Spatial trends of extreme temperature events and climate change indicators in climate zones of Jordan (Postprint)

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Date: 2025-11-17T00:00:00+00:00

Abstract

Extreme temperature events have intensified across Jordan over the past 40 a, increasing risks to agriculture, water availability, urban infrastructure, and public health. The purpose of this study is to assess the long-term spatial trends and regime shifts in extreme temperature indicators across Jordan's climate zones to explore climate adaptation strategies. This study presents a high-resolution and spatially explicit assessment of thermal extremes using daily data from 1982 to 2024 across 45 grid-based study points in Jordan. Thirteen temperature indices, including percentile-based thresholds, duration metrics, and absolute extremes, were computed using RClimDex and analyzed across four Köppen climate zones: hot desert (BWh), hot semi-arid (BSh), cold desert (BWk), and Mediterranean (Csa) climates. The analysis confirmed a statistically significant warming trend: annual mean maximum temperatures increased by 2.198°C, while annual mean minimum temperatures rose by 2.035°C. Cold extremes have sharply declined, with cold days (TX10p) decreasing by 70.0%-80.0%, and the cold spell duration indicator (CSDI) dropping from 12.6 to 4.0 d/a, particularly in the BWk zone. Heat indices intensified across all zones, with warm days (TX90p) increasing by over 300.0% in BWh, warm nights (TN90p) rising by 38.1%, and the warm spell duration indicator (WSDI) extending fourfold, indicating prolonged exposure to heatwaves. Mean value of maximum temperature (TXx) reached 45.600°C in most arid areas, while minimum temperature (TNx) exceeded 31.600°C, highlighting increased nocturnal heat stress. Change-point analysis indicated that 1998 was a pivotal year, marking a structural transition in both cold and warm temperature indices. Subsequent intensifications after 2010 in TN90p, TNx, and mean of daily maximum temperature (Tmaxmean) reflected an ongoing trend toward sustained thermal extremes. In addition to time-series trends, the study employed network-based correlation analysis to explore the coherence among climate indices. Strong positive correlations were observed among TXx, TX90p, and mean of daily minimum temperature (Tminmean) (r$ 0.94), aswellasamongTN90p, Tminmean, andTNx(r $0.87), indicating a tightly clustered heat subsystem. Duration metrics like the WSDI showed a close alignment with percentile extremes (between WSDI and TX90p; r=0.88), suggesting integrated heatwave behavior. In contrast, cold indices (TX10p, TN90p, frost days, and CSDI) exhibited weak or negative correlations and displayed peripheral positioning in the climate network, indicating their limited role under a warming regime. Absolute extremes showed weak internal linkages, suggesting episodic rather than systemic response characteristics. This structural realignment indicated a shift from a previously balanced thermal profile to a heat-dominated climate system. Regional variations revealed that BWh and BSh were experiencing the steepest warming, while Csa was transitioning more slowly but was showing signs of reduced winter cooling and increased irrigation demands. The findings establish a robust climate baseline for Jordan and offer actionable insights for climate adaptation planning. Recommended measures include precision irrigation, the development of heat-resilient crops, improvements to urban cooling infrastructure, and early warning systems for thermal extremes. By integrating spatial climate zoning, regime shift analysis, and inter-index correlation structures, this study provides a replicable framework for monitoring climatic transformations and informing resilience strategies in arid and semi-arid areas.

Full Text

Preamble

Journal of Arid Land (2025) 17(11): 1542-1557
doi: 10.1007/s40333-025-0033-7; CSTR: 32276.14.JAL.02500337
Science Press Springer-Verlag

Spatial Trends of Extreme Temperature Events and Climate Change Indicators in Climate Zones of Jordan

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Abstract: Extreme temperature events have intensified across Jordan over the past 40 years, increasing risks to agriculture, water availability, urban infrastructure, and public health. This study assesses long-term spatial trends and regime shifts in extreme temperature indicators across Jordan' s climate zones to inform adaptation strategies. Using daily data from 1982 to 2024 across 45 grid-based study points, we computed thirteen temperature indices—including percentile-based thresholds, duration metrics, and absolute extremes

—using RClimDex and analyzed them across four Köppen climate zones: hot desert (BWh), hot semi-arid (BSh), cold desert (BWk), and Mediterranean (Csa). The analysis confirmed a statistically significant warming trend: annual mean maximum temperatures increased by 2.198°C, while annual mean minimum temperatures rose by 2.035°C. Cold extremes declined sharply, with cold days (TX10p) decreasing by 70.0%–80.0% and the cold spell duration indicator (CSDI) dropping from 12.6 to 4.0 d/a, particularly in the BWk zone. Heat indices intensified across all zones, with warm days (TX90p) increasing by over 300.0% in BWh, warm nights (TN90p) rising by 38.1%, and the warm spell duration indicator (WSDI) extending fourfold, indicating prolonged heatwave exposure.

The mean value of maximum temperature (TXx) reached 45.600°C in the most arid areas, while minimum temperature (TNx) exceeded 31.600°C, highlighting increased nocturnal heat stress. Change-point analysis identified 1998 as a pivotal year marking a structural transition in both cold and warm temperature indices. Subsequent intensifications after 2010 in TN90p, TNx, and mean daily maximum temperature (Tmaxmean) reflected an ongoing trend toward sustained thermal extremes. Beyond time-series trends, we employed network-based correlation analysis to explore coherence among climate indices. Strong positive correlations were observed among TXx, TX90p, and mean daily minimum temperature (Tminmean) ($r \geq 0.94$), as well as among TN90p, Tminmean, and TNx ($r \geq 0.87$), indicating a tightly clustered heat subsystem. Duration metrics like WSDI showed close alignment with percentile extremes ($r = 0.88$ between WSDI and TX90p), suggesting integrated heatwave behavior. In contrast, cold indices (TX10p, TN90p, frost days, and CSDI) exhibited weak or negative correlations and peripheral positioning in the climate network, indicating their limited role under a warming regime. Absolute extremes showed weak internal linkages, suggesting episodic rather than systemic response characteristics. This structural realignment indicates a shift from a previously balanced thermal profile to a heat-dominated climate system.

Regional variations revealed that BWh and BSh zones experienced the steepest warming, while Csa transitioned more slowly but showed signs of reduced winter cooling and increased irrigation demands. These findings establish a robust climate baseline for Jordan and offer actionable insights for adaptation planning. Recommended measures include precision irrigation, development of heat-resilient crops, improvements to urban cooling infrastructure, and early warning systems for thermal extremes. By integrating spatial climate zoning, regime shift analysis, and inter-index correlation structures, this study provides a replicable framework for monitoring climatic transformations and informing resilience strategies in arid and semi-arid regions.

Keywords: climate change; extreme events; arid area; temperature trends; weather shift; Köppen climate classification; Jordan

Citation: Abdelaziz Q. BASHABSHEH, Kamel K. ALZBOON, Zeyad ALSHBOUL. 2025. Spatial trends of extreme temperature events and climate change indicators in climate zones of Jordan. *Journal of Arid Land*, 17(11): 1542–1557. https://doi.org/10.1007/s40333-024-0033-7; https://cstr.cn/32276.14.JAL.02500337

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1 Introduction

Climate change is accelerating globally due to rising greenhouse gas (GHG) concentrations—particularly carbon dioxide, methane, and nitrous oxide—from fossil fuel combustion, industrial activities, and land-use changes (IPCC, 2022). These elevated GHG levels have triggered widespread transformations in Earth' s climate system, leading to rising global temperatures, altered precipitation patterns, and increasing occurrences of extreme weather events such as heatwaves, floods, droughts, and tropical cyclones (Cheng et al., 2021; IPCC, 2023). Global mean surface temperature rose by approximately 1.100°C–1.200°C above pre-industrial levels between 2011 and 2020, with 2023 showing around a 1.450°C increase (WMO, 2024). These warming trends have resulted in glacial retreat, rising sea levels, marine heatwaves, coral bleaching, and ecosystem disruptions (IPCC, 2019; WMO, 2024). In low-income areas, these impacts have exacerbated inequalities and threatened food and water security, health systems, and economic stability (UNEP, 2022). Without immediate mitigation efforts, warming may exceed 2.000°C–4.000°C by 2100, leading to even more frequent and severe climate events (IPCC, 2023).

Extreme climate events are particularly sensitive to climate change, often causing substantial damage over short periods ranging from days to weeks (Cheong et al., 2018; Perera et al., 2020). Between 2000 and 2019, over 11,000 extreme climate events resulted in more than 475,000 deaths and economic losses of approximately 2.56 trillion USD across public and private sectors (Eckstein et al., 2021). At the continental level, Europe has faced numerous extreme events, particularly heatwaves. France experienced severe heatwaves in 2003, 2006, 2015, and 2022, resulting in approximately 27,000 deaths. Similarly, the Russian Federation recorded 55,000 deaths during the 2010 heatwave (Hoag, 2014; Douris and Kim, 2021; Pascal et al., 2024). Floods and storms have also caused significant economic losses, with Germany and Italy suffering damages of 37 billion and 28 billion USD, respectively. In Africa, water-related disasters tied to extreme events have accounted for 35.0% of climate-related deaths and 1.0% of global economic losses over the past fifty years (Douris and Kim, 2021).

Jordan, one of the world' s most water-scarce countries, is particularly vulnerable to these changes. Recent analyses indicate marked increases in temperature extremes and declining precipitation, with significant implications for water availability, public health, and infrastructure resilience. Smadi (2006) identified abrupt changes and a significant warming trend of 0.038°C/a at Amman' s airport station, while Bashabsheh and Alzboon (2024) recorded increases in mean maximum and minimum temperatures of 1.620°C and 1.390°C, respectively, in northern Yarmouk Basin, contributing to reduced streamflow due to intensified evapotranspiration. At the national scale, Al-Qinna (2018) applied the CoKriging technique to analyze climate variability using elevation data, revealing rising temperatures and evapotranspiration alongside a precipitation decline of 1.2 mm/a. Similarly, Alzboon et al. (2021) used the area method to trace temperature trends across ten stations, highlighting shifts in seasonal temperature thresholds, including delayed onset of cold months and expanded extreme heat periods.

Human vulnerability to climate extremes is increasing. Alwadi et al. (2024) quantified mortality burdens in Amman, showing that non-Jordanians face greater risk of cold-related health issues, while females are more sensitive to heat. A companion study found an average of 6.5 heat-attributable deaths per day in Amman beyond critical thresholds, emphasizing the urgent need for heat action planning. Heatwaves show particularly rapid intensification. Broader analyses confirm long-term increases in minimum temperatures, diminishing diurnal temperature ranges, and signs of enhanced radiative trapping in the atmosphere (Hamdi et al., 2009; Abu-Allaban et al., 2015). Although Jordan boasts diverse ecology ranging from arid deserts to Mediterranean highlands, few comprehensive spatial assessments of climate exist across the country. Projections indicate a worrying trend of increased extreme weather events, with recent high-resolution modeling for the Yarmouk Basin forecasting significantly more heatwaves, prolonged droughts, and volatile hydro-climatic conditions (Bashabsheh and Alzboon, 2025). These projections underscore the urgency of establishing a robust climate baseline and spatially explicit analysis of temperature extremes. This research fills that gap by utilizing high-quality temperature data from 45 weather stations and employing internationally recognized indices through the RClimDex platform (Zhang and Yang, 2004). The study applies the Köppen climate classification to examine regional disparities in climate extremes, which is essential for informing local adaptation efforts (Köppen and Wegener, 2015).

This study integrates percentile- and duration-based temperature indices with spatial climate zoning to reveal structural shifts in Jordan’ s thermal regime. Additionally, it includes correlation-based network analysis, providing a unique perspective on relationships among climate indicators. This analysis highlights clustering behavior and underscores the decreasing significance of cold extremes —an aspect seldom explored in regional studies. Moreover, by connecting long-term temperature trends to local vulnerabilities and incorporating spatial climate variability, this study establishes a solid baseline for monitoring risks and planning climate resilience. Finally, it offers methodological innovations applicable to other arid and semi-arid regions.

2 Materials and Methods

Jordan is located in southwestern Asia, sharing borders with Syria to the north, Palestine to the west, Saudi Arabia to the south, and Iraq to the east (29°11 –33°38 N, 35°25 –39°18 E; Fig. 1 [Figure 1: see original paper]). The terrain consists of three distinct types: the Jordan Valley, mountainous highlands, and desert plateau (Al-Bilbisi, 2013). Climate varies from Mediterranean in the west to desert in the east and south. Summers feature high temperatures and low humidity, making even temperatures in the low 30.000°C range relatively bearable (Hazaymeh et al., 2024). Summer temperatures rarely exceed 35.000°C. Winters are wetter and relatively cold, especially in the highlands, while autumn serves as a transitional period with gradually cooling temperatures and minimal precipitation (Atashi et al., 2020). We divided the study area by climatic zones because temperature patterns are closely associated with these zones, which facilitated analysis of how extreme climate events vary across different areas. According to the Köppen climate classification system (Köppen and Wegener, 2015), we categorized Jordan into four climatic zones: Mediterranean climate (Csa), hot semi-arid climate (BSh), cold desert climate (BWk), and hot desert climate (BWh) (World Bank Group, 2025).

We analyzed extreme events in Jordan over the past four decades using accurate, long-term daily temperature data that comprehensively covers all study areas without gaps or missing years. Daily temperature data were obtained from the NASA POWER data access viewer (https://power.larc.nasa.gov/data-access-viewer/). Many studies have examined the reliability of NASA datasets across different climatic zones by comparing obtained data with measured temperature data. These data have demonstrated reliability in hot desert and Mediterranean climates, with additional international assessments from South Asia and China' s Xizang Plateau further supporting their broader applicability (Zhu et al., 2019; Ali et al., 2021; Baig et al., 2021; Marzouk, 2021; Rodrigues and Braga, 2021; Hussain et al., 2022).

Daily minimum and maximum temperatures were obtained from 45 grids covering all of Jordan from 1982 to 2024 (Fig. 1). We utilized the Climatol package in R v.3.6.1 software for quality control, homogenization, and statistical analysis to ensure consistency and reliability (Guijarro, 2018). To assess changes in temperature extremes, we employed RClimDex, an R-based software developed by Environment Canada that calculates 27 internationally recognized climate indices (Zhang and Yang, 2004; Zhang et al., 2011). Although the full suite includes 16 temperature and 11 precipitation indices, this research specifically selected 13 temperature-based indices most relevant to extreme heat and cold events affecting Jordan' s climatic zones (Table 1). We applied the least-squares regression method to assess variable trends using the RClimDex package. Student' s t-test was performed to test the null hypothesis, with trends considered significant at the 0.05 level (Easterling et al., 2003). To identify statistically significant regime transitions in extreme temperature indices, we applied Change-Point Analyzer (CPA), a robust non-parametric tool developed by Taylor Enterprises (https://variation.com/product/change-point-analyzer/).

3 Results and Discussion

3.1.1 Cold Extremes and Frost Days Reduction

Figure 2 [Figure 2: see original paper] shows changes in temperature extremes. TX10p, representing the percentage of days with maximum temperatures below the 10th percentile, declined significantly across all of Jordan from 1982 to 2024 (Fig. 2a). The sharpest drops occurred in 1999 and 2007, with values falling to 2.7%-4.5%, notably below the 10.0% threshold. In contrast, 1992 was exceptionally cold in the BWh zone, reaching up to 34.8%. Similarly, TN10p (measuring nights with minimum temperatures below the 10th percentile) decreased steadily (Fig. 2b), dropping from 18.0%-34.0% in 1992 to 2.0%-3.0% in later years.

The CSDI also highlighted a downward trend (Fig. 2e), especially in BSh and BWh zones, where cold spells reduced to 2.400 d in 1999 and 4.200 d in 2007. Meanwhile, intensity indices TXn and TNn increased over time (Fig. 2c and 2d), signaling milder cold extremes. TXn reached 11.400°C in 1999 and 13.200°C in 2007, compared to the lowest value of 6.800°C in earlier years. The FD0 index indicated a decline across all zones (Fig. 2f), particularly in BWh, with values dropping below 5.000 d annually by the late 1990s. Trend analysis confirmed significant reductions in cold extremes, with average annual slope declines for TX10p and TN10p across zones ranging from -0.312°C/a to -0.447°C/a, respectively. Over the approximately four-decade study period, TXn increased most in the Csa zone (1.066°C), while TNn rose even more (1.250°C), also particularly in the Csa zone.

3.1.2 Hot Extremes and Intense Heatwaves

The TX90p index showed increased hot days across all climatic zones (Fig. 3a [Figure 3: see original paper]), peaking at 32.6%-36.4% in 1998, 2010, 2017, and 2021, particularly in BWh and BSh zones. In contrast, the index showed milder values (10.0%-12.0%) in 1982 and 1992. The TN90p index also rose significantly (Fig. 3b), reaching 29.6%-33.5% in recent years, especially in desert zones. The TXx and TNx indices continued to rise (Fig. 3c and 3d), with TXx hitting 44.200°C-45.600°C and TNx reaching 29.400°C-31.600°C in BWh and BSh zones during peak years.

The WSDI indicated longer heatwaves, with notable peaks in 1998, 2010, 2017, and 2021 extending to 13.200 d in the BSh zone and 15.800 d in the BWh zone (Fig. 3e). Conversely, shorter durations were recorded in 1982 (2.300 d) and 1992 (3.700 d). WSDI trends showed a pronounced slope increase in the BWh zone (0.523 d/a), followed by the BSh zone (0.487 d/a) and BWk zone (0.412 d/a). Regarding temperature intensity, TXx increased by 1.430°C in the BWh zone and 1.188°C in the BSh zone, while TNx rose by 1.370°C in the BWh zone and 1.124°C in the BSh zone.

3.1.3 Long-Term Warming Trend and Shift from Extreme Cold to Heat Events

The Tmaxmean index showed a clear warming trend (Fig. 4a [Figure 4: see original paper]). The hottest years, 2010 and 2023, had Tmaxmean values of 29.400°C and 31.200°C, while the coldest years, 1982 and 1992, had values of 24.100°C and 26.700°C, respectively. The BWh zone consistently had the highest values and steepest increase, while the Csa zone showed a slower rise. Similarly, the Tminmean index displayed an upward trend (Fig. 4b), with the warmest years recording values of 14.700°C and 16.200°C in 2023 and 2010, compared to 10.300°C–12.100°C in the coolest years. The BWh zone experienced the most considerable nighttime warming. Trend analysis showed Tmaxmean slopes rising by 0.050°C/a–0.056°C/a in the BSh zone and 0.050°C/a–0.054°C/a in the BWk zone. At the national scale, averages increased by 2.198°C for Tmaxmean and 2.035°C for Tminmean during the 40-year study period, indicating a pronounced warming signal across Jordan, with desert zones experiencing the strongest rise while the Mediterranean zone exhibited comparatively slower warming.

3.2 Change-Point Analysis of Temperature Extremes

Change-point analysis confirmed statistically significant regime shifts across multiple temperature-based extreme indices, which aligned with visual inspections and ecological observations of climatic transition in Jordan. Most shifts clustered around 1998, indicating a coordinated change affecting both cold and warm extremes. TX10p experienced a dramatic decline from 32.6% to 9.0% in 1993, followed by a further reduction to 5.8% in 2017. A significant decrease in its standard deviation was observed in 1998, suggesting not only fewer cold days but also reduced variability. CSDI exhibited a regime shift in 1995, with values dropping from 14.540 to 2.920 d/a. This reduction was visually confirmed in 1998, as values fell to nearly zero across various zones. While TXn did not show a significant mean shift, its variability increased in 1998, with standard deviation rising from 0.690°C to 1.680°C, indicating a wider range of extreme cold temperatures. The FD0 index experienced two regime shifts: an initial increase from 10.790 to 19.670 d/a in 1989, followed by a sharp and sustained decline to 7.310 d/a in 1994, supporting the observed reduction in frost events. TN10p also displayed a coordinated decrease around 1998, falling from 17.7% to 6.5%, with no change in variability. Conversely, TNn revealed no statistically significant regime shifts or changes in variability, indicating stability in annual absolute minimum temperatures (Figs. 2–4).

The TX90p index shifted in 1998 from 6.2% to 11.5%, with a subsequent increase to 15.0% in 2015. Both transitions were supported by 100.0% confidence and showed no significant change in variability. WSDI sharply increased in 1998 from 1.700 to 8.800 d/a, preceded by a subtler shift in 1985, although the 1998 change remained structurally dominant. TN90p exhibited two statistically significant transitions: an initial rise from 6.2% to 10.8% in 1998, followed by a further increase to 16.5% in 2015 (99.0% confidence), indicating stepwise nocturnal heat intensification. TXx rose from 41.200°C to 43.000°C in 1998, with no significant change in variability, suggesting a stable increase in extreme heat thresholds. TNx experienced a later regime shift in 2015, with annual TNx rising from 23.700°C to 25.680°C, reinforcing the trend of nocturnal warming after 2010. Tmaxmean increased from 25.990°C to 27.310°C in 1998, while Tminmean followed a stepwise pattern, rising from 11.440°C to 12.190°C in 1998 and then to 12.820°C in 2010, both without changes in variability, reinforcing consistent baseline warming trends (Figs. 2-4).

3.3 Frequency Analysis of Temperature Extremes

From 1982 to 2024, Jordan' s climatic zones showed significant warming, with a marked decline in cold events and a rise in warm occurrences (Fig. 5 [Figure 5: see original paper]). In the BWk zone, the percentage of cold days dropped from 19.7% (1982-1992) to 5.1% (2015-2024), while the BSh zone reduced from 16.8% to 3.4% (Fig. 5a). The percentage of cold nights also decreased, indicating fewer cold nighttime extremes (Fig. 5b). CSDI diminished from 12.600 d/a in the BWk zone to 4.000 d/a, and from 10.700 to 3.100 d/a in the BSh zone (Fig. 5c). Conversely, warm temperature extremes surged, especially in desert zones. The percentage of hot days quadrupled overall, with the BWh zone increasing from 11.1% to 35.2% (Fig. 5e). Similarly, the percentage of hot nights rose from 12.8% to 38.1% in the BWh zone, illustrating heightened nighttime heat retention (Fig. 5f). WSDI also extended significantly, from 5.400 d/a to 18.300 d/a in the BWh zone and from 3.800 to 15.200 d/a in the BSh zone (Fig. 5g).

A comparison of climatic zones confirmed the strongest warming trends in desert zones (BWh and BWk), with the hot semi-arid zone (BSh) also showing significant increases, while the Mediterranean zone (Csa) exhibited a more gradual but statistically significant trend. Analysis of extreme temperatures revealed a distinct upward shift. The distribution of TXx showed marked movement toward more extreme values, with the BWh zone displaying the most pronounced intensification (Fig. 6a [Figure 6: see original paper]). Specifically, the BWh zone recorded the 40.000°C-42.000°C range within 18 years, reinforcing greater heat accumulation in deserts. Conversely, TXn revealed a steady decline in extreme cold occurrences (Fig. 6b), with frequencies within the 10.000°C-12.000°C range dropping significantly, particularly in desert zones. Nocturnal warming was also severe. TNx increased significantly, with the most extreme range (27.000°C-30.000°C) occurring for 12 years in the BWh zone (Fig. 6c). Concurrently, TNn showed a diminishing presence of cold events: nights below 8.000°C became rare, and TNn shifted to the 8.000°C-10.000°C range in the BWh zone (Fig. 6d), indicating reduced frost frequency. This pattern of sustained warming was further confirmed by mean temperatures. Tmaxmean showed higher intervals persisting for longer durations, with the 26.000°C-28.000°C range dominating the BWh zone for 16 years (Fig. 6e). Similarly, Tminmean reinforced nighttime warming, with the 12.000°C-14.000°C range dominant in the BWh zone for 18 years (Fig. 6f), confirming a steady rise in minimum temperatures across all zones. This comprehensive analysis confirmed that desert regions experienced prolonged exposure to extreme heat, while all zones showed a consistent decline in cold events (Fig. 6a–f), signaling a fundamental shift in Jordan’ s climate dynamics and emphasizing the need for tailored adaptation strategies.

3.4 Correlation Between Climate Indices

Analysis of the Pearson correlation matrix revealed strong internal coherence among temperature-based climate indices (Fig. 7 [Figure 7: see original paper]), highlighting distinct behavioral clusters between warm and cold extremes. High positive correlations were found between TXx and TX90p (r = 0.94), as well as between TXx and Tmaxmean (r = 0.90). These correlations reflect structural interdependence among extreme heat thresholds, hot-day frequency, and mean maximum temperatures. Similarly, TN90p and Tminmean exhibited a strong association (r = 0.87), indicating that increases in nocturnal heat events were concurrent with rises in baseline nighttime temperatures.

Duration-based indicators such as WSDI also showed close correlation with TX90p (r = 0.82), emphasizing the link between prolonged heat spells and daytime heat intensity. In contrast, strong negative correlations were observed between TX10p and TXx (r = -0.85) and between TN10p and TN90p (r = -0.81). These findings support the idea of a coordinated thermal shift, where cold extremes decrease as heat indicators intensify. Additionally, the FD0 index displayed a notable inverse relationship with TX90p (r = -0.79), signifying a significant reduction in frost days accompanying warming trends. Meanwhile, indices representing absolute extremes, such as TXn and TNn, showed weak or negligible correlations with duration metrics, suggesting differentiated drivers or delayed responses. Collectively, these results validate the selection of indices and underscore a clustered network of warm indicators, reinforcing the emergence of a heat-dominated climate regime across Jordan.

4 Discussion

4.1 Interpretation of Warming Trends and Extreme Events

Our analysis indicates that Jordan is not just warming—it is undergoing a fundamental shift from a climate characterized by seasonal variability to one dominated by persistent heat. Modeling conducted under Representative Concentration Pathway 8.5 (RCP8.5) suggests heatwaves could increase by as much as 22.000 days by century’ s end (Bashabsheh and Alzboon, 2025). Additionally, consecutive dry days may extend by over 65.000 days, further worsening drought stress. These results underscore the urgency of the trends outlined in this study. The most significant warming is occurring in desert zones (BWh and BWk), where maximum temperatures have risen by over 2.198°C. This trend is not isolated but serves as a key indicator of accelerated aridification, aligning with global patterns where feedback loops such as reduced soil moisture and vegetation cover amplify warming in drylands (Zhang et al., 2011; Linnenluecke et al., 2013; Safriel, 2017). The simultaneous intensification of all heat extremes (TX90p, TN90p, and WSDI) and decline of all cold extremes (TX10p, TN10p, and FD0) confirm that this transformation is systemic rather than a change in isolated metrics.

Identifying 1998 as a pivotal change point is crucial, as it suggests Jordan' s climate crossed a threshold into a new, more volatile state during a period of strong global forcing. The subsequent intensification after 2010 indicates this new state continues evolving toward greater extremity. Regional studies reinforce this trend, showing similar warming patterns and reduced seasonal variability across Jordan and the eastern Mediterranean (Alzboon et al., 2021; Zittis et al., 2022; Alsalal et al., 2024). This study adds methodological depth by integrating percentile-based indices, duration metrics, and network correlation structures, offering a spatially explicit and temporally robust assessment. Compared to earlier station-based studies (Bashabsheh and Alzboon, 2024, 2025), the use of RClimDex and change-point analysis provides stronger statistical validation and reveals coordinated shifts in climate behavior.

Correlation network analysis further supports this interpretation (Fig. 8 [Figure 8: see original paper]). The strong clustering of heat indices indicates they are now part of a tightly coupled, self-reinforcing system. In contrast, the peripheral and weakening position of cold indices suggests they are becoming transient outliers in this new thermal regime. This structural realignment is consistent with tipping-point behavior observed in other regions, indicating a fundamental and likely irreversible reorganization of climate dynamics that moves beyond linear trends (Cheng et al., 2021; Armstrong McKay et al., 2022).

4.2 Sectoral Impacts and Vulnerabilities

The implications of increased heat extremes are significant for agriculture, water resources, and public health. In agriculture, elevated TX90p values and prolonged WSDI periods shorten crop growth cycles, reduce yields, and increase irrigation demands (Bisht et al., 2023; FAO, 2023). Warmer nighttime temperatures (TN90p and TNx) hinder plant recovery and increase transpiration, exacerbating drought stress. Crops requiring chilling hours, such as olives and grapes, are particularly vulnerable in Csa and BWk zones (Zeppel et al., 2014). Livestock, especially dairy cattle, suffer from heat-related metabolic disruptions that reduce productivity (Cartwright et al., 2023). These agricultural challenges are worsened by Jordan' s extreme water scarcity. Jordan ranks among the top five countries facing extreme water stress (Resource Watch, 2025), with groundwater extraction rates exceeding recharge and rising temperatures increasing evaporative losses (MoEnv, 2022). In the Yarmouk Basin, warming has decreased streamflow and increased evapotranspiration rates (Bashabsheh and Alzboon, 2024). Climate data from 2006 to 2017 already exceeded projections from the high-emissions RCP8.5 scenario, indicating faster acceleration of warming and drought trends than previously modeled (Bashabsheh and Alzboon, 2025). Consequently, impacts on water resources and agriculture may be more severe and immediate than initially anticipated.

Public health risks are also rising. Vulnerable populations—particularly the elderly, children, and those with chronic illnesses—experience increased morbidity and mortality related to heat (Hayhoe et al., 2010; Arsad et al., 2022). In Amman, an average of 6.5 deaths per day have been attributed to extreme temperatures, underscoring increased vulnerability (Alwadi et al., 2024). Rising demand for cooling days is straining Jordan' s energy infrastructure, while decreased demand for heating days offers only limited relief (MoEnv, 2022). These sectoral vulnerabilities are deeply interconnected. The strong correlation between WSDI and TX90p (r = 0.88) suggests that prolonged heatwaves are a fundamental aspect of Jordan' s climate system, necessitating integrated and proactive adaptation strategies rather than isolated reactive measures.

4.3 Zonal Adaptation Strategies

Jordan's four Köppen climate zones (Csa, BSh, BWk, and BWh) exhibit distinct vulnerabilities requiring tailored adaptation responses. In the Csa zone, reduced frost periods threaten crops like potatoes and olives. Protected agriculture, heat-resilient varieties, and efficient water-use programs are recommended (Al-Eisawi, 2005; FAO, 2023). Urban heat island effects intensify warming in the BSh zone, where rooftop gardens, tree planting, and water-conserving infrastructure can mitigate thermal stress (Shatnawi et al., 2025). Drought and rangeland degradation are key concerns in the BWk zone, requiring drought-tolerant crops, flexible grazing systems, and early warning mechanisms (Alzboon et al., 2021). The BWh zone faces the steepest warming, with biodiversity hotspots like Dana and Azraq threatened by groundwater depletion and heat stress. Desalination, conservation policies, and heatwave alerts are critical in these regions (Al-Eisawi, 2005; Ta' any et al., 2014). Comprehensive solutions such as climate-smart agriculture, precision irrigation, resilient infrastructure, and inclusive planning frameworks are necessary (Al Qudah et al., 2021; Al-Zghoul and Al-Homoud, 2025). Integrating spatial climate metrics with socio-economic vulnerability assessments will enhance predictive capacity and support targeted interventions.

4.4 Policy and Research Implications

The clear evidence of increasing heat extremes and ongoing climate change requires a shift from reactive crisis management to proactive, evidence-based climate risk governance. Policy frameworks should focus on establishing robust early warning systems and heat action plans designed for vulnerable communities. Additionally, implementing strict groundwater protection policies to prevent over-extraction and promoting climate-smart agriculture are needed to ensure food security (Ebi et al., 2021; MoEnv, 2022; UNEP, 2022). To support these policies, scientific research must progress through high-resolution regional climate modeling to reduce projection uncertainty, develop dynamic vulnerability maps incorporating both climatic and socio-economic data, and conduct longitudinal studies evaluating adaptation intervention effectiveness (Frame et al., 2018; Siders et al., 2019). Further analyses should explore impacts of large-scale teleconnections such as the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) on Jordan' s extreme weather events. These measures will enhance predictive capabilities and strengthen regional resilience strategies (Newman et al., 2016; Huang et al., 2023). By establishing a robust framework for monitoring heat extremes and linking them to sectoral vulnerabilities, this study lays the groundwork for improving evidence-based climate governance and supports Jordan' s essential transition toward a more resilient and secure future.

4.5 Limitations

This study offers a detailed spatial analysis of extreme temperature trends across Jordan. However, the use of least-squares regression with the RClimDex program does not consider temporal autocorrelation. Future research may investigate alternative non-parametric methods. The grid coverage may not accurately reflect microclimatic variations, particularly in areas with complex terrain or dense urbanization. The Köppen classification framework also falls short in incorporating dynamic socioeconomic factors. Future climate change adaptation planning should integrate multi-sectoral data.

5 Conclusions

We conducted an analysis of long-term spatial trends and regime shifts in extreme temperature indices across Jordan' s diverse climate zones. Using high-resolution daily data and internationally recognized indices, the study revealed a consistent and statistically significant warming trend over the past 40 years. There has been a systematic decline in cold extremes while heat-related events, particularly in desert zones, have intensified. A significant change point occurred around 1998, marking the onset of a heat-dominated climate regime that has continued evolving since 2010. To identify structural climate transitions, the analysis integrated percentile-based indices, duration metrics, and correlation network structures. This methodological framework provides a spatially explicit and temporally robust assessment, offering critical insights for climate adaptation planning in arid and semi-arid environments. The vulnerabilities of various sectors—especially agriculture, water resources, and public health—are closely linked to observed thermal shifts. The findings highlight the urgent need for heat-resilient infrastructure, precision irrigation, and early warning systems. By applying the Köppen climate classification and spatial zoning, the study reveals regional disparities in climate impacts, reinforcing the necessity for tailored adaptation strategies. Future research may investigate teleconnection influences and incorporate socio-economic data to improve vulnerability assessments.

Conflict of Interest: The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgments: We thank Al-Balqa Applied University and Ajloun National University in Jordan for their support of this scientific research.

Author Contributions: Conceptualization, writing—original draft preparation, and writing—review and editing: Abdelaziz Q. BASHABSHEH; Supervision and writing—review and editing: Kamel K. ALZBOON; Conceptualization, formal analysis, writing—review and editing, and supervision: Zeyad ALSHBOUL. All authors approved the manuscript.

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