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Spatiotemporal Characteristics Analysis of the Berlin Extreme Heat Event Based on ERA5 and MODIS

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Abstract

This study takes the Berlin urban agglomeration in Germany as an example and uses ERA5 reanalysis data and Moderate-resolution Imaging Spectroradiometer (MODIS) remote sensing surface temperature data to systematically identify and assess the trends of extreme high-temperature events between 2010 and 2023.Using 2010–2019 as the base period, the 90th percentile temperature threshold was determined. Combining the Mann–Kendall trend test and Sen's slope estimation, the variation characteristics of heat wave frequency and intensity were analyzed, and the consistency between the two was compared. The results show that the number of heatwave days in the Berlin area has increased significantly over the past decade, with temperatures in the central urban area being significantly higher than those in the surrounding areas, showing a steady upward trend. ERA5 and MODIS show a high degree of consistency in their temporal variation, but ERA5 is slightly underestimated in densely built-up areas. The two types of data complement each other in terms of spatiotemporal resolution, and their combined application can effectively improve the accuracy of urban heat wave monitoring, providing a reference for climate risk assessment and adaptive planning in mid-to-high latitude cities.

Keywords

climate change, ERA5 reanalysis data, MODIS surface temperature, urban heatwave trend, spatiotemporal feature analysis

1. Introduction

Against the backdrop of intensifying global warming, the frequency and intensity of extreme heat events in Europe have increased significantly. In 2022, many places broke historical heat records, causing serious health, energy, and ecological impacts (Ballester et al., 2023, Van Der Woude et al., 2023) High temperatures have become a key challenge to urban sustainable development and residents' safety. As the most sensitive areas to changes in the thermal environment, cities exhibit significant spatial heterogeneity in their surface temperature, influenced by factors such as building density, land use, and human activities (Jiang et al., 2023).

Existing research mostly focuses on global or national scales, while detailed analysis of heat waves in mid- to high-latitude urban clusters remains insufficient (Rahman et al., 2024, Perkins-Kirkpatrick and Lewis, 2020). Berlin, as a typical highly urbanized area, is affected by both the continental climate and the urban heat island effect. Traditional weather stations are unable to reflect temperature differences within a city, so multi-source data fusion is necessary. ERA5 reanalysis data have temporal continuity, while Moderate-resolution Imaging

Spectroradiometer (MODIS) surface temperature products have high spatial resolution, but the two differ in scale and observation conditions. Constructing a complementary and integrated framework is an important way to improve the accuracy of heat wave identification at the urban scale (Hersbach et al., 2020, Ticehurst et al., 2014).

This study takes the Berlin urban agglomeration in Germany as an example, and combines ERA5-Land reanalysis data with MODIS surface temperature data to identify and analyze the spatiotemporal characteristics of extreme high-temperature events from 2010 to 2023. This study identifies heatwave events using the 90th percentile threshold method (TX90p), compares the performance and bias of the two types of data at the urban scale, aims to reveal the spatiotemporal evolution characteristics of the Berlin heatwave, and constructs a reproducible urban extreme heat monitoring framework to provide a reference for European urban climate adaptation research.

2. Data and Methods

2.1 Overview of the Study Area

This study selected the Berlin urban agglomeration in Germany as the research area (52.2°–52.8°N, 13.0°–13.8°E). Berlin has a flat terrain and a climate that is between temperate maritime and continental, with frequent high temperatures in summer. High urbanization level, high building density, and significant heat island effect(Scherer et al., 2013). Due to the combined effects of intensified urbanization and global warming, Berlin has experienced several significant heat waves in the past decade, especially in 2022, becoming one of the cities in Europe most severely affected by extreme heat(Ballester et al., 2023). Therefore, Berlin serves as a typical sample area for analyzing the heat wave response mechanisms of mid-to-high latitude cities, and also provides ideal conditions for assessing the applicability of reanalysis data and remote sensing data at the urban scale.

2.2 Data Sources and Processing

The study integrates ERA5 reanalysis data with MODIS satellite surface temperature products, covering the period from 2010 to 2023. The period from 2010 to 2019 was used as the climate base period for calculating the high temperature threshold; the period from 2020 to 2023 was the research and analysis period (Hersbach et al., 2023, Wan et al., 2021).

First, data is downloaded and preprocessed, and missing values are interpolated, and time is resampled. The ERA5 reanalysis data came from the Copernicus Climate Data Store (CDS) of the European Centre for Medium-Range Weather Forecasts (ECMWF), using single-level diurnal data with a spatial resolution of 0.25° × 0.25°(Hersbach et al., 2020). The study selected key variables such as 2-meter air temperature (T2m), daily maximum temperature (Tmax), and net solar radiation at the Earth’s surface.ERA5 data have the advantages of strong temporal continuity and high physical consistency, and is widely used in regional climate analysis and extreme temperature research (Wang et al., 2022). The raw data is stored in NetCDF format and read and converted to UTC+1 time. Missing data were filled in using linear interpolation, and the nearest neighbor resampling method was used to adjust the ERA5 raster to a resolution that matches the MODIS data to ensure the accuracy of subsequent spatial comparisons.

MODIS remote sensing surface temperature data comes from NASA Terra satellite MOD11A2 products, with a spatial resolution of 1 km and a temporal resolution of 8 days, covering the period from 2010 to 2023 (Wan and Dozier, 1996). This study selected daytime surface temperature (LST Day 1km) as the main analytical variable. Cloud-contaminated pixels are removed using a quality control (QC) mask, and an approximate daily sequence is generated using linear interpolation. The data is uniformly projected to the WGS84 coordinate system and strictly registered with the ERA5 raster. MODIS LST data can effectively characterize differences in urban surface thermal environment and is widely used in urban heat island and surface temperature research (Li et al., 2013, Zhou et al., 2014). This study uses MODIS data to verify the applicability and spatial bias of ERA5 results at the urban scale.

2.3 Identification and Indicator Calculation of Extreme High Temperature Events

Extreme high-temperature events were identified using the 90th percentile threshold method (TX90p) recommended by the World Meteorological Organization (WMO) (Perkins, 2015). Based on daily maximum temperature data from ERA5, the 90th percentile threshold for the base period from 2010 to 2019 was calculated. During the study period, an extreme high-temperature event is defined as when the daily maximum temperature exceeds this threshold for three or more consecutive days. To reduce the impact of short-term temperature anomalies, a three-day moving average was used to smooth the time series. Heatwave intensity (HWI) is calculated using the following formula:

$$\mathrm{HWI} = \sum_{i=1}^{n} (T_{\max,i} - T_{90}) \quad (1)$$

Where $T_{\max,i}$ represents the daily maximum temperature during the event, and T_{90} is the 90th percentile threshold of the base period. Duration is defined as the number of consecutive days exceeding the threshold, and frequency (HWF) is the number of events within a year. This method has been widely used for heatwave identification in Europe and China (Russo et al., 2015).

2.4 Time and Space Analysis Methods

Time series trend analysis was performed using the ERA5 annual average number of high-temperature days and the HWI series. The rate of change was calculated using linear regression, and the Mann–Kendall (MK) test was used to verify the significance of the trend (α=0.05). This method can effectively identify long-term trends in climate time series (Yue et al., 2002).

Spatial distribution analysis based on rasterized results of annual mean temperature and heat wave frequency from ERA5 and MODIS data. Spatial temperature distribution was plotted using inverse distance weighted (IDW) interpolation to compare the differences between the urban core and peripheral areas (Li et al., 2013). Raster interpolation (MODIS−ERA5) was performed between ERA5 and MODIS data to identify the spatial pattern of the deviation and the location of the heat island center. Spatial mapping was performed in QGIS 3.34 and R 4.3.3.

To assess the reliability of ERA5 at the urban scale, the Pearson correlation coefficient (R) and root mean square error (RMSE) of ERA5 paired with MODIS pixels were calculated. When $R > 0.8$ and RMSE < 2°C, the two are considered to have good agreement (Zhou et al., 2014, Russo et al., 2015).

2.5 Methodological Rationality

The complementarity of ERA5 and MODIS in terms of temporal and spatial resolution allows for their combined use to simultaneously capture the temporal variations and spatial details of heatwave processes (Hersbach et al., 2020, Li et al., 2013). Using the TX90p threshold method ensures that the results are in line with international research standards, while the MK test and Sen’s slope method can quantitatively reflect the significance of the trend and the rate of change (Yue et al., 2002). Overall, the analytical process developed in this study is reproducible and scientifically robust, providing a reliable technical framework for urban climate monitoring and heat wave research.

3. Results

3.1 Overall Changes in 2018

Figure 1 shows the annual variation series of daytime surface temperature (MODIS LST, solid green line) and reanalysis daily maximum temperature (ERA5 Tmax, dashed blue line) in the Berlin area from 2010 to 2023. The horizontal axis represents the years (2010–2023), and the vertical axis represents the average annual temperature (°C). Looking at the annual series, both curves show a fluctuating upward long-term trend, indicating that the Berlin region has experienced a significant warming process over the past decade. There are some differences between the two data sources: MODIS LST is generally about 1–2°C higher than ERA5 Tmax, especially showing significant peaks in 2018 and 2022, corresponding to years with frequent heat waves in Europe. The ERA5 curve is relatively smooth, reflecting its spatial average characteristics, while MODIS is more significantly affected by surface heterogeneity and can capture the local enhancement effect of the urban heat island. Overall, MODIS reveals a larger range of changes, while ERA5 shows a more stable trend.

Figure 1: Comparison of annual series of MODIS LST and ERA5 Tmax (2010–2023) (Photo/Picture credit: Original).

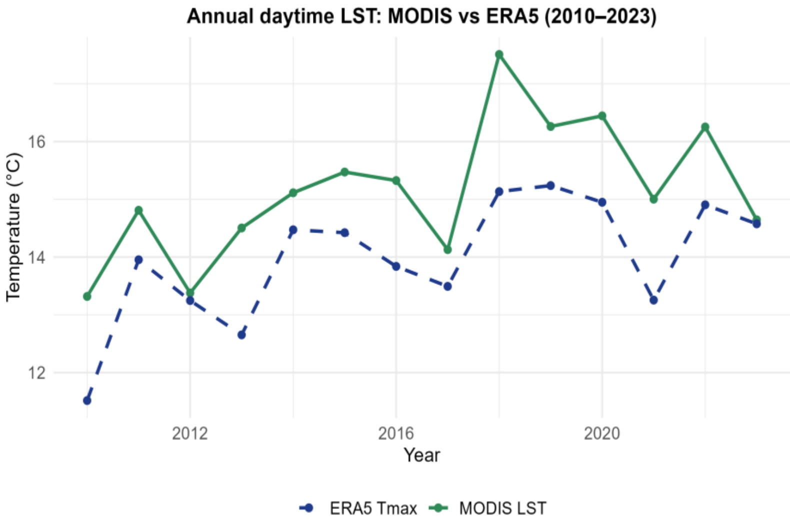
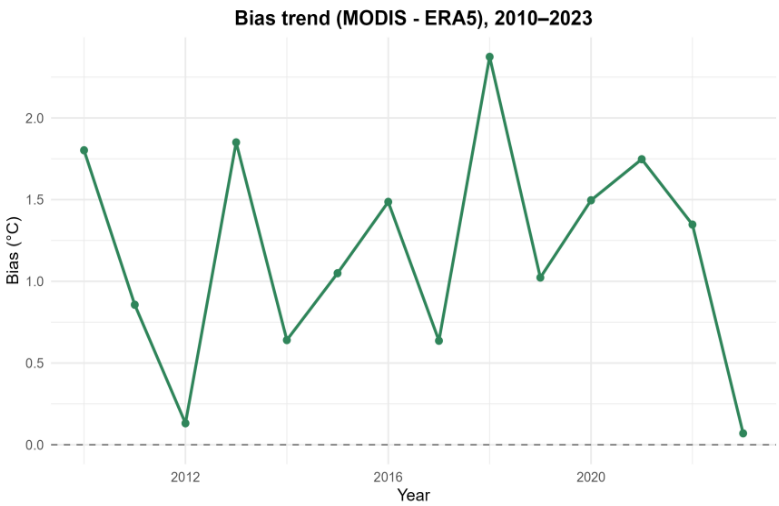


Figure 2 shows the temperature deviation sequence between MODIS and ERA5 (Bias = MODIS − ERA5). The horizontal axis represents the years (2010–2023), and the vertical axis represents the deviation value (°C). As can be seen, the biases are all positive during this period, indicating that the surface temperature estimated by MODIS is consistently higher than the ERA5 reanalysis results. The deviation values fluctuated across different years, with significant upward peaks in 2011, 2015, 2018, and 2022, indicating that MODIS observations in these years responded more strongly to heat waves or high-temperature processes. Overall, the deviation did not show a systematic downward trend, which means that the systematic underestimation of ERA5 in the urban core area still exists. As can be seen from Figures 1 and 2, MODIS and ERA5 show consistent trends over many years, but MODIS is better able to reflect the actual intensity of surface heat exposure and is especially suitable for monitoring extremely high temperatures at the urban scale.

Figure 2: Annual temperature deviation trend (MODIS−ERA5, 2010–2023) (Photo/Picture credit: Original).



Meanwhile, the annual number of heatwave days (HWF) shows an overall increase: approximately 31 days in 2010, a sharp increase to 62 days in 2018, and approximately 49 days in 2023 (Table 1). The Mann–Kendall test showed a significant upward trend in HWF ($\mu \approx 0.47$, $p \approx 0.021$); the estimate of Sen's slope indicated an annual increase on the order of 1–2 days/year.

Table 1: Number of heatwave days(2010–2023)

Year	Mean HWF days
2010	31.09
2011	25.14
2012	27.61
2013	28.91
2014	33.17
2015	40.26
2016	41.05
2017	23.90
2018	62.33
2019	51.54
2020	39.93
2021	38.17
2022	45.73
2023	49.08

3.2 Spatial Distribution Pattern

Spatial images show that the city center (Berlin city proper) is significantly hotter than the surrounding suburbs (Figure 3), exhibiting a typical "high in the center, low in the suburbs" distribution. MODIS offers higher spatial detail than ERA5: the former can distinguish temperature differences between densely networked areas, industrial and commercial areas, and large green spaces; the latter presents a gentler spatial gradient, indicating that MODIS can capture more subtle differences in the thermal environment at the urban scale. The temperature deviation grid (Figure 4) shows that the deviation is concentrated in the built-up area and is positive, indicating that ERA5 has a spatial smoothing effect in densely built areas.

Figure 3: Spatial distribution of MODIS annual mean land surface temperature (2010–2023 average) (Photo/Picture credit: Original).

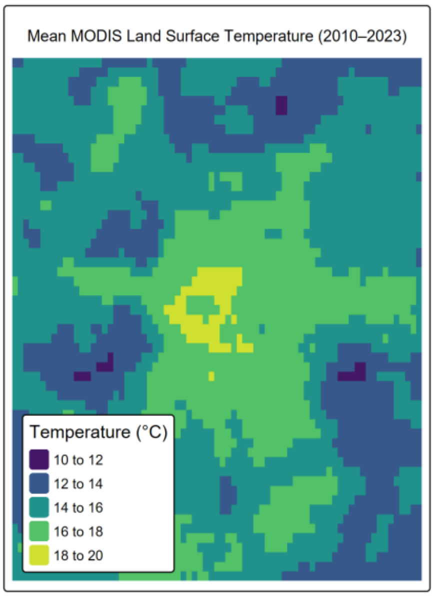
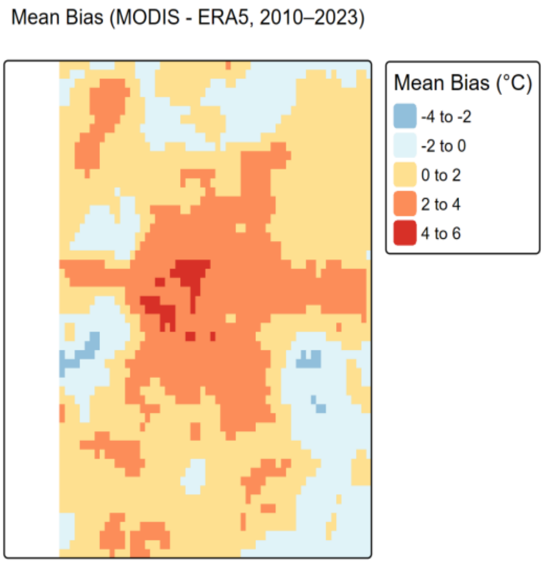


Figure 4: Spatial distribution of annual average temperature deviation(MODIS−ERA 5,2010–2023) (Photo/Picture credit: Original).



3.3 Characteristics of Heat Waves and Interannual Differences

Results of extreme high-temperature events identified based on the TX90p threshold show that the frequency of heat waves generally increased between 2010 and 2023, with a particularly significant increase in the number of high-temperature days in 2018 and 2022.HWF was relatively low in 2010–2013 (approximately 25–30 days), and then gradually increased to more than 40 days after 2020. The Mann–Kendall test showed a significant trend ($\tau=0.47$, $p<0.05$) (Table 2). Spatially, the high-frequency areas of heat waves are mainly concentrated in the southern and eastern parts of the city, which highly overlap with the off-center hotspots, indicating a link between the off-center and heat exposure.

Table 2: Trend Dataset

Year	Mean HWF days	MODIS LST	ERA5 Tmax	bias
2010	31.09	11.68	13.32	1.8
2011	25.14	14.07	14.81	0.86
2012	27.61	13.29	13.38	0.14
2013	28.91	12.80	14.5	1.86
2014	33.17	14.59	15.11	0.65
2015	40.26	14.59	15.47	1.05
2016	41.05	13.92	15.32	1.49
2017	23.90	13.56	14.13	0.64
2018	62.33	15.20	17.51	2.37
2019	51.54	15.33	16.26	1.02
2020	39.93	15.04	16.44	1.50
2021	38.17	13.43	15.00	1.75
2022	45.73	15.02	16.25	1.35
2023	49.08	14.73	14.64	0.07

3.4 ERA5 and MODIS Consistency

Meta-level correlation analysis shows that the correlation coefficients (R) between the two types of data in the Berlin area are mostly between 0.75 and 0.90, with an RMSE of approximately 1–2°C (Figure 5), which meets the reliability requirements for urban-scale climate monitoring. The linear relationship between heat wave frequency and temperature deviation (Figure 6) further validated that the two were significantly positively correlated (r=0.33, p<0.05), indicating that the deviation of the reanalysis data is related to the intensity of urban heat exposure to some extent.

Figure 5: Spatial correlation between heat wave frequency and temperature deviation (Photo/Picture credit: Original).

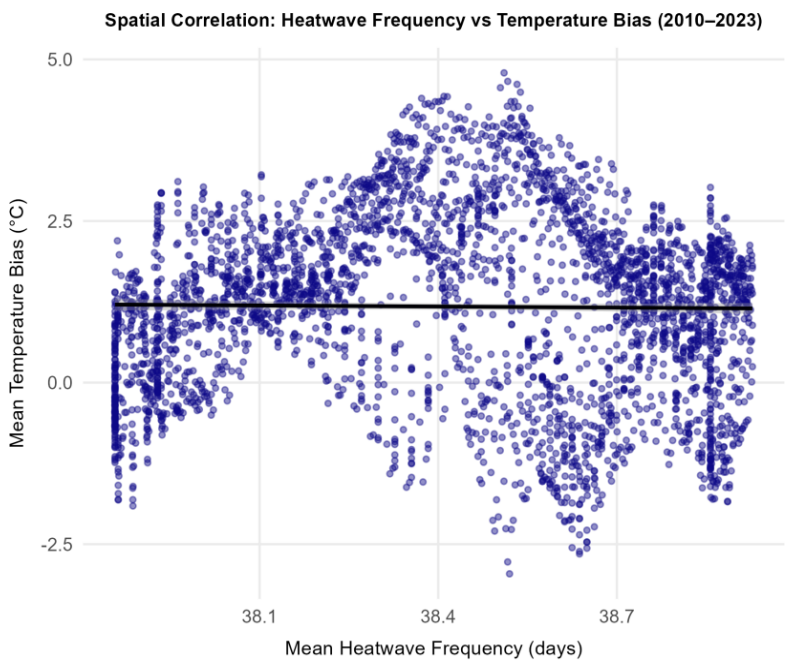
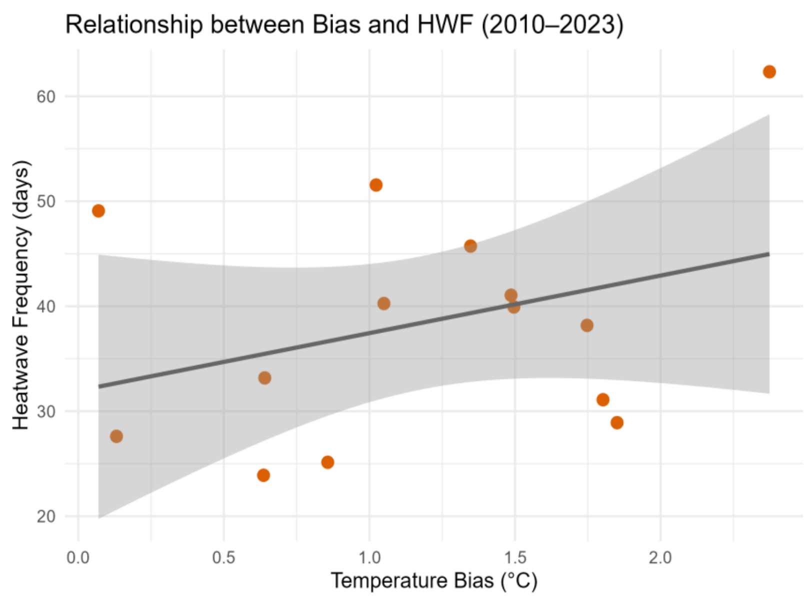


Figure 6: Scatter plot showing the linear relationship between heat wave frequency and temperature deviation.(2010–2023)



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4. Discussion

This study reveals a significant increase in extreme heat events in the Berlin urban agglomeration over the past decade, while also highlighting the limitations and room for improvement of multi-source climate data in urban-scale heat wave analysis. The combined use of ERA5 and MODIS achieves a complementary balance between temporal continuity and spatial accuracy. ERA5 reanalysis data exhibit stability and consistency in characterizing climate trends, but its 0.25° grid resolution smooths out microclimate differences within cities. While MODIS land surface temperature data offers higher spatial resolution and can identify the local amplification effect of urban heat islands, its temporal continuity is insufficient due to cloud cover and an 8-day composite period, resulting in incomplete responses to some extreme events. Future research will combine high-resolution ground observation networks or high spatiotemporal resolution satellite data, such as Landsat and ECOSTRESS, to improve the accuracy and completeness of urban heat wave identification.

The study also shows that high-frequency heat wave areas are mainly concentrated in the southern and eastern parts of Berlin, and the spatial overlap between the off-center hotspots and the heat island area indicates a systematic underestimation of heat waves in the built-up area by the reanalysis data. This phenomenon is consistent with the conclusions of Zhou et al. regarding the urban heat island effect, indicating that land cover type, urban morphology, and green space distribution play a crucial role in local climate regulation (Zhou et al., 2014). Compared to previous regional-scale studies on European heat waves, this study provides a more precise spatial characterization and data fusion validation at the mid-to-high latitude urban level, filling the gap in existing research regarding the insufficient identification of urban microclimate structures (Ballester et al., 2023, Russo et al., 2015). Regarding the identification of extreme high-temperature events, this paper adopts the 90th percentile threshold method (TX90p) recommended by the World Meteorological Organization (WMO). This method can effectively reflect the overall trend of climate anomalies, but its definition, based on statistical percentiles, is somewhat sensitive to the length of the time series and the climate background. Future research may consider introducing a comprehensive heat index (such as UTCI or Heat Index) or adopting an adaptive thresholding method based on machine learning to improve the scientific accuracy of heat wave identification from both meteorological and human heat exposure perspectives.

Overall, this study validated the applicability of reanalysis data in urban extreme heat research by fusing ERA5 and MODIS and highlighted the important value of remote sensing data in capturing details of surface thermal structure. However, differences in data resolution, MODIS cloud occlusion error, and the statistical assumptions of the threshold method can all bias the results. Future research will further integrate high-resolution reanalysis data (such as ERA5-Land or CORDEX regional model output), urban functional zone classification, building density and green space indicators, and other variables to improve the spatial accuracy of heat wave identification. It will also combine socioeconomic and population exposure data to construct a multi-dimensional urban thermal risk assessment framework.

5. Conclusion

This study uses the Berlin urban agglomeration in Germany as the research area and integrates ERA5 reanalysis data with MODIS remote sensing land surface temperature products to construct a framework for the identification and assessment of extreme high temperatures in mid-to-high latitude cities. The spatiotemporal characteristics of heatwave events in the Berlin area from 2010 to 2023 were systematically characterized using the climate base period threshold (TX90p) method, the Mann–Kendall trend test, and spatial comparison analysis of multi-source data. The study yielded the following main conclusions: The frequency of heat waves in Berlin has increased significantly, and the trend is stable; Temperatures are higher in the city's core area, with significant spatial differentiation; The multi-source data maintains a consistent trend, but differences exist in spatial details. The established data processing and analysis workflow (threshold identification—trend verification—spatial comparison) can be directly applied to other European or mid-to-high latitude cities, comparing the performance of different data sources in urban thermal monitoring and providing a unified reference for urban climate assessment. However, due to limitations in MODIS cloud masking and temporal resolution, some short-term events may be underestimated; ERA5's spatial resolution also makes it difficult to fully reflect intra-city differences. In the future, ground-based observation networks, high-resolution remote sensing imagery, and social exposure data will be combined to further reveal the coupling relationship between heat waves and urban structure, green space distribution, and population exposure.

Overall, this study validates the feasibility of combining ERA5 and MODIS for urban-scale heat wave monitoring. The results provide a scientific basis for assessing the thermal risks of mid-to-high latitude cities under the background of climate warming, and also provide data support and methodological reference for future urban thermal environment management and adaptive planning.

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Conflicts of Interest

The authors declare no conflict of interest.

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