultan' s annual mean heat island intensity exhibited a significant weakening trend, mainly due to winter heat island intensity decline. This winter weakening correlates with both Nur-Sultan's weak cooling trend and Akkol' s weak warming trend. The cold island effect emerging after 1998 primarily resulted from accelerated warming at the comparison station. These findings demonstrate that comparison station selection substantially influences heat island results, necessitating multiple comparison stations

to eliminate confounding effects when data permit.

(3) Winter heat island intensity weakening is associated with urban development. Nur-Sultan' s population showed significant negative correlation with winter heat island intensity, while urban fuel and energy consumption and motor vehicle service sales also correlated significantly negatively. As a coal-dependent city, intensifying air pollution from urban development may represent an additional factor contributing to winter cold island effects since 1998.

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