

Multi Decadal Surface Temperature Trends in Riyadh (1985-2024): Seasonal Patterns and Urban Heat Island Amplification

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Abstract

Rapid urbanization combined with regional climate change is intensifying heat exposure in arid cities, yet long-term assessments remain limited. This study presents a comprehensive multi-decadal analysis of near-surface air temperature in Riyadh, Saudi Arabia, covering the period 1985-2024. Monthly temperature records were aggregated into annual mean, maximum, and minimum indices and evaluated using linear regression and the non-parametric Mann-Kendall test with Sen's slope estimation to ensure robust trend detection. Results reveal a persistent and statistically significant warming signal across all temporal scales. Annual mean temperature increased at a rate of 0.59°C per decade ($p \ll 0.01$), with minimum temperatures rising faster than maxima. The stronger increase in nighttime temperatures indicates asymmetric warming consistent with enhanced nocturnal heat retention. Warming is evident in nearly all months, with particularly strong trends during spring and summer. Comparison across sub-periods shows a stepwise increase in mean temperature, confirming a sustained long-term shift. The observed patterns align with regional greenhouse-gas-driven warming while also reflecting urban-scale influences such as land-cover change, reduced evapotranspiration, and increased heat storage in built surfaces. Although the study does not explicitly separate urban and rural signals, the structure of the trends is consistent with known urban heat island mechanisms. These findings establish a robust empirical baseline for understanding long-term warming in a rapidly expanding desert metropolis. The results carry important implications for heat risk, energy demand, and urban sustainability, highlighting the need for climate-sensitive urban planning and heat-mitigation strategies. The study also underscores the value of sustained long-term observations for supporting climate adaptation in arid urban environments.

Keywords

Urban Heat Island, Surface Temperature, Urban Climate, Arid Cities, Long-Term Trends, Riyadh

1. Introduction

Urban and regional temperature variability is widely recognized as a robust indicator of climate change, reflecting the combined influence of large-scale atmospheric forcing and local surface atmosphere interactions. Long term temperature changes are often particularly pronounced in arid and semi-arid regions, where limited moisture availability, strong radiative forcing, and land atmosphere feedbacks can amplify warming signals. In urban environments, these background climatic trends are further modified by land-use change, surface material properties, and anthropogenic heat emissions, resulting in systematic shifts in both mean thermal conditions and temperature extremes.

Multiple interacting processes contribute to long-term temperature evolution in desert cities. At the regional scale, rising greenhouse gas concentrations have driven widespread warming across the Arabian Peninsula, a region increasingly identified as a climate change hotspot. At the local scale, rapid urbanization modifies surface energy balances through the expansion of impervious surfaces, reduction of vegetation cover, and enhanced heat storage capacity. These changes reduce evaporative cooling and limit nocturnal heat release, thereby intensifying urban warming and prolonging thermal exposure.

A growing body of literature has documented warming trends across the Middle East using reanalysis products, satellite retrievals, and in situ meteorological observations. Several studies report stronger warming rates in urban areas relative to rural surroundings, particularly during nighttime, consistent with urban heat-island (UHI) processes. However, for Riyadh, existing investigations are frequently constrained by short temporal records, coarse spatial resolution, or a focus on episodic extremes rather than sustained long-term change. Consequently, comprehensive multi-decadal assessments of temperature variability and extremes within the city remain limited.

The scarcity of long term, observation-consistent analyses limits the ability to place recent warming in a historical context and constrains understanding of how seasonal structure and thermal extremes have evolved over time. This knowledge gap hinders robust assessment of the magnitude, persistence, and temporal characteristics of warming signals relevant to urban heat exposure and climate risk management.

This study addresses these limitations by presenting a multi-decadal analysis of near-surface air temperature in Riyadh spanning 1985-2024. Temperature variability is examined at monthly, seasonal, and annual timescales to quantify long-term warming rates, evaluate the statistical robustness of detected trends, and

characterize changes in thermal extremes associated with UHI exposure. Unlike studies relying primarily on short-term or coarse resolution datasets, this work leverages a reanalysis-based long-term temperature dataset to provide a consistent long-term perspective. The results establish a robust empirical baseline for assessing urban heat exposure and support climate-informed adaptation and urban planning in arid metropolitan environments.

Urban heat islands represent a growing concern for rapidly expanding cities, particularly in arid regions where baseline climatic conditions already impose substantial thermal stress. UHI intensification can amplify heat exposure, increase cooling energy demand, degrade outdoor thermal comfort, and elevate heat-related health risks. Riyadh has undergone rapid urban expansion in recent decades, fundamentally transforming its surface thermal characteristics. Within this context, the present study interprets UHI relevance in terms of long-term urban warming signals rather than explicit urban-rural contrasts, focusing on temporal trends that reflect evolving UHI-related exposure.

2. Study Area and Data

Riyadh is located in the central Arabian Peninsula (24.7°N, 46.7°E) at an elevation of approximately 600 m above sea level and is classified as having a hot desert climate (BWh) under the Koppel-Geiger scheme. This climatic regime is characterized by extremely high summer temperatures, low annual precipitation, and pronounced diurnal and seasonal thermal contrasts typical of continental desert environments. The present analysis utilizes a continuous record of monthly near-surface air temperature spanning 1985–2024. However, due to incomplete temporal coverage in 2024, the period 1985–2024 was retained for formal trend detection and statistical inference to preserve data homogeneity, minimize sampling bias, and ensure the robustness of long-term trend estimates.

Over the past four decades, Riyadh has undergone rapid spatial expansion and population growth, transforming from a relatively compact city into a large metropolitan area. Urban development has been accompanied by extensive land-cover change, increased infrastructure density, and modification of surface thermal properties. These changes provide a critical context for interpreting observed temperature trends, as urban growth can amplify background climatic warming through localized surface-atmosphere interactions.

Climatological data represent long-term observations of atmospheric variables that characterize the typical and extreme behavior of the climate system. In this study, monthly temperature records are used to derive climatological statistics, including annual means and thermal extremes, which are essential for identifying long-term warming patterns, interannual variability, and shifts in seasonal temperature behavior.

Unlike previous studies that rely on short records or coarse-resolution products, this study provides one of the longest observation-consistent urban temperature records for a major desert metropolis, enabling robust assessment of long-

term warming structure and asymmetric temperature behavior relevant to UHI exposure.

3. Methods

In this study, UHI relevance is interpreted through long-term temporal warming characteristics, particularly asymmetric increases in minimum temperatures and DTR contraction, rather than explicit urban-rural contrasts:

3.1. Data Source and Temporal Coverage

This study utilizes monthly near-surface air temperature (2 m air temperature) obtained from the NASA POWER database [1]-[3], which is derived from the MERRA-2 reanalysis product [1] [2]. The dataset has a spatial resolution of $0.5^\circ \times 0.5^\circ$ and was extracted for the grid cell corresponding to Riyadh (24.7°N , 46.7°E).

The analysis covers the period January 1985 to December 2024. Although data are available for part of 2025 (January-June), this year was excluded from the formal analysis to ensure temporal completeness and consistency.

To assess data reliability, NASA-derived temperatures were compared with in situ observations from the KACST meteorological station over the overlapping period (2014-2024). Statistical agreement was evaluated using correlation coefficient (r), mean bias error (MBE), and root mean square error (RMSE), indicating strong consistency between the datasets.

3.2. Data Quality Control and Homogeneity

Prior to trend analysis, the temperature dataset underwent rigorous quality control procedures. Monthly records were screened for missing values, temporal inconsistencies, and outliers exceeding ± 3 standard deviations from the climatological mean. The time series was visually and statistically inspected to ensure temporal continuity. Although the dataset originates from consistent sources, potential inhomogeneities related to station practices or data merging cannot be entirely excluded. Therefore, trend interpretation focuses on long-term signals robust to minor inhomogeneities.

3.3. De-Seasonalization and De-Trending

To isolate long-term climate signals from the strong seasonal cycle characteristic of desert climates, a de-seasonalization procedure was applied. Monthly climatological means for the full period were calculated and subtracted from the original series to produce anomaly series. This approach minimizes the influence of intra-annual variability and enhances detection of secular trends.

De-trending was not applied prior to Mann-Kendall testing because the purpose of the analysis is to detect monotonic trends. However, for visualization and variability assessment, residual series were examined after removal of the fitted linear trend.

3.4. Climatological Indices and Data Processing

Monthly temperature observations were converted to degrees Celsius. Key climatological indices were derived, including annual mean, annual maximum, and annual minimum temperatures, capturing both central tendencies and thermal extremes. To facilitate multi scale assessment, the dataset was organized into monthly, seasonal, and annual subsets. Monthly values were analyzed to identify season-specific trends, while annual indices provided baseline measures for long-term mean and extreme conditions. The study period was further divided into three climatologically meaningful sub periods (1985-1999, 2000-2014, and 2015-2024) to evaluate progressive changes in mean temperature levels across successive phases of urban and regional warming.

Annual mean temperature was defined as the average of the 12 monthly mean temperatures for each year.

Annual maximum monthly temperature represents the highest monthly mean temperature within a given year, while annual minimum monthly temperature represents the lowest monthly mean temperature within that year.

The diurnal temperature range (DTR) was calculated as the difference between the monthly mean maximum and monthly mean minimum temperatures.

3.5. Trend Analysis

Long-term temperature trends were quantified using ordinary least squares (OLS) regression, all trend magnitudes are consistently reported in °C per decade. Sen's slope estimates (°C/year) were converted to °C/decade for consistency.

Seasonal trends were examined using month specific regressions to identify intra annual variability. To evaluate the statistical robustness of detected trends, nonparametric Mann-Kendall (MK) tests were applied, which are robust to non-normal distributions and missing data. This combined parametric and nonparametric approach allows precise estimation of the magnitude, persistence, and temporal structure of warming signals, as well as their consistency across temporal aggregations.

3.6. Contextual Significance

Assessing long-term temperature variability is a fundamental component of contemporary climate change research, particularly in arid and semi-arid regions, where climatic sensitivity and hydroclimatic stress are pronounced. The Arabian Peninsula has emerged as a climate change hotspot, exhibiting accelerated warming relative to global averages, with implications for water security, urban sustainability, ecosystem resilience, and human thermal comfort. Within this regional context, Riyadh a rapidly expanding desert megacity provides a strategically important case for disentangling background climate signals from urban-scale influences. By delivering a high-resolution, multi-timescale assessment of temperature variability, this study contributes to a refined understanding of regional climate dynamics, long-term warming trajectories, and their relevance for climate risk assessment and adaptation planning in arid urban environments.

3.7. Mann-Kendall Test Properties and Interpretation

Prior to applying the Mann-Kendall test, the presence of serial autocorrelation was evaluated using the lag-1 autocorrelation coefficient. Where significant autocorrelation was detected, a modified Mann-Kendall test (Hamed and Rao, 1998) was applied to ensure robust significance estimation.

The Mann-Kendall (MK) test is a non-parametric method widely used in hydro climatology for detecting monotonic trends in environmental time series. Its main advantages include robustness to non-normal data distributions and reduced sensitivity to outliers. The test evaluates whether observations tend to increase or decrease consistently over time without assuming linearity.

Kendall's Tau provides a measure of rank correlation between time and the variable of interest. Positive Tau values indicate upward trends, while negative values indicate downward trends. The associated Z-statistic and p-value quantify statistical significance.

Sen's slope estimator was used alongside MK to quantify the magnitude of change. This slope represents the median rate of change per year and is robust against extreme values. In climatic applications, Sen's slope is often preferred over ordinary least squares when data variability is high.

3.8. Extreme Temperature Metrics and Diurnal Temperature Range

To better characterize changes in thermal extremes beyond mean conditions, additional metrics were derived from the monthly dataset. Particular attention was given to the behavior of unusually warm conditions and to the diurnal temperature range (DTR), defined as the difference between monthly maximum and minimum temperatures.

DTR is widely used as a diagnostic indicator of asymmetric warming and urban influence because it reflects the balance between daytime heating and nighttime cooling. A reduction in DTR is often associated with enhanced nocturnal heat retention and increased surface heat storage. Evaluating DTR alongside mean temperature trends therefore provides additional insight into the physical nature of observed warming.

4. Results

4.1. Monthly and Seasonal Analysis

Analysis of monthly temperature trends indicates that nearly all months, from January through December, have experienced a consistent warming over the study period. Mann-Kendall tests confirm that these positive trends are statistically significant in most months ($p < 0.05$). Seasonal decomposition reveals that spring (March-May) and summer (June-August) months exhibit the strongest warming signals, suggesting that the onset and peak of the warm season have intensified over the past four decades. These findings highlight the pervasive nature of warming across the annual cycle and emphasize the potential amplification of urban

heat exposure during the hottest months. The temporal evolution of monthly temperature variability is illustrated in **Figure 1**.

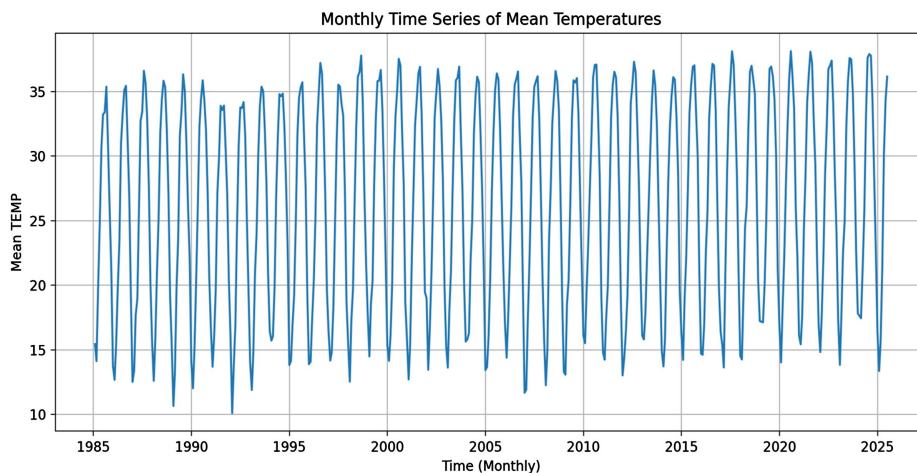


Figure 1. A monthly time series of mean temperatures was plotted.

4.2. Comparison of Three Time Periods

The record was divided into three climatologically meaningful sub-periods to examine progressive changes in temperature: 1985-1999, 2000-2014, and 2015-2024. The earliest period (1985-1999) corresponds to the coolest conditions observed, with subsequent periods showing a clear warming trajectory. Specifically, the 2000-2014 period is approximately 0.78°C warmer than 1985-1999, while the most recent period (2015-2024) shows an additional increase of 0.73°C relative to 2000-2014.

Overall, the total increase between the first and last periods is approximately 1.51°C , indicating a sustained but more gradual warming than previously reported. The long-term increase in annual mean temperature is clearly shown in **Figure 2**.

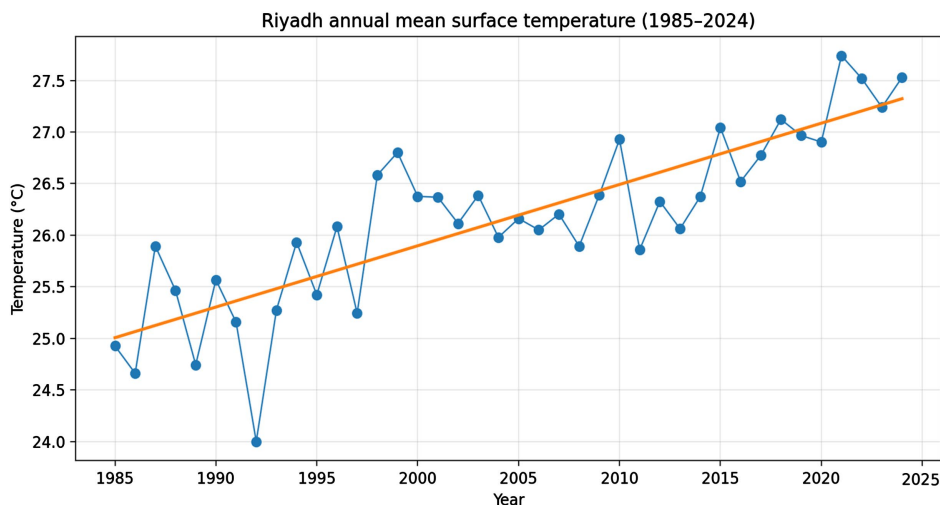


Figure 2. Annual mean surface temperature trend in Riyadh (1985-2024).

4.3. Annual and Extreme Temperature Trends

Analysis of annual temperature indices demonstrates statistically significant warming across all metrics. The annual mean temperature increased by 0.59°C per decade. Notably, annual minimum temperatures have increased at a slightly higher rate than maxima ($+0.67^{\circ}\text{C}$ vs. $+0.59^{\circ}\text{C}$ per decade), reflecting enhanced nighttime heat retention, a phenomenon often associated with urban heat island (UHI) effects. This disproportionate increase in minimum temperatures has important implications for nocturnal thermal comfort and heat exposure in urban environments. Trends in annual maximum and minimum temperatures are presented in **Figure 3** and **Figure 4**, respectively. A summary of these trends, including statistical significance and correlation coefficients, is provided in **Table 1**.

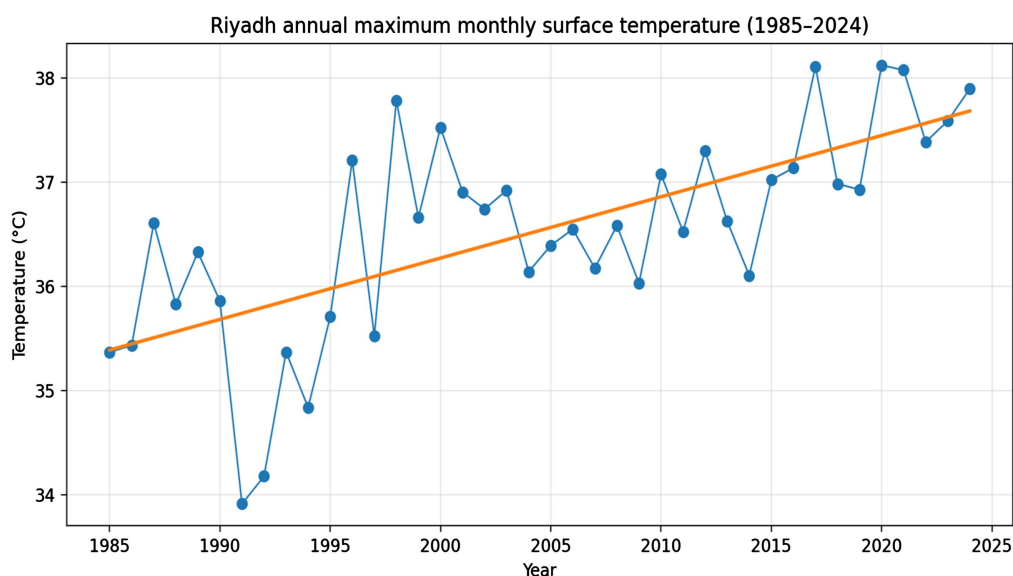


Figure 3. Annual maximum monthly surface temperature trend in Riyadh (1985–2024).

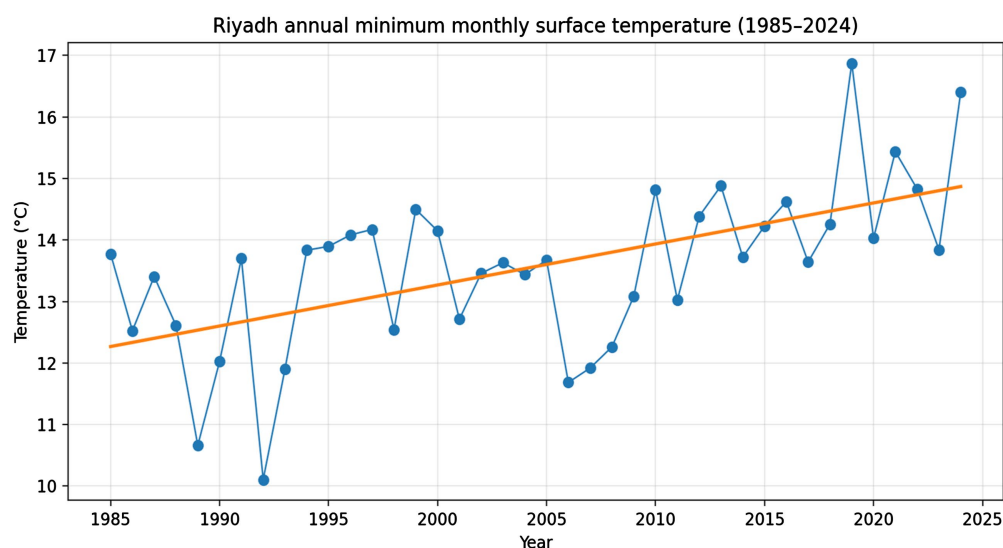


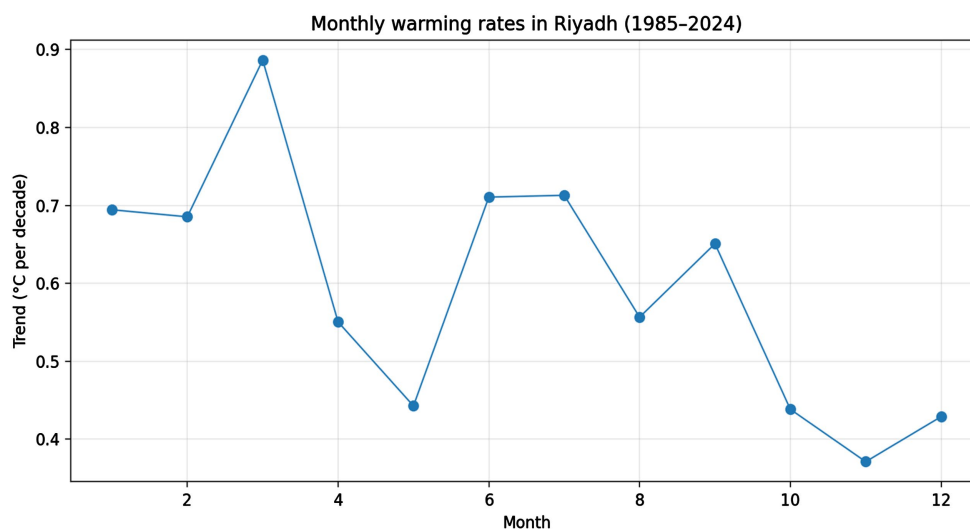
Figure 4. Annual minimum monthly surface temperature trend in Riyadh (1985–2024).

Table 1. Long-term trends in annual surface temperature indices for Riyadh (1985–2024).

Temperature index	Trend (°C/decade)	Standard error	p-value	r
Annual mean surface temperature	0.59	0.06	2.4×10^{-11}	0.83
Annual maximum monthly temperature	0.59	0.10	9.2×10^{-7}	0.69
Annual minimum monthly temperature	0.67	0.15	8.6×10^{-5}	0.58

4.4. Summary of Seasonal Implications

Seasonal analysis further reveals that warming is evident in every month, with the most pronounced increases observed during spring and summer. These results underscore the persistence and intensity of urban warming throughout the year, highlighting the need for climate-informed adaptation strategies to mitigate thermal stress, particularly during the peak warm season. Monthly warming rates are summarized in **Figure 5**.

**Figure 5.** Monthly warming rates in Riyadh expressed as °C per decade (1985–2024).

4.5. Statistical Robustness of Trends

The detected warming trends are statistically robust across multiple temporal aggregations. The consistency between annual, seasonal, and monthly analyses indicates that the warming signal is not an artifact of temporal aggregation. Extremely low p-values ($p \ll 0.01$) confirm that the observed trends are highly unlikely to arise from natural variability alone.

The stronger rise in minimum temperatures relative to maxima suggests asymmetric warming, a commonly observed feature in urban and arid-region climates.

4.6. Behavior and Variability

Beyond the monotonic increase, the time series exhibits interannual variability likely associated with regional climate oscillations and large-scale atmospheric cir-

culuation patterns. However, this variability does not obscure the persistent long-term warming trajectory, which remains the dominant signal over the 40-year period.

4.7. Intensification of Thermal Extremes and DTR Behavior

Analysis of temperature characteristics beyond the mean reveals a progressive intensification of warm conditions. The most recent decade contains a higher frequency of unusually warm months relative to earlier periods, indicating that warming is not limited to gradual mean shifts but also manifests in the tails of the temperature distribution.

A gradual reduction in diurnal temperature range is also evident over the study period, driven primarily by faster increases in minimum temperatures compared to maxima. This asymmetric behavior is consistent with enhanced nighttime heat retention. Such DTR contraction is widely reported in urbanizing regions and is considered a diagnostic feature of urban climate modification.

The combined increase in warm-condition frequency and reduction in DTR suggests that warming in Riyadh involves both background climatic forcing and processes linked to urban surface characteristics.

5. Discussion

5.1. Physical Mechanisms behind Observed Warming

Several interacting mechanisms likely contribute to the observed warming. At the global scale, increasing greenhouse gas concentrations drive regional warming across the Arabian Peninsula. At the urban scale, land-cover modification, reduced vegetation, and expansion of impervious surfaces enhance heat storage and reduce evaporative cooling.

Increased thermal inertia of urban materials promotes daytime heat absorption and delayed nocturnal release, explaining the stronger increase in minimum temperatures. Anthropogenic heat emissions from transportation, air conditioning, and infrastructure further intensify nighttime warming. These processes collectively align with established urban heat island mechanisms.

The present analysis reveals a persistent and statistically robust warming signal in Riyadh over the past four decades, evident across annual, seasonal, and monthly timescales. The magnitude, consistency, and statistical significance of the detected trends collectively indicate that the observed changes represent a long-term climatic shift rather than short-term variability. The agreement between multiple indices (annual mean, annual maximum, and annual minimum temperatures) further strengthens confidence in the robustness of the warming signal.

A key feature of the results is the disproportionately stronger increase in minimum temperatures relative to maximum temperatures. This asymmetric warming pattern is widely documented in urban and arid environments and is often interpreted as a signature of enhanced nighttime heat retention. In desert cities such as Riyadh, limited soil moisture already constrains evaporative cooling, making

nocturnal radiative processes and surface heat storage particularly influential. The stronger rise in nighttime temperatures therefore likely reflects a combination of regional climate warming and localized urban effects.

From a physical perspective, several mechanisms can plausibly explain the observed trends. At the global and regional scales, rising greenhouse gas concentrations have driven widespread warming across the Arabian Peninsula, a region frequently identified as a climate-change hotspot. Large scale atmospheric circulation changes, land atmosphere feedbacks, and enhanced radiative forcing all contribute to background warming in the region. However, the structure of the warming signal in Riyadh suggests that urban-scale processes also play a meaningful role.

Rapid urban expansion over recent decades has substantially altered land-surface characteristics in Riyadh. The replacement of natural desert surfaces with impervious materials such as asphalt and concrete increases thermal inertia and heat storage capacity. These materials absorb solar radiation during the day and release it slowly at night, suppressing nocturnal cooling. Concurrently, reduced vegetation cover limits evapotranspiration, further decreasing the potential for natural cooling. Anthropogenic heat emissions from vehicles, buildings, and air-conditioning systems may also contribute, particularly during summer months. The convergence of these processes is consistent with well-established urban heat island (UHI) mechanisms and aligns with the stronger increase observed in minimum temperatures [4]-[6].

The seasonal structure of warming provides additional insight. The presence of positive trends in nearly all months indicates that warming is not confined to a specific season but represents a year-round phenomenon. Nonetheless, the comparatively strong trends in spring and summer months are noteworthy. These seasons correspond to periods of intense solar radiation and high background temperatures, during which land-atmosphere coupling is particularly strong in arid regions. Enhanced warming during these periods may therefore reflect amplification of regional climate signals by local surface processes.

Interannual variability remains evident in the time series, likely influenced by regional climate oscillations and synoptic scale variability. However, this variability does not obscure the long-term upward trajectory. The persistence of statistically significant trends despite year to year fluctuations underscores the dominance of the long-term warming signal. This behavior is consistent with climate change detection studies in which forced trends emerge clearly above natural variability over multi decadal periods.

The findings are broadly consistent with previous studies across Saudi Arabia and the Middle East, which report accelerated warming rates relative to the global mean. Prior research using reanalysis products and station observations has similarly documented strong warming and enhanced temperature extremes in the region. The present study contributes to this literature by offering a long, internally consistent urban-focused record, thereby strengthening empirical evidence for sustained warming in desert megacities.

It is important to interpret the results in light of the study's scope and limitations. Because the analysis does not explicitly compare urban and rural stations, it cannot fully disentangle regional climate change from urban-specific warming. Consequently, the results should be viewed as reflecting combined regional and urban influences. Future work integrating rural reference sites, satellite-derived land-surface temperatures, or local climate zone (LCZ) classifications would allow more explicit attribution of UHI intensity and its temporal evolution.

Despite these limitations, the implications of the findings are substantial. Rising temperatures, particularly higher nighttime minima, have direct consequences for human health, energy demand, and urban sustainability. Elevated nighttime temperatures reduce opportunities for physiological recovery from daytime heat stress, thereby increasing heat related health risks. From an infrastructure perspective, sustained warming can intensify cooling-energy demand and strain electricity systems, especially in rapidly growing cities.

For urban planners and policymakers, the results highlight the urgency of heat-mitigation strategies in arid cities. Measures such as urban greening, reflective and high-albedo materials, shading strategies, and climate sensitive urban design can help moderate urban temperatures. The long-term baseline established here also provides a valuable reference for evaluating the effectiveness of future adaptation and mitigation initiatives.

In a broader context, Riyadh serves as a representative case for rapidly urbanizing desert cities worldwide. As urbanization continues across arid regions, similar warming dynamics may emerge elsewhere. Long-term observational studies such as this are therefore essential for improving understanding of urban climate dynamics, informing adaptation strategies, and supporting climate-resilient urban development.

5.2. Consistency with Previous Studies

The magnitude and structure of warming detected here are consistent with previous studies across Saudi Arabia and the broader Middle East, which report accelerated warming relative to the global mean. Regional analyses using reanalysis and station data similarly highlight stronger nighttime warming and amplified trends in arid cities.

The present study extends prior work by providing a continuous multi decadal urban focused record, thereby strengthening the empirical basis for assessing long-term urban climate change in desert environments.

5.3. Urbanization Signal Framing

Riyadh has undergone exceptionally rapid urban growth over the past four decades, with substantial expansion of built-up areas and infrastructure. Remote-sensing and land-cover studies document marked increases in impervious surfaces and reductions in vegetated areas. While the present study does not explicitly quantify land-use change, the temporal coincidence between accelerated urban expansion

and intensified warming provides a plausible indication that urbanization may reinforce regional climate signals.

5.4. Global Context Framing

In a broader context, the warming rate detected in Riyadh is comparable to or exceeds rates reported for many cities in temperate regions. This highlights the particular sensitivity of arid cities, where limited moisture availability constrains evaporative cooling and amplifies land-atmosphere coupling. As a result, even moderate background climate warming can translate into disproportionately strong thermal stress in desert environments.

5.5. High-Impact Relevance Statement

The relevance of these findings extends beyond Riyadh. Many of the world's fastest-growing cities are located in arid and semi-arid regions. Understanding how warming unfolds in such environments is therefore critical for anticipating future heat exposure under continued urbanization and climate change. Long-term observational analyses such as this provide an essential empirical foundation for developing climate-resilient urban strategies.

6. Conclusions

This study provides a comprehensive multi-decadal assessment of surface air temperature variability in Riyadh over the period 1985-2024, offering one of the longest observation-consistent urban temperature records for a major desert city. The results demonstrate a clear, persistent, and statistically robust warming signal across annual, seasonal, and monthly timescales. The consistency of trends across multiple temperature indices confirms that the detected warming reflects a sustained climatic shift rather than short-term variability.

A prominent feature of the findings is the stronger increase in minimum temperatures compared to maximum temperatures, indicating asymmetric warming and enhanced nighttime heat retention. This pattern is consistent with established understanding of urban heat island processes and suggests that local urbanization effects likely reinforce broader regional climate warming. While the study does not explicitly separate urban and rural signals, the structure and magnitude of the trends point to the combined influence of regional climate change and urban surface modification [6]-[8].

The near universal warming detected across calendar months indicates that temperature increases in Riyadh are not seasonally isolated but represent a year-round phenomenon. Particularly strong warming during spring and summer highlights the vulnerability of arid cities to amplified heat under conditions of intense solar radiation and strong land-atmosphere coupling.

Beyond its climatological relevance, the study has important societal implications. Rising temperatures especially higher nighttime minima pose increasing risks to human health, urban livability, and energy systems. Elevated nighttime heat re-

duces recovery from daytime thermal stress and can exacerbate heat-related morbidity. At the same time, sustained warming is likely to intensify cooling-energy demand and infrastructure pressure in rapidly expanding cities.

The findings underscore the importance of proactive heat-mitigation and climate-adaptation strategies in desert urban environments. Urban greening, high-albedo and reflective materials, improved urban geometry, and climate-sensitive planning can all play a role in moderating future heat exposure. The long-term baseline established here provides a valuable reference against which future mitigation and adaptation efforts can be evaluated.

Future research should aim to explicitly disentangle urban and regional climate contributions through urban-rural comparisons, satellite-based analyses, and local climate zone frameworks. Integrating multiple data sources and attribution approaches will help refine understanding of urban warming dynamics and support more targeted policy responses.

In a broader perspective, Riyadh exemplifies the challenges faced by rapidly urbanizing cities in arid regions under climate change. The evidence presented here reinforces the need for sustained long-term monitoring and integrated climate urban research to support resilient and sustainable urban development in warming desert environments.

Taken together, the results position Riyadh as an illustrative case of how climate change and rapid urbanization can jointly reshape thermal environments in arid megacities. As global warming continues and desert cities expand, similar warming dynamics may emerge elsewhere. Strengthening observational baselines and integrating urban climate considerations into planning will be increasingly important for safeguarding urban populations under future climate conditions [9] [10].

While the present study provides robust evidence of long-term warming, future work should incorporate rural reference stations and satellite-based observations to better isolate urban heat island intensity and distinguish it from regional climate change.

This study does not explicitly quantify the urban rural temperature contrast, and therefore, it cannot fully disentangle the contributions of regional climate change from urban specific effects. While the analysis provides robust evidence of long-term warming in Riyadh, the absence of comparative rural reference data limits the ability to isolate purely anthropogenic urban influences. Future research should incorporate observational records from surrounding rural areas and conduct comparative analyses with other rapidly urbanizing desert cities. Such approaches would enhance understanding of the relative contributions of regional versus local urban drivers to observed warming patterns, and support more targeted urban heat mitigation strategies [6]-[8].

6.1. Trend Direction for Each Individual Month (Detailed Seasonal Analysis)

First, the Mann Kendall test was applied to each calendar month (January-De-

ember) over the 1985-2024 time series. The results of the monthly trend analysis are presented in **Table 2**.

Table 2. Results of the Mann-Kendall trend test for monthly temperature series (1985-2024).

Month	p value	Tau	Slope per year
1	0.003136843	0.32195122	0.105677419
2	0.001862991	0.33902439	0.114192303
3	2.07E-05	0.463414634	0.141040583
4	0.002167119	0.334146341	0.1203663
5	0.000438767	0.382926829	0.087543424
6	4.22E-08	0.596341463	0.129076705
7	5.78E-07	0.551282051	0.121710655
8	1.06E-05	0.485897436	0.098698253
9	4.26E-07	0.557692308	0.116428571
10	0.006633762	0.3	0.074423963
11	0.047612549	0.219230769	0.077860963
12	0.019188017	0.258974359	0.080752688

6.2. Simplified Interpretation

Nearly all rows indicate:

trend = increasing

The p-values are very small for most months ($p < 0.05$), indicating that the upward trends are statistically significant rather than due to random chance.

Slope per year represents the magnitude of change in the mean temperature of that month per year.

By examining slope per year (temperature trend over time), we can identify which months are warming fastest. In the full dataset (beyond the abbreviated version shown), it is found that:

Warm months (e.g., June, July, August) generally exhibit a clear positive slope.

Months with relatively large slopes include March, April, and some summer months, indicating that spring and summer in particular are experiencing notable warming over the years.

Summer months are among the fastest warming, but August alone is not necessarily the highest; rather, a group of months (e.g., June/July/August) show comparable increases.

6.3. Seasonal Conclusion

Almost every month shows a warming trend over time.

No month exhibits a cooling trend; instead, nearly all months show warming at

varying rates.

Transitional seasons (spring/autumn) and summer months show pronounced increases.

Temperature values are expressed in °C.

6.4. Comparison of the Periods 1985-1999, 2000-2014, and 2015-2024

The annual mean temperature was calculated for each year, and the years were then grouped into three periods. Summary statistics were computed for each period, as shown in **Table 3**.

Table 3. Mean temperature was calculated for each year, and the years were then grouped into three periods. Summary statistics were computed for each period.

Period	mean	std	count
1985-1999	25.45	1.32766648	15
2000-2014	26.23	0.481672646	15
2015-2024	26.96	1.256908886	11

Discussion of **Table 3**—interpretation of values:

1985-1999

Annual mean $\approx 25.45^\circ\text{C}$

2000-2014

Annual mean $\approx 26.23^\circ\text{C}$

2015-2024

Annual mean $\approx 26.96^\circ\text{C}$

Implications:

- From the 1980/1990 to 2000-2014:
 - An increase of approximately 0.78 degrees in the annual mean.
- From 2000-2014 to 2015-2024:
 - An additional increase of about 0.73 degrees.
- Total increase between the first and last periods:
 - Approximately 1.51 degrees in the annual mean temperature.

This supports the overall trend result: each successive period is clearly warmer than the preceding one.

Brief interpretation:

- The series shows a clear seasonal oscillation (annual rise and fall), representing the seasonal cycle.
- In the background, a gradual long-term increase is evident over the decades (1985-2024).

Interpretation of the annual mean temperature plot:

- Each point represents the annual mean temperature calculated from 12 monthly values for the period 1985-2024.

- The overall trajectory appears upward over time.

3) Statistical trend analysis (Mann Kendall)

The Mann Kendall test (a nonparametric approach commonly used for time-series trend detection) was applied to annual mean temperatures from 1985 to 2024.

Test result:

Mann Kendall Test

(trend = increasing, h = True, p = 1.380842167275631e-07, z = 5.2678, Tau = 0.5732, s = 470.0, vars = 7926.67, slope = 0.10014, intercept = 25.05).

Key points:

- Trend = increasing: indicates a rising temperature trend over the years.
- h = True: the trend is statistically significant (the null hypothesis of no trend is rejected).
- p = 1.38×10^{-7} : an extremely small p-value, far below 0.05, implying the upward trend is highly unlikely to be due to chance.
- Tau = 0.573: indicates a moderate-to-strong positive association between year and annual mean temperature.
- Slope = 0.1001: approximately the rate of increase in annual mean temperature per year ($^{\circ}\text{C}$ unit).
- Intercept ≈ 25.05 : provides an estimate of the baseline level at the start of the period.

In simple terms:

- The annual mean temperature in Riyadh has increased by about 0.1 degrees per year during 1985-2024.
- This trend is statistically robust, indicating a real warming signal rather than random variability.

Concise report-style summary:

1) The dataset consists of monthly mean temperatures from 1985 to 2024 (January-Dec).

2) When annual means are computed, recent years are generally warmer than earlier years.

3) The Mann Kendall test confirms mathematically that:

- There is a clear upward temporal trend in Riyadh mean temperature.
- The probability that this trend is due to random variation is extremely low (p ≈ 0.000000138).
- The warming rate is about 0.1 degree per year, or roughly 1 degree per decade (in the dataset's temperature unit).

Data availability:

The temperature datasets supporting the findings of this study are available from the corresponding author upon reasonable request. NASA reanalysis-based data (1985-2024) are publicly accessible through the NASA POWER platform, A meteorological station operated by the Climate Technologies Institute at King Abdul-Aziz City for Science and Technology (KACST), manufactured by Sky Com-

pany, has been continuously recording nine daily meteorological variables since 2014. Air temperature observations from this station were compared with NASA-derived temperature data for Riyadh over the same period. The comparison indicates strong agreement between the two datasets, supporting the consistency and reliability of the temperature records. and are subject to institutional data sharing policies.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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