

# A Semi-Physical Framework for Attributing Long-Term Urban Warming in Desert Cities: Integrating Climatic Forcing and Urban Energy Dynamics over Riyadh (1985–2024) and Projections to 2050

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# Abstract

Urban warming results from the combined effects of regional climate change and rapid urbanization, yet separating these contributions remains challenging. This study develops a semi-physical climate–urban attribution framework to investigate the long-term evolution of urban warming in Riyadh, Saudi Arabia, during 1985–2024. The framework combines background climatic warming, anthropogenic heat, urban energy loading, thermal memory, and a newly developed Thermal Energy Index (TEI) to distinguish regional climatic forcing from urban thermal amplification.

The framework successfully reproduces the observed long-term temperature evolution and demonstrates that urbanization progressively amplifies the background climatic warming through increasing anthropogenic heat, enhanced urban energy loading, and cumulative thermal storage. Future sensitivity experiments further indicate that alternative urban development pathways lead to increasingly divergent warming trajectories, highlighting the importance of urban growth in shaping future thermal environments.

Beyond its application to Riyadh, the proposed framework provides a physically interpretable and computationally efficient methodology for long-term urban climate attribution using readily available observational datasets. The introduction of TEI offers an integrated measure of urban energy loading that complements existing urban climate indicators and provides a transferable basis for investigating urban thermal amplification in rapidly developing cities.

## Highlights

- A semi-physical framework separates background climatic warming from urban thermal amplification.
- Anthropogenic heat and population-energy interactions are represented using physically interpretable variables.
- The Riyadh application demonstrates a significant warming trend of approximately  $0.60\text{ }^{\circ}\text{C decade}^{-1}$ .
- Model validation supports the ability of the framework to reproduce multi-decadal thermal evolution.
- Future scenarios show that urban development pathways can modulate additional warming to 2050.

## 1. Introduction

Urbanization and climate change are two of the most pervasive drivers of environmental change during the Anthropocene, and their interaction has fundamentally altered the thermal characteristics of cities worldwide. While global climate change has produced a persistent increase in near-surface air temperature over recent decades, rapid urban expansion has introduced additional local-scale modifications to the surface energy balance through land-cover transformation, anthropogenic heat emissions, increased thermal storage, altered aerodynamic properties, and reduced evaporative cooling.

The superposition of these global and local processes has intensified urban warming in many metropolitan regions, creating complex thermal environments that affect human health, energy demand, water resources, ecosystem functioning, and the resilience of urban infrastructure. Consequently, understanding the relative roles of regional climatic forcing and urban development has become one of the central challenges in contemporary urban climatology.

The physical mechanisms responsible for urban warming are well established. The replacement of natural landscapes by impervious surfaces modifies surface albedo, thermal admittance, and moisture availability, increasing the partitioning of available energy into sensible heat while reducing latent heat flux. Urban geometry further enhances multiple reflections of shortwave radiation and restricts longwave radiative cooling through the well-known canyon effect. At the same time, increasing anthropogenic heat emissions associated with buildings, transportation, industry, and air-conditioning systems provide an additional source of thermal energy that is particularly important in densely populated cities. These processes interact continuously rather than independently, producing cumulative warming that extends beyond the classical concept of the urban heat island and influences both daytime and nighttime thermal regimes over seasonal to multi-decadal time scales.

Considerable progress has been made in quantifying urban warming using observational analyses, urban–rural temperature contrasts, remotely sensed land surface temperatures, numerical weather prediction models, and urban canopy parameterizations. These approaches have substantially improved our understanding of urban thermal environments and their controlling mechanisms. Nevertheless, important methodological limitations remain. Urban–rural comparisons often depend strongly on the selection of reference stations and may not adequately represent long-term regional climatic variability. Remote sensing products primarily characterize surface temperature rather than near-surface atmospheric conditions and are frequently limited by temporal sampling constraints. High-resolution numerical models provide detailed process representations but require extensive computational resources, numerous input datasets, and complex parameterizations that are rarely available for long-term historical applications. Consequently, despite decades of research, quantitatively separating background climatic warming from urban thermal amplification over multi-decadal periods remains a significant scientific challenge.

This limitation is particularly evident in rapidly developing desert cities. Arid environments are characterized by intense solar radiation, scarce vegetation, low soil moisture, and weak evaporative cooling, conditions that naturally favor strong sensible heat fluxes and high surface temperatures. Under these circumstances, additional anthropogenic heat release and urban expansion can produce disproportionately large thermal responses compared with more humid environments. Furthermore, the growing dependence on mechanical cooling generates a positive feedback in which increasing ambient temperatures stimulate greater energy consumption, which in turn enhances anthropogenic heat emissions. These interacting processes create a coupled climate–urban system whose long-term thermal evolution cannot be adequately interpreted using either regional climate trends or conventional urban heat island metrics alone.

Riyadh provides an exceptional natural laboratory for investigating these interactions. Over the past four decades, the city has experienced rapid population growth, extensive expansion of its built-up area, increasing energy demand, and continuous modification of its urban surface characteristics while simultaneously being exposed to the broader warming observed across the Arabian Peninsula. The coexistence of these climatic and urban drivers provides a unique opportunity to investigate how background climate change and local urban processes jointly shape long-term temperature evolution. Beyond its regional importance, Riyadh is representative of many rapidly expanding arid cities where urban development is expected to continue throughout the coming decades, making the development of transferable attribution methodologies both scientifically and practically relevant.

Although numerous studies have documented long-term warming over cities and investigated the physical mechanisms responsible for urban thermal environments, relatively few have developed physically interpretable frameworks capable of explicitly separating background climatic forcing from urban thermal amplification using long-term observational datasets. Existing approaches are commonly based on statistical trend analyses, empirical regressions, urban–rural comparisons, or computationally intensive numerical simulations. While each approach has distinct strengths, none provides a simple, physically interpretable framework that simultaneously incorporates regional climatic forcing, anthropogenic heat emissions, urban energy-density interactions, delayed thermal storage, and long-term observational constraints within a unified attribution methodology. Bridging this methodological gap represents an important step toward improving both scientific understanding and practical assessment of urban warming.

The present study addresses this challenge by developing a semi-physical climate–urban attribution framework that combines physically meaningful representations of climatic warming and urban energy processes within a parsimonious modelling structure. The framework separates the observed temperature evolution into a background climatic component and an urban amplification component while explicitly accounting for anthropogenic heat release, urban energy-density interactions through a Thermal Energy Index (TEI\*), and delayed heat release associated with urban thermal memory. Rather than replacing physically based numerical models, the proposed framework seeks to provide an intermediate level of complexity that preserves physical interpretability while remaining applicable to long-term observational datasets commonly available for rapidly developing cities.

The central hypothesis of this study is that the observed multi-decadal warming over Riyadh results from the coupled influence of regional climatic forcing and progressively intensifying urban energy processes, and that these contributions can be quantitatively separated through a physically interpretable semi-physical framework. We further hypothesize that urban thermal amplification has become increasingly important as population growth, energy consumption, and urban expansion have accelerated, thereby strengthening the interaction between anthropogenic heat release and the urban surface energy balance.

Accordingly, the objectives of this study are to (i) quantify the long-term warming characteristics of Riyadh during 1985–2024; (ii) develop and calibrate a semi-physical attribution framework that

separates background climatic warming from urban thermal amplification; (iii) evaluate the capability of the framework to reproduce observed thermal evolution using long-term observations; (iv) investigate the respective roles of anthropogenic heat release, urban energy-density interactions, and thermal memory in amplifying urban warming; and (v) explore the sensitivity of future warming trajectories to alternative urban development pathways through 2050. Beyond the specific application to Riyadh, this study introduces a transferable methodological framework that may support physically interpretable attribution of long-term urban warming in rapidly developing arid cities where observational records are available but computationally intensive modelling approaches remain impractical.

*Figure 1. Conceptual framework of the semi-physical climate-urban attribution workflow. The redesigned workflow links long-term observations, background climatic forcing, anthropogenic heat emissions, TEI\*, thermal memory, validation, uncertainty assessment, and future scenario projections within a single attribution structure.*

## 2. Materials and Methods

### 2.1 Study Area

Riyadh, the capital and largest metropolitan area of the Kingdom of Saudi Arabia, is located in the central Arabian Peninsula (24.71°N, 46.67°E) at an average elevation of approximately 600 m above mean sea level. According to the Köppen–Geiger climate classification, Riyadh is characterized as a hot desert climate (BWh), with extremely hot summers, mild winters, very low annual precipitation, and persistently high incoming solar radiation throughout most of the year. Mean annual rainfall is typically less than 100 mm and occurs mainly during spring, whereas summer months are dominated by clear skies, intense solar heating, and prolonged dry conditions.

These climatic characteristics produce a surface energy balance that is strongly dominated by sensible heat flux, while latent heat exchange remains comparatively limited because of scarce vegetation and low soil moisture availability. Consequently, Riyadh exhibits a naturally high thermal sensitivity to additional energy inputs associated with urbanization, including anthropogenic heat emissions, increasing impervious surface cover, and modifications of urban morphology. Such conditions make the city particularly suitable for investigating the interaction between regional climatic warming and locally generated urban thermal amplification.

Beyond its climatic characteristics, Riyadh has undergone one of the most rapid urban transformations in the Middle East over the last four decades. Continuous population growth, expansion of the built-up area, increasing energy consumption, and intensive infrastructure development have substantially altered the urban surface properties and energy dynamics. These concurrent climatic and socioeconomic changes provide an ideal natural laboratory for developing and evaluating methodologies capable of separating long-term background climatic warming from urban-induced thermal amplification.

## 2.2 Data Sources and Pre-processing

The analysis was conducted using annually resolved climatic and urban-development datasets covering the period 1985–2024. The selected variables were chosen to represent both the background climatic forcing and the principal indicators of urban development influencing long-term urban warming.

Annual near-surface air temperature observations were obtained from the Saudi National Center for Meteorology (NCM). The NCM observational records constitute the primary climatic dataset used to characterize the long-term thermal evolution of Riyadh. Population statistics were obtained from the General Authority for Statistics (GASTAT), providing the official annual demographic record used to quantify urban growth throughout the study period.

Additional variables describing urban development—including effective urban area, anthropogenic heat proxy, Thermal Energy Index (TEI\*), modelled temperature, and residual error—were either derived directly from the observational datasets or calculated using the semi-physical framework described in the following sections. These variables collectively represent the principal components governing the interaction between climatic forcing and urban thermal amplification.

To ensure consistency among datasets originating from different sources, all variables were aggregated to an annual temporal resolution prior to analysis. Annual averaging was selected to emphasize long-term climatic evolution while minimizing the influence of short-term weather variability and seasonal fluctuations. Each dataset was subsequently harmonized using a common temporal reference covering 1985–2024, thereby ensuring complete temporal alignment among all variables used within the attribution framework.

Prior to model development, the datasets underwent standard quality-control procedures. The observational records were examined for missing values, temporal inconsistencies, and anomalous outliers. Where necessary, consistency checks were performed against adjacent years to ensure that no unrealistic discontinuities were introduced into the long-term series. Variables representing different physical quantities were maintained in their original units during model calibration to preserve physical interpretability.

## 2.3 Physical Basis of the Climate–Urban Attribution Framework

Long-term urban temperature evolution results from the combined influence of large-scale climatic forcing and local urban processes that modify the surface energy balance. While regional climate change establishes the background warming trajectory, urban development alters the partitioning, storage, and release of thermal energy through changes in land cover, urban morphology, anthropogenic heat emissions, and population concentration. Consequently, the observed temperature record represents the integrated response of multiple interacting processes rather than a single forcing mechanism.

The proposed attribution framework is founded on the assumption that the observed annual mean temperature can be conceptually decomposed into two principal components: (i) a background climatic component representing large-scale atmospheric warming, and (ii) an urban amplification component representing additional warming generated by urban development. A residual term accounts for unresolved variability arising from meteorological fluctuations, observational uncertainty, and processes not explicitly represented within the framework. This decomposition provides the conceptual foundation for separating regional climatic forcing from local urban thermal amplification while maintaining direct physical interpretation.

Unlike purely statistical regression models, the proposed framework was designed to preserve the physical relationships governing urban warming. Each model component corresponds to a specific process influencing the urban surface energy balance. The background climatic component represents long-term regional warming, whereas the urban component incorporates anthropogenic heat release, energy-density interactions associated with urban growth, and delayed thermal release from urban materials. By explicitly linking mathematical terms to identifiable physical mechanisms, the framework provides a transparent interpretation of the processes governing long-term temperature evolution.

The methodology intentionally adopts an intermediate level of complexity. Fully coupled numerical urban climate models provide detailed process representations but require extensive input datasets, computational resources, and parameterization schemes that are often unavailable for long-term historical analyses. Conversely, purely empirical statistical models frequently achieve satisfactory predictive performance but provide limited physical insight into the mechanisms responsible for observed warming. The present framework seeks to bridge these approaches by combining physically interpretable variables with a parsimonious mathematical formulation that can be calibrated using long-term observational records.

The underlying hypothesis is that progressive urbanization modifies the urban energy balance sufficiently to generate measurable thermal amplification beyond the regional climatic trend. Anthropogenic heat emissions provide an additional source of energy, increasing population density enhances urban energy loading, and urban construction materials store and gradually release thermal energy, thereby reinforcing long-term warming. These mechanisms operate simultaneously and collectively determine the observed evolution of urban temperature.

## 2.4 Development of the Semi-Physical Attribution Model

Following the conceptual decomposition presented above, the long-term evolution of annual temperature was represented as the superposition of a background climatic trend and an urban amplification component. The background climatic contribution was assumed to represent the large-scale warming signal affecting the region independently of local urban development. At annual time scales, this component was approximated by a linear function,

$$T_{\text{base}}(t) = a_0 + a_1 t,$$

where  $T_{base}$  denotes the background climatic temperature,  $a_0$  is the intercept,  $a_1$  is the long-term warming rate, and  $t$  represents time measured relative to the initial year of the analysis.

The residual urban warming signal was subsequently defined as the difference between the observed temperature and the estimated climatic background,

$$T'(t) = T_{obs}(t) - T_{base}(t).$$

thereby representing the portion of the observed thermal evolution potentially attributable to urban processes.

Anthropogenic heat release was represented using an energy-density formulation in which annual urban energy release was normalized by the effective urbanized area,

$$Q_{urban}(t) = \eta E(t) / A_{eff}(t),$$

Where  $E(t)$  denotes the annual urban energy proxy,  $A_{eff}$  represents the effective urban area, and  $\eta$  is an energy-conversion coefficient that scales the proxy to an effective urban heating indicator. This formulation reflects the physically reasonable assumption that identical energy consumption distributed over different urban extents produces different levels of thermal loading.

To account for the increasing efficiency with which expanding cities retain and accumulate thermal energy, the framework introduces the \*Thermal Energy Index ( $TEI^*$ ), defined as

$$TEI^*(t) = Q_{urban}(t) \times [P(t) / A_{eff}(t)].$$

where  $P(t)$  denotes the annual population. The  $TEI^*$  therefore represents the combined influence of urban energy release and population density, providing a physically interpretable indicator of urban energy loading rather than merely an empirical fitting variable. As cities become denser and more energy intensive,  $TEI^*$  increases, reflecting enhanced potential for urban thermal amplification.

Urban materials possess substantial thermal inertia, enabling heat absorbed during one period to be gradually released over subsequent periods. Although this process occurs over daily to seasonal time scales, its cumulative influence contributes to long-term urban warming. To represent this delayed response, the framework incorporates a lagged anthropogenic heat term that approximates urban thermal memory without introducing unnecessary model complexity.

The complete semi-physical attribution model is therefore expressed as

$$T_{model}(t) = a_0 + a_1 t + \lambda Q_{urban}(t - 1) + \beta TEI^*(t),$$

where  $\lambda$  represents the sensitivity of annual temperature to delayed anthropogenic heat release and  $\beta$  quantifies the contribution of urban energy-density interactions represented by  $TEI^*$ . Together, these

terms describe the combined influence of regional climatic forcing, anthropogenic heat emissions, urban population dynamics, and thermal storage within a unified physically interpretable framework.

Unlike conventional empirical regressions, every component of the proposed formulation is directly associated with a recognizable physical process governing urban climate. This explicit correspondence between model parameters and physical mechanisms enhances both the interpretability and the transferability of the framework while maintaining sufficient simplicity for application to long-term observational datasets.

## 2.5 Model Calibration and Parameter Estimation

The parameters of the semi-physical attribution framework were estimated by calibrating the model against the observed annual mean air temperature record for Riyadh during the period 1985–2024. Model calibration aimed to identify the parameter combination that minimized the discrepancy between simulated and observed temperatures while preserving the physical interpretation of each model component.

The calibration procedure simultaneously estimated the background climatic trend ( $a_0$  and  $a_1$ ), the anthropogenic heat sensitivity coefficient ( $\lambda$ ), and the urban energy-density coupling coefficient ( $\beta$ ). These parameters were treated as empirical coefficients representing the magnitude of the physical processes included in the framework rather than universal physical constants. Consequently, although the mathematical structure of the model is transferable, parameter values remain location dependent and should be recalibrated for each study area.

Calibration was performed using the complete observational record because the primary objective of this study was to develop and evaluate a physically interpretable attribution framework rather than to construct an operational forecasting model. Model parameters were iteratively adjusted until the overall agreement between observed and simulated annual temperatures was optimized. Throughout the calibration process, physically unrealistic parameter combinations were avoided to preserve consistency with the conceptual framework described in the previous section.

Unlike purely statistical regression models, parameter estimation within the proposed framework was constrained by the physical interpretation assigned to each model component. The optimization therefore sought not only statistical agreement with observations but also consistency with established understanding of urban energy balance, anthropogenic heat release, and thermal storage processes. This approach reduces the likelihood of obtaining statistically acceptable but physically implausible parameter values.

## 2.6 Model Validation and Performance Assessment

Following calibration, model performance was evaluated by comparing simulated annual temperatures with the corresponding observations. Validation focused on assessing whether the proposed framework

could reproduce the observed long-term thermal evolution while maintaining physically realistic behaviour over the entire study period.

Several complementary statistical metrics were used to quantify model performance. The Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) were calculated to measure the average magnitude of model deviations from observations, while the Mean Bias Error (MBE) was used to identify any systematic tendency toward overestimation or underestimation. The coefficient of determination ( $R^2$ ) was used to evaluate the ability of the model to reproduce the temporal variability of the observed temperature record.

Although these statistics quantify overall model skill, they do not provide complete information regarding model behaviour. Consequently, residual diagnostics were also examined to determine whether the remaining errors exhibited systematic temporal structure or persistent bias. The residual time series was inspected for long-term drift, clustering, and anomalous deviations that might indicate deficiencies in the conceptual representation of the underlying physical processes. A satisfactory model is expected to produce residuals that fluctuate randomly around zero without exhibiting persistent temporal patterns.

Because the proposed framework was developed as an explanatory attribution model rather than a predictive forecasting tool, validation was interpreted primarily in terms of physical consistency and the capability to reproduce the observed long-term warming trajectory rather than short-term predictive accuracy. The combination of statistical performance metrics and residual diagnostics therefore provides complementary evidence regarding the robustness and reliability of the proposed attribution methodology.

## 2.7 Future Scenario Development

To investigate the long-term implications of continued urban development, the calibrated framework was applied to simulate future temperature evolution from 2025 to 2050 under three alternative urban development pathways representing contrasting rates of urban expansion and energy demand.

The scenarios were designed to illustrate the sensitivity of long-term urban warming to different trajectories of population growth, urban expansion, anthropogenic heat emissions, and energy-density evolution. Rather than representing deterministic forecasts, the scenarios provide physically plausible trajectories intended to examine how different patterns of urban development may influence future thermal conditions.

The low-impact scenario assumes moderated population growth, improvements in energy efficiency, and implementation of urban cooling measures that reduce the rate of anthropogenic heat accumulation. The moderate scenario represents a continuation of recent urban development trends with gradual increases in population, urban area, and energy demand. The high-impact scenario assumes accelerated urban growth accompanied by higher energy consumption, greater urban density, and enhanced anthropogenic heat release, resulting in stronger thermal amplification.

For all scenarios, the mathematical structure and calibrated parameters of the attribution framework were preserved. Only the urban development trajectories controlling the anthropogenic heat indicator and the Thermal Energy Index were modified according to the assumptions associated with each scenario. This approach allows differences among future temperature projections to be interpreted directly in terms of changes in urban development rather than changes in model structure.

The future projections presented in this study should therefore be regarded as sensitivity analyses that explore the potential influence of alternative urban growth pathways rather than deterministic climate predictions. Their primary objective is to demonstrate the capability of the proposed framework to evaluate how urban planning and energy-management strategies may influence long-term thermal evolution.

## **2.8 Model Assumptions and Sources of Uncertainty**

The proposed attribution framework is intentionally semi-physical and therefore relies on several simplifying assumptions. First, the background climatic warming component is assumed to vary smoothly over the study period and is represented by a linear trend at the annual time scale. This assumption is appropriate for multi-decadal attribution but does not attempt to reproduce short-term climate variability associated with interannual atmospheric oscillations or extreme weather events.

Second, anthropogenic heat emissions are represented through a temporally consistent proxy rather than direct measurements of urban heat flux. Although this approach does not quantify the absolute magnitude of anthropogenic heat release, it provides a robust indicator of long-term changes in urban energy loading that is appropriate for attribution analyses conducted over several decades.

Third, the Thermal Energy Index (TEI\*) is interpreted as an integrated indicator of urban energy-density interactions rather than a direct physical measurement. Accordingly, the index is intended to represent the cumulative influence of urban growth and energy concentration on thermal amplification rather than any individual physical process.

Finally, uncertainty arises from several sources, including observational measurements, proxy estimation, parameter calibration, structural simplifications within the model, and assumptions regarding future urban development. These uncertainties should be considered when interpreting quantitative projections. Nevertheless, because the primary objective of the framework is to separate physically meaningful contributions to long-term urban warming rather than provide deterministic forecasts, these uncertainties do not diminish its usefulness as an attribution methodology.

## **2.9 Statistical Analysis**

A combination of parametric and non-parametric statistical techniques was employed to quantify long-term temperature trends, evaluate the performance of the proposed attribution framework, and assess the statistical robustness of the results. The use of complementary statistical approaches reduces the

dependence on a single analytical method and provides a more comprehensive assessment of long-term thermal evolution.

Long-term warming rates were initially estimated using ordinary least-squares (OLS) linear regression. The regression slope represents the average rate of temperature change throughout the study period, while the associated coefficient of determination ( $R^2$ ) quantifies the proportion of temporal variability explained by the fitted trend. Statistical significance was evaluated using the corresponding regression p-value, with results considered statistically significant at the 95% confidence level ( $p < 0.05$ ).

Because climatic time series may deviate from normality and may contain outliers capable of influencing least-squares regression, long-term trends were independently verified using the non-parametric Mann–Kendall trend test. Unlike classical linear regression, the Mann–Kendall test does not require assumptions regarding the probability distribution of the observations and is widely regarded as one of the most robust methods for detecting monotonic trends in hydroclimatic and meteorological records.

To complement the Mann–Kendall analysis, the magnitude of the long-term trend was estimated using the Theil–Sen estimator. The Sen slope provides a robust estimate of the median rate of change and is considerably less sensitive to extreme values than ordinary least-squares regression. The combined application of OLS regression, the Mann–Kendall test, and Sen's slope therefore provides a statistically rigorous assessment of both the significance and magnitude of long-term temperature change.

The performance of the proposed semi-physical attribution framework was evaluated by comparing observed and simulated annual mean temperatures using several widely adopted performance statistics. The Root Mean Square Error (RMSE) was used to quantify the overall magnitude of simulation errors, whereas the Mean Absolute Error (MAE) measured the average absolute deviation between modelled and observed temperatures. Systematic model bias was assessed using the Mean Bias Error (MBE), while the coefficient of determination ( $R^2$ ) quantified the agreement between observed and simulated temporal variability.

Residual analysis was performed to examine whether systematic model deficiencies remained after calibration. The temporal distribution of residuals was inspected to identify persistent overestimation, underestimation, or long-term drift that might indicate structural limitations within the proposed framework. The absence of systematic residual behaviour was interpreted as evidence that the principal mechanisms governing long-term temperature evolution were adequately represented by the semi-physical attribution model.

All statistical analyses were performed using standardized scientific computing procedures, and identical analytical methods were consistently applied throughout the observational period (1985–2024) to ensure methodological consistency and facilitate reproducibility.

Table 1

Principal variables and parameters used within the semi-physical climate-urban attribution framework.

| Variable / parameter | Definition                          | Role in framework                                    |
|----------------------|-------------------------------------|------------------------------------------------------|
| Tobs                 | Observed annual mean temperature    | Provides the long-term observational warming record  |
| Tmodel               | Modelled annual mean temperature    | Evaluates the coupled framework against observations |
| Qurban               | Anthropogenic heat proxy            | Represents direct urban energy release               |
| TEI*                 | Thermal Energy Index                | Represents coupled population-energy amplification   |
| $\lambda$            | Anthropogenic heat sensitivity      | Controls the effect of lagged heat release           |
| $\beta$              | Energy-density coupling coefficient | Controls TEI* contribution to thermal amplification  |

### 3. Results

The results are presented according to the logical sequence of the proposed attribution framework. The analysis first identifies the long-term warming signal, then evaluates framework performance, quantifies urban thermal amplification, and finally explores future warming trajectories under alternative development pathways.

#### 3.1 Long-term warming characteristics

The observational record demonstrates that Riyadh has experienced a persistent and statistically robust increase in annual mean air temperature throughout the period 1985–2024. Rather than exhibiting isolated warm episodes or short-term fluctuations, the annual temperature series reveals a sustained upward trajectory extending across the entire observational record (Fig. 2). This behaviour indicates that long-term warming has become an intrinsic feature of Riyadh recent climate and provides the observational basis upon which the subsequent attribution analysis is constructed. Establishing the existence of a statistically significant warming signal is an essential prerequisite because any attempt to separate climatic and urban contributions must first demonstrate that the observed temperature evolution represents a genuine climatic trend rather than random interannual variability.

Quantitative trend analysis confirms the persistence of this warming. Ordinary least-squares regression yields a warming rate of  $0.060^{\circ}\text{C yr}^{-1}$ , equivalent to approximately  $0.60^{\circ}\text{C decade}^{-1}$ , indicating a cumulative increase of approximately  $2.4^{\circ}\text{C}$  over the 40-year study period. The regression explains approximately 69% of the temporal variance in annual temperature ( $R^2 = 0.69$ ), demonstrating that a substantial proportion of the long-term variability is associated with a systematic warming trend rather than random fluctuations. Furthermore, the extremely small regression probability ( $p = 0$ ) indicates that

the likelihood of obtaining such a trend by chance is negligible, confirming that the warming signal is statistically robust. These results identify Riyadh as one of the rapidly warming metropolitan environments within the Arabian Peninsula and highlight the importance of understanding the mechanisms responsible for this sustained temperature increase.

The robustness of the warming trend is further supported by the close agreement among the independent statistical approaches adopted in this study. The Mann–Kendall test produces a positive Kendall's  $\tau$  of 0.65, indicating a strong monotonic increase throughout the observational period, while the Theil–Sen estimator yields a median warming rate of  $0.059^{\circ}\text{C yr}^{-1}$ , which differs only marginally from the ordinary least-squares estimate. The close correspondence between these independent estimators demonstrates that the observed warming is not sensitive to the choice of statistical technique and is not dominated by isolated extreme years or short-term climatic anomalies. Instead, all methods consistently indicate a progressive warming tendency that has persisted over multiple decades, thereby increasing confidence in the observational foundation upon which the attribution framework is developed.

From a physical perspective, the observed warming should not be interpreted solely as evidence of regional climate change. Riyadh has simultaneously undergone profound urban expansion, rapid population growth, increasing energy consumption, and extensive modification of land cover during the same period. Consequently, although the statistical analyses clearly establish the existence of long-term warming, they do not identify the relative contributions of background climatic forcing and locally generated urban thermal amplification. The temperature record therefore represents the integrated response of multiple interacting processes operating over several decades. Distinguishing these contributions constitutes the principal objective of the proposed semi-physical attribution framework.

An important implication of these findings is that the observational trend provides a robust benchmark against which the proposed framework can be evaluated. Before interpreting the physical roles of anthropogenic heat emissions, urban energy loading, and thermal memory, it is first necessary to demonstrate that the model is capable of reproducing the observed evolution of annual temperature with acceptable accuracy. The following section therefore evaluates the performance of the coupled climate–urban attribution framework through comparison of simulated and observed temperature records [21–23].

*Figure 2. Long-term annual temperature trend in Riyadh during 1985–2024. Observed annual data points are visually distinguished from the fitted trend line, showing a persistent warming rate of approximately  $0.60^{\circ}\text{C decade}^{-1}$ .*

Table 2  
Statistical diagnostics of the long-term observed warming signal over Riyadh.

| Metric             | Value                                                   | Interpretation                                  |
|--------------------|---------------------------------------------------------|-------------------------------------------------|
| OLS slope          | 0.060°C yr <sup>-1</sup> (0.60°C decade <sup>-1</sup> ) | Persistent long-term warming                    |
| OLS R <sup>2</sup> | 0.69                                                    | Strong explanatory power of the long-term trend |
| OLS p-value        | 2.60e-11                                                | Statistically significant trend                 |
| Kendall tau        | 0.65                                                    | Monotonic warming tendency                      |
| Sen slope          | 0.059°C yr <sup>-1</sup>                                | Robust non-parametric slope estimate            |

## 3.2 Framework validation

Before the individual climatic and urban contributions can be interpreted, it is essential to demonstrate that the proposed semi-physical framework is capable of reproducing the observed long-term thermal evolution with sufficient accuracy. Model validation therefore represents a critical step in the attribution methodology because any subsequent interpretation of anthropogenic heat, urban energy loading, or thermal memory depends upon the ability of the framework to capture the principal characteristics of the observed temperature record. Rather than evaluating short-term forecasting skill, the objective of the validation is to determine whether the proposed physically interpretable model adequately represents the dominant processes governing multi-decadal warming over Riyadh.

Figure 3 compares the observed annual mean temperatures with those simulated by the calibrated attribution framework. Overall, the model successfully reproduces the long-term warming trajectory throughout the entire observational period, indicating that the combined representation of background climatic forcing, anthropogenic heat release, Thermal Energy Index (TEI), and urban thermal memory captures the dominant controls governing temperature evolution. The simulated series follows both the gradual increase in annual mean temperature and much of the observed interannual variability without exhibiting systematic divergence over time. This agreement demonstrates that the framework remains dynamically stable throughout the 40-year calibration period and does not accumulate unrealistic errors as the simulation progresses.

The quantitative validation statistics further support the capability of the framework to reproduce the observed thermal evolution. The Root Mean Square Error (RMSE) is 0.74°C, indicating that the average discrepancy between simulated and observed annual temperatures remains below 1°C over the entire study period. The Mean Absolute Error (MAE) of 0.63°C confirms that the typical annual deviation is relatively small considering the simplicity of the model formulation and the use of annual-scale urban indicators. Furthermore, the observed-model coefficient of determination ( $R^2 = 0.70$ ) indicates that approximately 70% of the observed interannual variability is explained by the coupled climate–urban framework. Collectively, these statistics demonstrate that the proposed methodology successfully reproduces the dominant temporal behaviour of Riyadh long-term warming while maintaining a relatively simple and physically interpretable structure.

The Mean Bias Error (MBE) of  $0.50^{\circ}\text{C}$  indicates that the simulated temperatures are, on average, slightly warmer than the observations. Although this positive bias suggests a modest tendency toward overestimation, its magnitude remains relatively small compared with the total observed warming during the study period. More importantly, the bias does not increase systematically with time, indicating that it reflects a nearly constant offset rather than progressive model deterioration. Such behaviour is consistent with the simplified semi-physical formulation adopted in this study and suggests that the framework adequately captures the long-term warming trajectory despite minor systematic deviations. Consequently, the observed bias is unlikely to influence the interpretation of the relative contributions of climatic and urban processes, which depend primarily on temporal evolution rather than absolute temperature values.

Residual analysis provides an additional and independent assessment of model performance (Fig. 4). The residual time series fluctuates around zero without exhibiting persistent long-term drift, systematic clustering, or progressive error accumulation. Positive and negative residuals are distributed throughout the observational period, suggesting that the remaining discrepancies largely reflect short-term climatic variability and unresolved processes rather than structural deficiencies within the framework itself. Importantly, no evidence is observed for increasing residual variance during the later stages of urban development, implying that the model retains comparable performance despite substantial changes in population, urban extent, and anthropogenic energy release over the past four decades. This behaviour provides further confidence that the framework remains physically consistent across a wide range of urban development conditions.

The agreement between observations and simulations has important implications for the interpretation of the subsequent attribution results. Because the framework reproduces both the long-term warming trend and a substantial proportion of the observed interannual variability, the individual model components can be interpreted as physically meaningful contributors to the overall thermal evolution rather than merely empirical fitting terms. In particular, the satisfactory model performance provides confidence that the estimated contributions of anthropogenic heat release, urban energy-density interactions represented by the Thermal Energy Index, and delayed thermal storage reflect genuine physical processes operating within Riyadh urban climate system. While the model is intentionally simpler than fully coupled numerical urban climate models, its ability to reproduce the observed temperature evolution demonstrates that considerable explanatory power can be achieved through a parsimonious framework grounded in physically interpretable variables [24].

Table 3  
Model validation metrics for the coupled climate-urban attribution framework.

| Metric                        | Value  | Meaning                                                    |
|-------------------------------|--------|------------------------------------------------------------|
| RMSE                          | 0.74°C | Typical model-observation deviation                        |
| MAE                           | 0.63°C | Mean absolute deviation                                    |
| Mean bias                     | 0.50°C | Average model minus observation difference                 |
| Observed-model R <sup>2</sup> | 0.70   | Agreement between observed and modelled temporal evolution |

### 3.3 Urban thermal amplification and TEI\* behavior

Having demonstrated that the proposed semi-physical framework satisfactorily reproduces the observed long-term temperature evolution, the individual urban components can now be examined to understand the physical mechanisms responsible for thermal amplification. The primary objective of this analysis is not merely to document changes in urban indicators, but to investigate how progressive urban development modifies the efficiency with which additional thermal energy is introduced, accumulated, and retained within the urban environment. This distinction is fundamental because background climatic warming establishes the regional thermal baseline, whereas urban processes determine the magnitude of the additional warming experienced within the city itself.

Figure 5 illustrates the long-term evolution of the anthropogenic heat proxy together with the Thermal Energy Index (TEI). Both variables exhibit a persistent upward trend throughout the study period, reflecting the sustained expansion of Riyadh urban system over the past four decades. The gradual increase in the anthropogenic heat proxy indicates a continuous rise in urban energy release associated with population growth, infrastructure expansion, increasing building density, transportation activity, and greater demand for mechanical cooling. Unlike short-term fluctuations associated with weather variability, these long-term increases represent structural changes in the city energy metabolism and therefore constitute an increasingly important source of urban thermal forcing.

Although the anthropogenic heat proxy alone provides useful information regarding the magnitude of urban energy release, it does not fully describe the efficiency with which this energy contributes to urban warming. This additional information is provided by the Thermal Energy Index (TEI), which combines anthropogenic energy release with population density through the effective urban area. Consequently, TEI represents an integrated measure of urban energy loading rather than simply total energy consumption. The persistent increase in TEI therefore indicates that Riyadh has not only become more energy intensive, but has also become progressively more efficient at concentrating thermal energy within the urban environment. This distinction is important because urban thermal amplification depends on both the quantity of energy released and the spatial characteristics governing its accumulation and retention.

The simultaneous increase in anthropogenic heat and TEI further suggests that urban warming has evolved through a cumulative process rather than through isolated episodes of rapid development. As urban expansion progressed, increasing population density and intensified energy use acted together to enhance the overall thermal loading of the city. This behaviour is consistent with the conceptual framework proposed in Section 2, where anthropogenic heat provides the direct thermal input while TEI represents the increasing efficiency with which urban development amplifies that energy. The observed co-evolution of these variables therefore provides empirical support for the physical assumptions underlying the proposed attribution model.

The demographic context for this evolution is illustrated in Fig. 6, which compares long-term population growth with observed annual mean temperature. Both variables display sustained increases throughout the observational period, indicating that the warming trend developed concurrently with rapid urban expansion. It is important to emphasize that this temporal correspondence should not be interpreted as evidence that population growth alone causes temperature increases. Rather, population growth serves as an integrated indicator of broader urban development, including increased infrastructure, energy consumption, transportation activity, and modifications of the built environment. Within the proposed framework, population therefore functions as a physically meaningful driver of urban energy demand rather than as an independent climatic forcing.

An important characteristic of the population–temperature relationship is its progressive nature. During the earlier years of the observational record, relatively modest demographic growth was accompanied primarily by the regional climatic warming signal. As urban expansion accelerated, however, increasing energy demand and higher urban density enhanced the efficiency of heat accumulation, resulting in progressively stronger urban thermal amplification. This behaviour supports the central hypothesis of the study that urban processes increasingly reinforce, rather than replace, the background climatic warming trend. Consequently, the observed temperature evolution should be interpreted as the product of coupled climatic and urban processes operating simultaneously over multiple decades rather than as the consequence of either mechanism acting independently.

The correlation matrix presented in Fig. 7 provides an integrated assessment of the relationships among the principal climatic and urban variables included in the attribution framework. Strong positive correlations are observed between observed temperature, modelled temperature, the anthropogenic heat proxy, TEI, and population, indicating that these variables evolve coherently over the study period. This result is physically consistent with the conceptual model because each variable represents a different aspect of the coupled climate–urban system. The close agreement between observed and modelled temperatures further demonstrates that the framework successfully captures the dominant interactions among these processes while maintaining a relatively simple mathematical formulation.

In contrast, the residual component exhibits substantially weaker relationships with the principal framework variables. This behaviour indicates that the majority of the systematic long-term warming signal has already been explained by the combined effects of background climatic forcing,

anthropogenic heat release, urban energy loading, and thermal memory. The remaining residual variability is therefore likely associated with shorter-term meteorological fluctuations, observational uncertainty, or secondary physical processes that are intentionally omitted from the parsimonious framework. The relatively weak correlation of the residual component provides additional evidence that the principal mechanisms governing long-term urban warming have been successfully represented.

Having established the physical mechanisms responsible for urban thermal amplification, the calibrated framework can now be applied to investigate how different future urban development pathways may influence the continued evolution of Riyadh thermal environment through the middle of the twenty-first century.

### 3.4 Future warming pathways to 2050

One of the principal advantages of the proposed semi-physical attribution framework is that, once calibrated against long-term observations, it can be used to investigate how different trajectories of urban development may influence future thermal evolution. Rather than providing deterministic climate forecasts, the future simulations presented here should be interpreted as physically based sensitivity experiments designed to evaluate the response of Riyadh thermal environment to alternative patterns of urban growth, energy demand, and urban energy loading. This distinction is important because future temperatures will ultimately depend on numerous climatic, socioeconomic, technological, and policy-related factors that cannot be predicted with certainty. The objective of the present analysis is therefore to examine the relative sensitivity of long-term urban warming to plausible changes in urban development while maintaining the physical structure of the calibrated attribution framework.

Figure 8 presents the simulated evolution of annual mean temperature under three contrasting urban development pathways extending from 2025 to 2050. Although all scenarios exhibit continued warming throughout the projection period, the magnitude and rate of temperature increase differ progressively according to the assumed intensity of future urban development. The low-impact pathway produces the slowest warming trajectory, whereas the moderate scenario broadly maintains the historical rate of warming. In contrast, the high-impact scenario exhibits the most rapid increase in temperature, indicating that accelerated urban expansion and increasing energy demand substantially enhance the cumulative thermal response of the urban system. The progressive divergence among the three trajectories demonstrates that urban development has the potential to significantly modulate future thermal conditions even when the underlying climatic framework remains unchanged.

An important characteristic of the projections is that the scenario trajectories remain relatively close during the early years following 2024 before gradually separating as the simulation progresses. This behaviour reflects the cumulative nature of urban thermal amplification represented within the proposed framework. Initially, differences in anthropogenic heat release and TEI remain comparatively modest because the assumed urban development pathways have only recently begun to diverge. However, as population growth, energy demand, and urban energy loading continue to evolve, these differences

accumulate through time, producing increasingly distinct thermal responses. The widening separation among the projected temperature trajectories therefore illustrates the cumulative effect of sustained urban development rather than an immediate response to short-term changes in urban conditions.

The physical mechanisms responsible for this divergence are directly linked to the structure of the attribution framework. The background climatic component contributes similarly to all scenarios because it represents the large-scale regional warming signal. Consequently, the increasing separation among the projections originates primarily from differences in the urban amplification component. Under the high-impact pathway, accelerated anthropogenic heat release, increasing urban energy density, and enhanced thermal storage collectively strengthen the urban contribution to total warming. Conversely, the low-impact scenario assumes slower growth in these urban drivers, thereby limiting the efficiency with which additional thermal energy accumulates within the city. The framework therefore demonstrates that future differences in urban temperature need not arise solely from changes in regional climate but may also result from the evolution of local urban characteristics that influence the surface energy balance.

The projected behaviour of TEI is particularly informative in this context. Because TEI integrates anthropogenic heat release with population density through the effective urban area, it responds not only to increases in energy consumption but also to changes in the spatial organization of urban development. As a result, the divergence among future scenarios is driven by differences in both the quantity of energy released and the efficiency with which that energy is concentrated within the urban environment. This finding highlights one of the principal conceptual contributions of the present framework. It suggests that future urban warming cannot be understood solely through increasing energy demand or population growth considered independently; rather, it is the interaction between these processes that governs the efficiency of urban thermal amplification.

The scenario analysis also provides important insight into the long-term behaviour of urban climate systems. The results suggest that urban warming is fundamentally path dependent. Once additional heat is introduced into the urban environment through sustained development, increasing thermal storage within buildings, roads, and other impervious surfaces reinforces subsequent warming through delayed heat release and cumulative energy accumulation. Consequently, relatively modest differences in urban development rates during the early stages of city growth may ultimately produce substantially different thermal environments several decades later. This cumulative behaviour emphasizes the importance of considering long-term urban development strategies rather than focusing exclusively on short-term mitigation measures.

From an urban planning perspective, these findings indicate that local development policies can meaningfully influence future thermal conditions even though they cannot eliminate the background climatic warming associated with global climate change. Measures such as improving building energy efficiency, reducing anthropogenic heat emissions, increasing urban vegetation, optimizing urban density, enhancing natural ventilation, and employing high-albedo construction materials primarily

influence the urban amplification component represented within the proposed framework. The scenario analysis therefore provides a physically interpretable basis for evaluating how urban planning interventions may alter future warming trajectories. Although the framework does not explicitly simulate individual mitigation measures, it demonstrates the extent to which modifying the principal drivers of urban energy loading can reduce the cumulative amplification of regional climatic warming.

It is equally important to recognize the intended scope of these projections. The future scenarios are not predictions of the exact temperatures that Riyadh will experience by 2050. Instead, they represent internally consistent sensitivity experiments constructed to examine the response of the coupled climate–urban system to different assumptions regarding urban growth. The value of the analysis therefore lies less in the absolute projected temperatures than in the relative differences among scenarios, which reveal the degree to which future urban development may influence the magnitude of additional warming beyond the regional climatic trend. Interpreting the scenarios in this manner avoids overconfidence in specific numerical projections while preserving the scientific value of the framework as a tool for exploring urban climate sensitivity [1, 19, 20].

Table 4  
Scenario assumptions used for future temperature projection pathways to 2050.

| Scenario    | Assumed pathway                                               | Approximate warming rate | Interpretation                                        |
|-------------|---------------------------------------------------------------|--------------------------|-------------------------------------------------------|
| Low-impact  | Improved efficiency, moderated growth, urban cooling measures | 0.035°C yr <sup>-1</sup> | Additional warming remains constrained                |
| Moderate    | Continuation of current development trajectory                | 0.050°C yr <sup>-1</sup> | Sustained warming under current urbanisation patterns |
| High-impact | Rapid intensification, high density, high energy demand       | 0.065°C yr <sup>-1</sup> | Strongest thermal amplification pathway               |

### 3.5 Synthesis of Climatic and Urban Contributions to Long-Term

The preceding analyses collectively demonstrate that the long-term warming observed over Riyadh cannot be attributed to a single controlling factor. Instead, the results indicate that the city recent thermal evolution reflects the combined influence of persistent regional climatic warming and progressively intensifying urban development. The proposed semi-physical attribution framework provides a coherent interpretation of these interacting processes by explicitly separating the background climatic signal from the urban amplification component while maintaining direct links between the mathematical formulation and the underlying physical mechanisms governing the urban surface energy balance.

The observational analyses established that Riyadh experienced a statistically significant warming of approximately 2.4°C during 1985–2024, confirming the presence of a persistent long-term climatic signal. Independent statistical techniques including ordinary least-squares regression, the Mann–Kendall

trend test, and the Theil–Sen estimator produced highly consistent results, demonstrating that the observed warming is both statistically robust and largely insensitive to methodological choice. These findings provide a reliable observational foundation for subsequent attribution because they confirm that the temperature evolution represents a genuine long-term climatic trend rather than a consequence of short-term variability or isolated extreme events.

Validation of the proposed attribution framework further demonstrated that the dominant characteristics of the observed temperature evolution can be reproduced using a relatively simple semi-physical formulation. The close agreement between observed and simulated temperatures, together with satisfactory performance statistics and the absence of systematic residual drift, indicates that the principal processes governing long-term warming are adequately represented within the model structure. Importantly, this agreement provides confidence that the estimated urban contribution reflects physically meaningful mechanisms rather than purely empirical statistical relationships. The framework therefore succeeds in balancing physical interpretability with computational simplicity, making it suitable for long-term attribution studies based primarily on observational datasets.

Analysis of the urban development indicators revealed that anthropogenic heat release, demographic growth, and the Thermal Energy Index (TEI) evolved coherently throughout the observational period. Their simultaneous increase demonstrates that urbanization progressively strengthened the efficiency with which thermal energy was generated, concentrated, and retained within the metropolitan environment. Rather than functioning as an independent climatic forcing, urbanization acted as an amplifier of the regional warming signal by modifying the urban surface energy balance through increased energy loading and enhanced thermal storage. This interpretation represents one of the principal scientific outcomes of the present study because it provides a physically consistent explanation for how rapidly expanding arid cities experience warming beyond that expected from regional climate change alone.

The future sensitivity experiments extend this interpretation by demonstrating that the magnitude of additional warming depends strongly on the trajectory of future urban development. Although all simulated pathways exhibit continued warming associated with the background climatic component, differences in urban energy loading produce progressively divergent thermal responses over time. This behaviour highlights the cumulative nature of urban thermal amplification and suggests that long-term planning decisions affecting urban density, energy demand, and infrastructure development may substantially influence future urban temperatures even under similar regional climatic conditions. Consequently, the framework provides not only a tool for interpreting historical warming but also a physically interpretable basis for evaluating the long-term implications of alternative urban development strategies.

Taken together, these results support the central hypothesis of this study that long-term urban warming is best understood as the outcome of coupled climatic and urban processes rather than the consequence of either mechanism operating independently. The analyses consistently indicate that

regional climate change establishes the background warming trajectory, while urbanization progressively increases the efficiency with which thermal energy is accumulated and retained within the city. This conceptual separation between climatic forcing and urban amplification represents the principal contribution of the proposed framework and provides a physically interpretable basis for understanding the evolution of urban warming in rapidly developing arid metropolitan environments.

The synthesis presented here also establishes the foundation for the Discussion section. Having demonstrated that the framework successfully reproduces the observed thermal evolution and identifies the principal mechanisms responsible for urban amplification, the following section examines these findings within the broader context of urban climatology, compares them with previous observational and modelling studies, evaluates the strengths and limitations of the proposed methodology, and discusses their implications for future research and sustainable urban planning.

## 4. Discussion

The present study demonstrates that the long-term thermal evolution of Riyadh is best understood as the consequence of coupled regional climatic forcing and progressively intensifying urban energy processes rather than either mechanism acting independently. The observational analyses established a statistically robust warming trend over the past four decades, while the proposed semi-physical attribution framework successfully reproduced this evolution using physically interpretable representations of climatic warming, anthropogenic heat release, urban energy loading, and thermal memory. Collectively, these findings indicate that urbanization does not replace the regional climate signal but progressively amplifies it by modifying the urban surface energy balance and increasing the efficiency with which thermal energy is generated, stored, and retained within the metropolitan environment.

This interpretation is consistent with the fundamental principles of urban climatology. In arid environments such as Riyadh, naturally high incoming solar radiation, limited vegetation cover, scarce soil moisture, and weak evaporative cooling favour large sensible heat fluxes throughout much of the year. Urban development further alters these conditions through the replacement of natural surfaces with buildings, asphalt, and other impervious materials possessing substantially greater heat-storage capacity. Simultaneously, urban geometry enhances multiple reflections of shortwave radiation, reduces long-wave radiative loss during the night, and increases thermal inertia within the built environment. The combined effect is a progressive increase in the efficiency with which absorbed energy is retained and subsequently released, producing cumulative warming that extends beyond the immediate influence of regional climate change. Rather than representing an isolated urban heat island phenomenon, the observed temperature evolution therefore reflects the long-term interaction between climatic forcing and a continuously evolving urban energy system.

The role of anthropogenic heat becomes particularly important within this context. As cities expand, increasing population, infrastructure, transportation, and economic activity lead to progressively greater

energy consumption. In hot desert cities, where mechanical cooling represents one of the largest components of electricity demand, increasing ambient temperatures further stimulate energy use, thereby introducing additional anthropogenic heat into the urban atmosphere. This creates a positive feedback mechanism in which climatic warming increases cooling demand, enhanced cooling demand increases urban energy release, and additional energy release contributes to further warming. Although the present framework represents this behaviour through an integrated anthropogenic heat indicator rather than explicit building-energy simulations, the observed long-term evolution strongly suggests that such feedbacks become increasingly important as urbanization proceeds.

These physical considerations explain why a framework based solely on statistical trend analysis cannot fully describe long-term urban warming. Statistical models often reproduce historical temperature evolution successfully, yet they provide limited insight into the mechanisms responsible for the observed changes. Conversely, fully coupled numerical models explicitly resolve atmospheric dynamics, radiative transfer, turbulence, and urban morphology, but they require extensive input datasets, detailed urban parameterization, and substantial computational resources that frequently limit their application to long-term historical investigations. The semi-physical framework developed in this study was designed to occupy the methodological space between these two approaches. By linking every mathematical component directly to an identifiable physical process, it preserves the interpretability of process-based modelling while maintaining the simplicity necessary for application to long-term observational datasets.

One of the principal methodological advances of the framework is the explicit separation of background climatic warming from urban thermal amplification. This distinction has important scientific implications because observed urban temperature records invariably contain contributions from both regional atmospheric change and local urban development. Many previous investigations have documented long-term warming without explicitly partitioning these components, making it difficult to determine the relative importance of climate change and urbanization. By representing these processes separately within a unified framework, the present methodology provides a clearer physical interpretation of urban temperature evolution and establishes a more direct connection between observed warming and the underlying mechanisms governing the urban surface energy balance.

The introduction of the Thermal Energy Index (TEI) further extends this conceptual framework. Conventional indicators of urbanization including population size, built-up area, and anthropogenic heat considered independently describe important characteristics of urban growth but cannot fully represent the cumulative interaction between energy generation and its spatial concentration within the built environment. TEI was developed to address this limitation by integrating anthropogenic heat release with demographic concentration through the effective urban area, thereby representing the efficiency with which urban systems accumulate thermal energy rather than simply the magnitude of individual urban characteristics. The results indicate that the progressive increase in TEI closely parallels the enhancement of urban thermal amplification, suggesting that the evolution of urban warming depends not only on increasing energy consumption but also on the manner in which that energy is distributed within the metropolitan landscape.

This interpretation also shifts the focus of urban climate research from viewing cities primarily as expanding land-cover units toward understanding them as evolving energy systems. Urban thermal environments are governed not solely by the extent of urban expansion but by the continuous interaction between energy production, population dynamics, infrastructure development, thermal storage, and atmospheric exchange. Within this broader perspective, urbanization becomes a dynamic process in which cumulative changes in energy loading progressively modify the trajectory of long-term warming. This conceptual shift represents one of the broader scientific contributions of the present study because it emphasizes physical processes rather than empirical indicators as the basis for understanding urban climate evolution.

The framework also complements existing methodologies rather than competing with them. Urban–rural temperature comparisons remain valuable for quantifying spatial thermal contrasts, satellite observations provide unparalleled spatial coverage of land surface thermal characteristics, and numerical urban climate models remain indispensable for resolving neighborhood-scale atmospheric processes. However, each approach addresses different scientific questions and possesses distinct practical limitations. The methodology presented here contributes an additional capability by providing a physically interpretable attribution framework capable of separating climatic and urban contributions using readily available long-term observations. Consequently, it should be regarded as complementary to existing observational and modelling approaches, particularly for cities where detailed urban energy inventories or computationally intensive simulations are impractical.

Beyond its methodological contribution, the framework has broader implications for sustainable urban development. Because the model explicitly distinguishes between background climatic warming and urban thermal amplification, it provides a conceptual basis for identifying which component of future warming may be influenced through local intervention. While regional climate change depends primarily on global greenhouse gas emissions, urban thermal amplification is affected by decisions regarding land-use planning, building materials, urban density, vegetation, transportation systems, and energy efficiency. The framework therefore establishes a direct connection between urban planning decisions and long-term thermal evolution, providing a scientific basis for evaluating adaptation strategies designed to reduce the accumulation and retention of thermal energy within rapidly expanding metropolitan environments.

Although the framework demonstrates considerable explanatory capability, its intended scope should be clearly recognized. The analysis was performed using annual observations to investigate long-term climate evolution rather than seasonal variability or individual extreme events. Anthropogenic heat was represented using a temporally consistent proxy rather than direct flux measurements, and urban morphology was simplified through the effective urban area rather than explicitly resolving building geometry or Local Climate Zones. Similarly, the future scenarios represent sensitivity experiments illustrating the influence of alternative urban development pathways rather than deterministic climate forecasts. These simplifications were adopted deliberately to preserve the transparency, reproducibility, and broad applicability of the methodology. Future developments incorporating higher temporal

resolution observations, improved anthropogenic heat inventories, explicit urban morphology, satellite-derived thermal characteristics, and regional climate model projections would further strengthen the physical representation of the framework while maintaining its conceptual simplicity.

## **Conclusions and Future Research**

This study developed a semi-physical climate–urban attribution framework to investigate the long-term evolution of urban warming in Riyadh during 1985–2024. The framework explicitly separates background climatic warming from urban thermal amplification by integrating physically interpretable representations of anthropogenic heat, urban energy loading, thermal memory, and the newly proposed Thermal Energy Index (TEI).

The results demonstrate that the observed warming is best explained by the combined influence of regional climate change and progressively intensifying urban development. While background climatic forcing establishes the long-term warming trajectory, urbanization increasingly amplifies this signal through enhanced energy release, greater thermal storage, and more efficient accumulation of heat within the built environment. The proposed framework successfully reproduces the observed temperature evolution while maintaining a balance between physical interpretability and computational simplicity.

Beyond the Riyadh case study, this work introduces a transferable methodology for long-term urban climate attribution using readily available observational datasets. The proposed TEI provides an integrated indicator of urban energy loading that complements existing urban climate metrics and offers new opportunities for investigating thermal amplification in rapidly developing cities.

Future research should evaluate the framework across contrasting climatic regions, incorporate higher-resolution urban morphology and anthropogenic heat datasets, and couple the methodology with regional climate projections to strengthen its applicability for urban climate adaptation and sustainable planning.

## **4.1 Physical interpretation of long-term warming**

The long-term warming observed over Riyadh represents the combined response of large-scale climatic forcing and progressively intensifying urban development. While the observational record demonstrates a statistically significant increase in annual mean temperature, the attribution analysis indicates that the warming cannot be interpreted as the consequence of a single process. Instead, the observed thermal evolution emerges from the interaction between regional climate change and local anthropogenic modifications of the urban surface energy balance [1, 2, 4, 10, 11, 17, 18].

The proposed semi-physical framework provides a physically consistent interpretation of this interaction by separating the background climatic component from the urban amplification component. This distinction is particularly important in rapidly expanding desert cities, where climatic warming and

urbanisation evolve simultaneously and can reinforce one another through energy demand, surface modification, and thermal storage [6, 7, 9–11].

This interpretation is consistent with the physical understanding of urban climate systems, where anthropogenic heat release, reduced evaporative cooling, increased thermal inertia of built materials, and modified radiative exchange collectively contribute to elevated urban temperatures [2–4, 7, 8, 11]. Rather than acting independently, these mechanisms interact continuously, producing a long-term amplification effect that becomes more evident as urban development intensifies.

## **4.2 Climatic forcing versus urban thermal amplification**

One of the principal outcomes of this study is the demonstration that long-term warming over Riyadh cannot be adequately explained by regional climatic forcing alone. Although large-scale climate change establishes the background warming signal, the attribution framework indicates that progressive urban development amplifies the observed thermal response through modifications of the urban surface energy balance [1, 10, 11, 17, 18].

The distinction between climatic forcing and urban amplification has important implications for climate adaptation. Measures that reduce anthropogenic heat emissions, increase vegetative cover, improve surface reflectivity, or enhance ventilation primarily target the urban amplification component, whereas the background climatic trend is controlled by larger-scale atmospheric processes [1, 11, 12, 19, 20]. The framework therefore provides a practical basis for distinguishing global mitigation challenges from local urban thermal management strategies.

## **4.3 Physical role of TEI\*, anthropogenic heat, and urban thermal memory**

A distinguishing feature of the proposed framework is its explicit representation of the coupling between anthropogenic heat emissions, urban energy accumulation, and long-term thermal response. TEI\* should be interpreted as a physically meaningful proxy for cumulative urban energy loading rather than as a purely empirical fitting parameter [6, 7, 14–16].

Within the framework, anthropogenic heat provides the direct source of additional thermal energy, whereas TEI\* represents the long-term efficiency with which population concentration and urban development facilitate retention and accumulation of that energy. This distinction between energy release and energy retention is important because two cities with comparable energy use may differ substantially in thermal response depending on density, morphology, and ventilation conditions.

Urban thermal memory further strengthens this interpretation. Materials with high thermal inertia accumulate heat during daytime and release it during evening and nighttime hours, a mechanism widely recognised in urban boundary-layer and surface-energy-balance studies [2–4, 8]. As development intensifies, this storage-release cycle becomes more effective, contributing to elevated nighttime

temperature and reducing the effectiveness of nocturnal cooling. The thermal-memory term therefore provides a physical basis for representing delayed urban heat release within an annual-scale framework.

## **4.4 Methodological contribution and transferability**

Beyond reproducing the long-term thermal evolution of Riyadh, the principal contribution of the proposed framework lies in its ability to provide a physically interpretable methodology for separating background climatic warming from urban thermal amplification. This addresses a broader methodological challenge in urban climate research: distinguishing regional climatic trends from locally generated thermal forcing in rapidly urbanising environments [4, 6, 7, 10, 11].

The framework has been calibrated using Riyadh as a representative rapidly expanding desert metropolis. Nevertheless, its conceptual structure is not inherently restricted to this location. Cities experiencing sustained urban expansion, increasing energy demand, and progressive modification of the urban surface energy balance may benefit from a similar attribution strategy, provided that local observations and calibration datasets are available [13–16].

Transferability does not imply direct transfer of calibrated parameter values. Urban morphology, climate, construction materials, vegetation characteristics, and energy-use patterns differ among cities. Parameter values should therefore be recalibrated for each application while preserving the underlying physical structure of the framework. This distinction between transferable methodology and location-specific calibration is central to the scientific contribution of the study.

## **4.5 Limitations and future research**

The framework is intentionally parsimonious and relies on annual-scale variables. This choice improves interpretability and enables multi-decadal analysis, but it also limits the representation of seasonal extremes, daily heatwave behaviour, and intra-urban spatial heterogeneity. The use of an energy proxy introduces additional uncertainty because long-term city-scale energy inventories were not available at the same temporal consistency as the climate record [7, 15, 16, 24].

Future research should incorporate higher-resolution urban morphology datasets, remotely sensed land-surface properties, observed electricity-consumption records, and physically based urban canopy parameterisations [8, 11, 12]. These additions would improve the representation of local heat fluxes and support more detailed seasonal and spatial attribution. The framework presented here should therefore be viewed as a physically interpretable foundation that can be strengthened as more detailed urban datasets become available.

Although the proposed framework preserves physical interpretability, it is not intended to replace fully coupled numerical urban climate models (e.g., urban canopy or mesoscale atmospheric models). Instead, it provides an intermediate-level attribution methodology that bridges empirical statistical analyses and computationally intensive process-based models, enabling physically interpretable assessment of long-term urban warming where detailed numerical modelling is impractical.

## 5. Conclusions

This study presents a semi-physical climate-urban attribution framework capable of distinguishing background climatic warming from urban thermal amplification through the integration of long-term observations, anthropogenic heat emissions, urban energy-density dynamics, and future scenario analysis within a unified modelling structure. By combining physically interpretable variables with observational validation, the framework provides a robust basis for interpreting the multi-decadal thermal evolution of rapidly urbanising desert environments.

Application to Riyadh demonstrates that the observed long-term warming cannot be attributed solely to regional climatic forcing. Instead, the results indicate that progressive urban development increasingly amplifies the background climatic signal through cumulative anthropogenic heat release, urban energy accumulation, and enhanced thermal storage within the built environment. The close agreement between simulated and observed temperatures supports the capability of the framework to reproduce long-term thermal evolution while maintaining physical consistency with urban energy processes.

An important contribution of the methodology lies in the explicit representation of the interaction between anthropogenic heat emissions and TEI\*, allowing urban warming to be interpreted through physically meaningful processes rather than solely through empirical statistical relationships. Beyond the Riyadh case study, the framework establishes a transferable methodological structure that can be adapted to other rapidly developing metropolitan regions, provided that local observations are available for calibration and validation.

From an applied perspective, the framework provides a scientific tool for distinguishing warming driven by large-scale climatic change from warming associated with local urban development. This distinction is essential for designing adaptation strategies, evaluating urban mitigation measures, and improving long-term climate resilience in rapidly expanding cities [1, 11, 12, 19, 20]. Future work should integrate higher-resolution urban morphology, dynamic energy inventories, remotely sensed surface characteristics, and urban canopy model outputs to further strengthen process-level attribution.

## Declarations

## Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

## Author Contribution

CRedit Author Contributions: -Mohammed Almutairi: Conceptualization; Methodology; Formal analysis; Investigation; Data curation; Visualization; Writing – original draft; Writing – review &

editing.Abdulrahman Maghrabi: Conceptualization; Methodology; Supervision; Validation; Writing – review & editing.Abdullah Al-Dosari: Investigation; Validation; Writing – review & editing.Mohammed Altlassi: Investigation; Validation; Writing – review & editing.Abdullah Alshehri: Investigation; Validation; Writing – review & editing.All authors have read and approved the final manuscript and consent to its submission for publication.

## Data availability

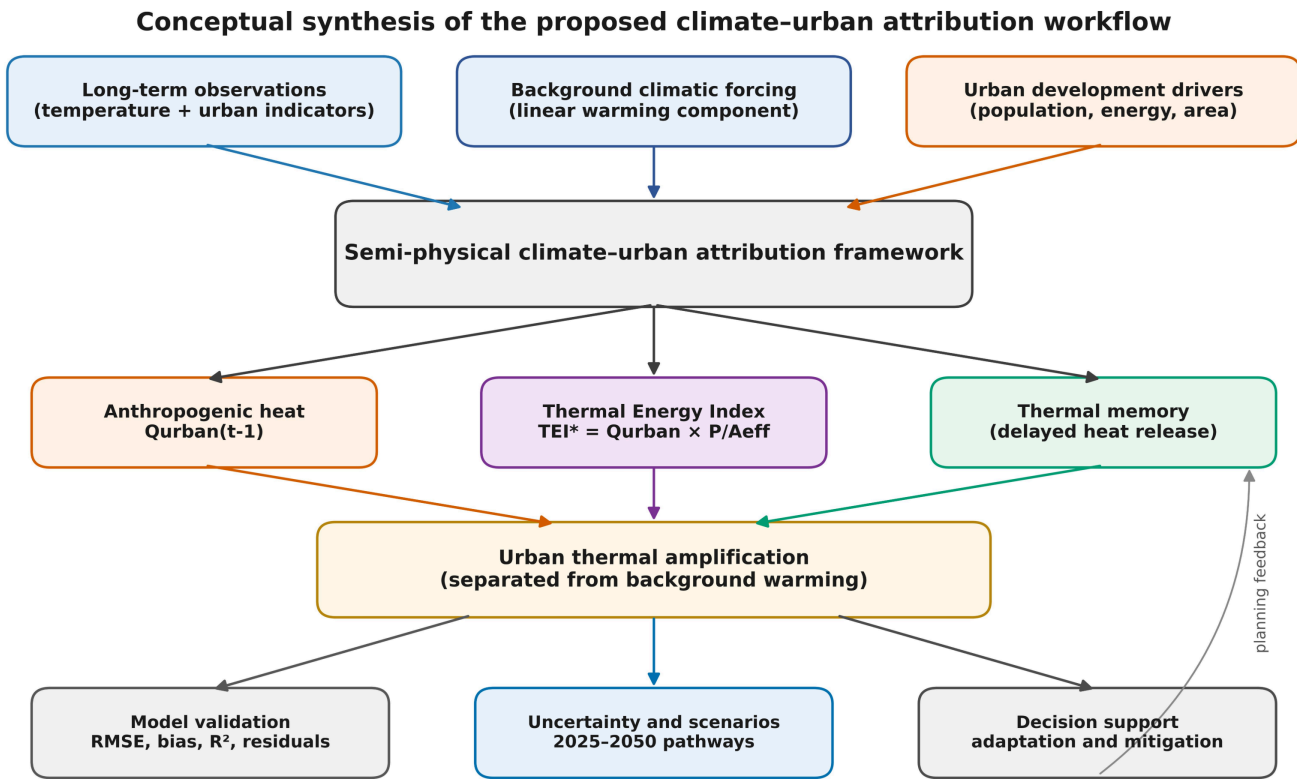
The annual climate and urban-indicator dataset used in this study underpins all analyses presented. Derived datasets and figure-generation scripts are available from the corresponding author upon reasonable request.

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## Figures



The framework links observations, climatic forcing, urban energy processes, validation, and future pathways within a single attribution structure.

**Figure 1**

Conceptual framework of the semi-physical climate-urban attribution workflow. The redesigned workflow links long-term observations, background climatic forcing, anthropogenic heat emissions, TEI\*, thermal memory, validation, uncertainty assessment, and future scenario projections within a single attribution structure.

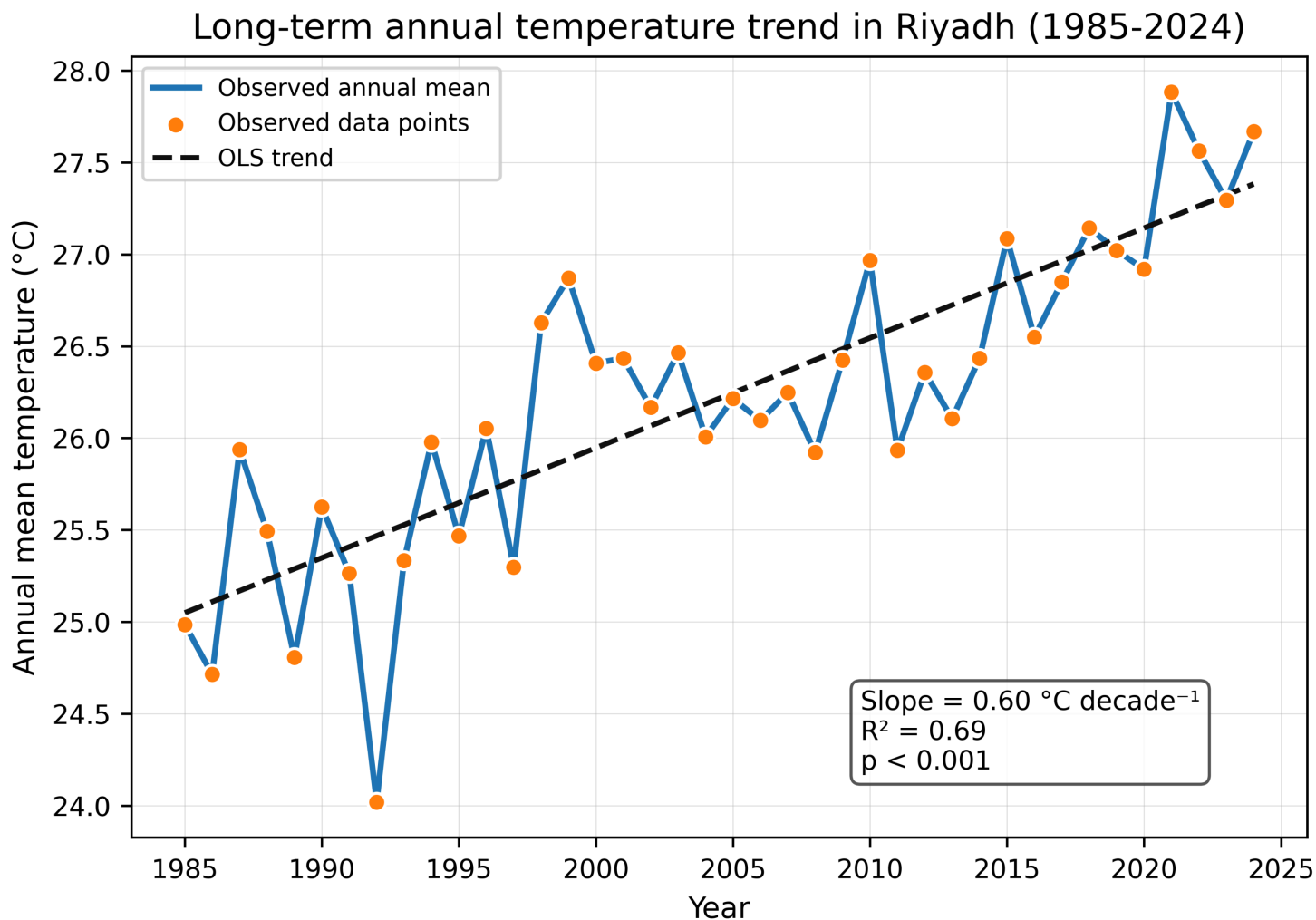


**Figure 2**

Long-term annual temperature trend in Riyadh during 1985-2024. Observed annual data points are visually distinguished from the fitted trend line, showing a persistent warming rate of approximately 0.60 °C decade<sup>-1</sup>.

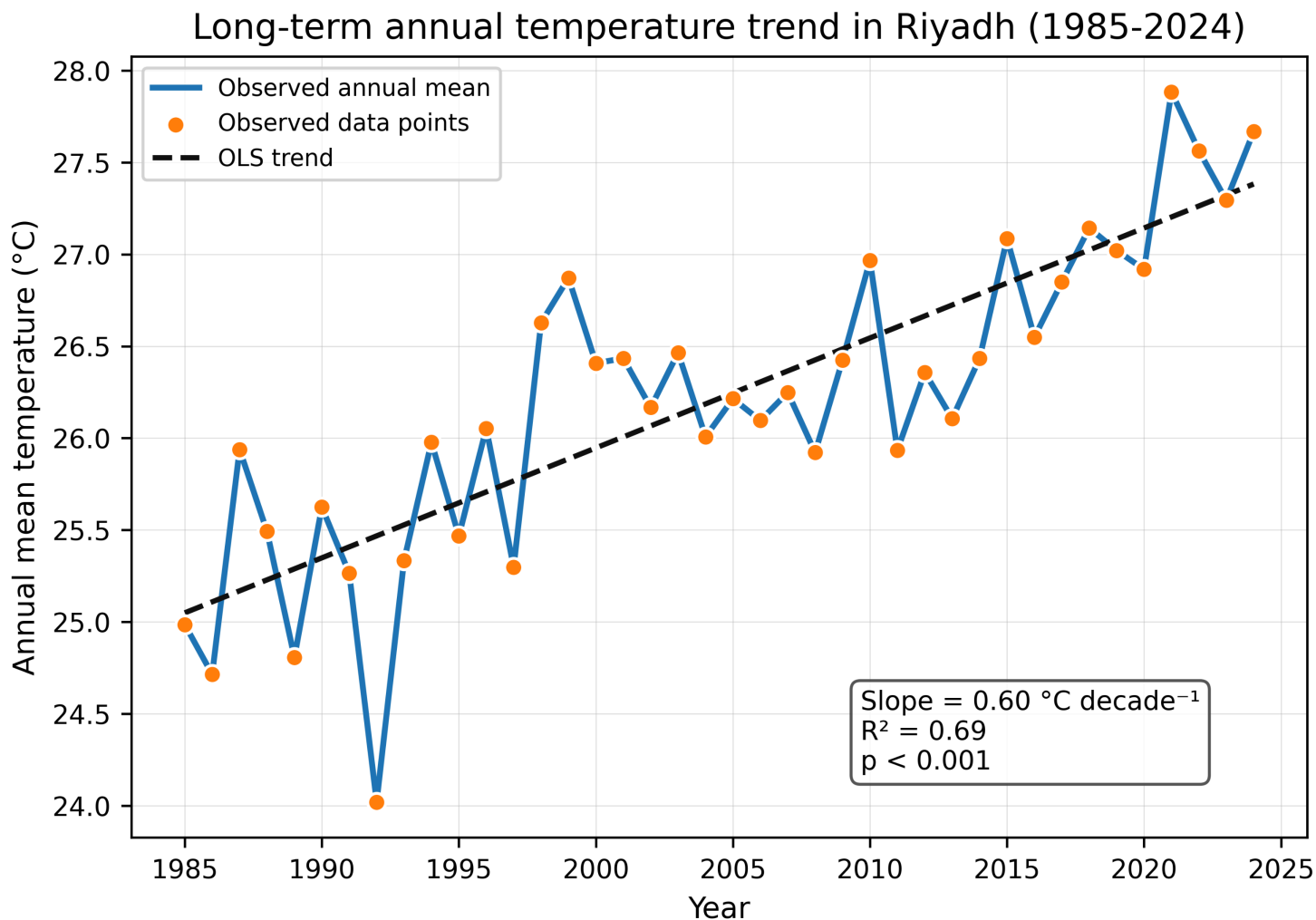


**Figure 3**

Comparison between observed and modelled annual mean temperatures in Riyadh. Distinct marker and line colours show the observed record and simulated response, demonstrating the ability of the coupled framework to reproduce the long-term thermal evolution.

## Residual behaviour of the coupled climate-urban framework

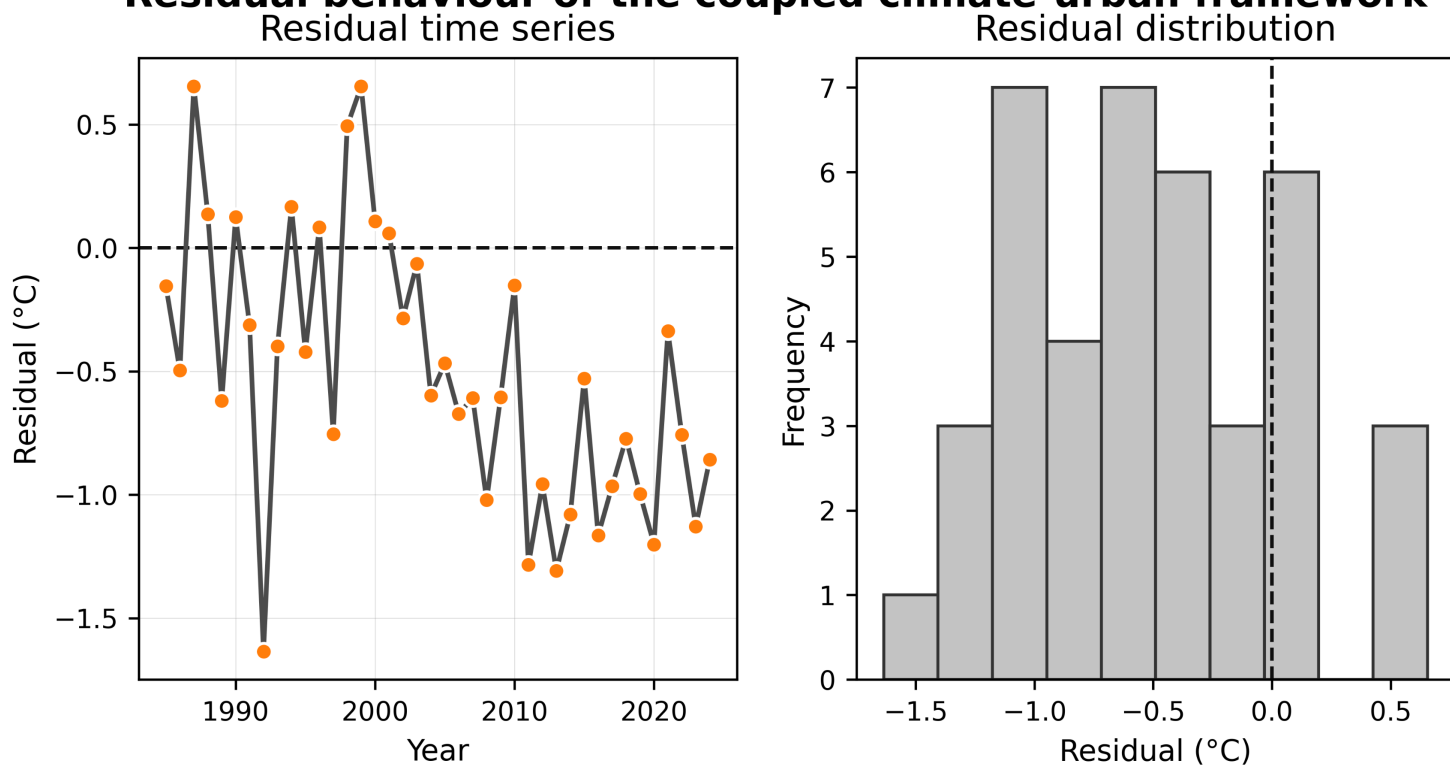


**Figure 4**

Residual analysis of the coupled climate-urban attribution framework. The residual time series and distribution provide a diagnostic assessment of remaining discrepancies between observations and simulations.

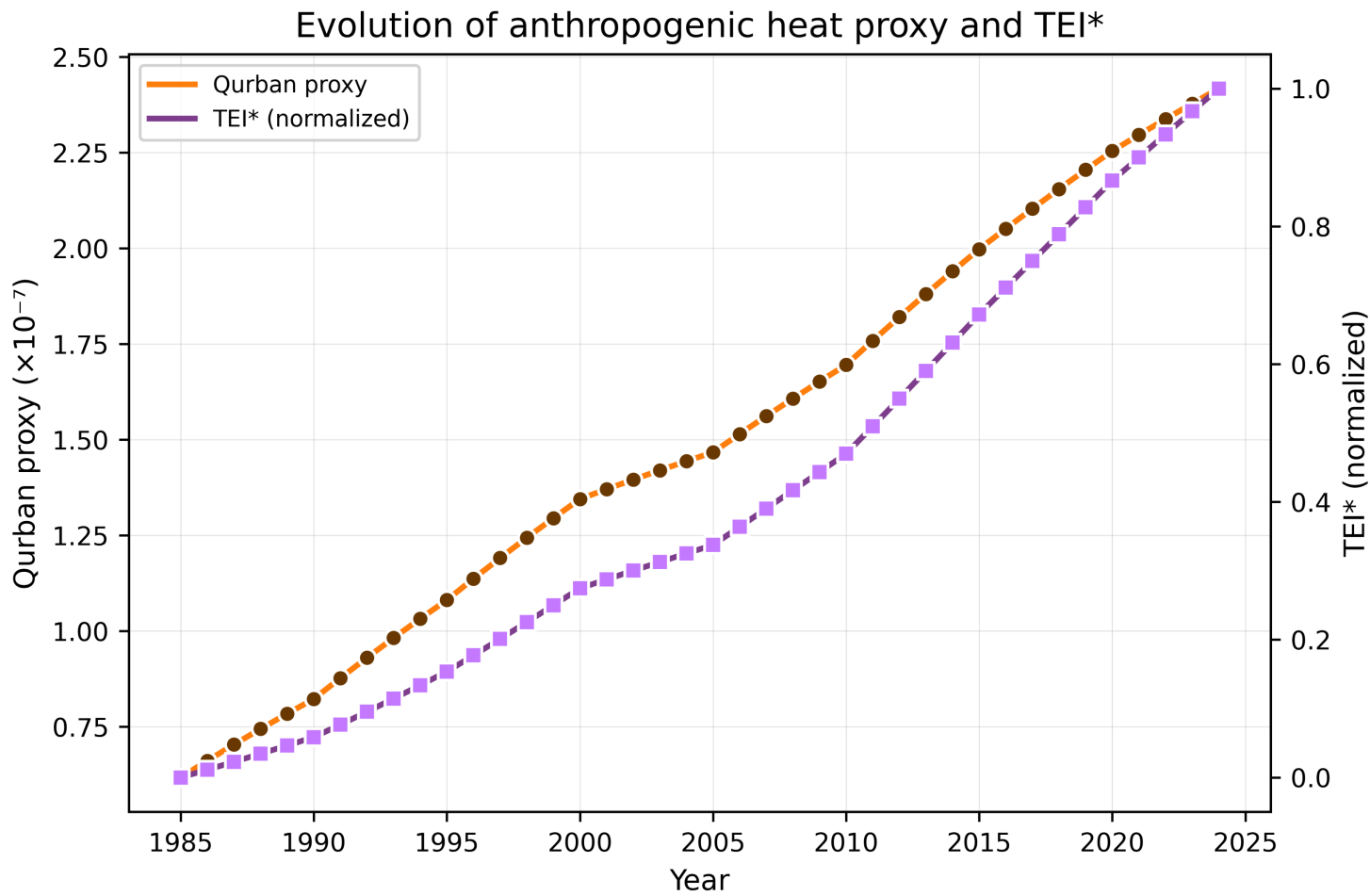


**Figure 5**

Long-term evolution of the anthropogenic heat proxy and TEI\*. Data markers are shown in colours distinct from their lines to emphasise the annual values used in the attribution framework.

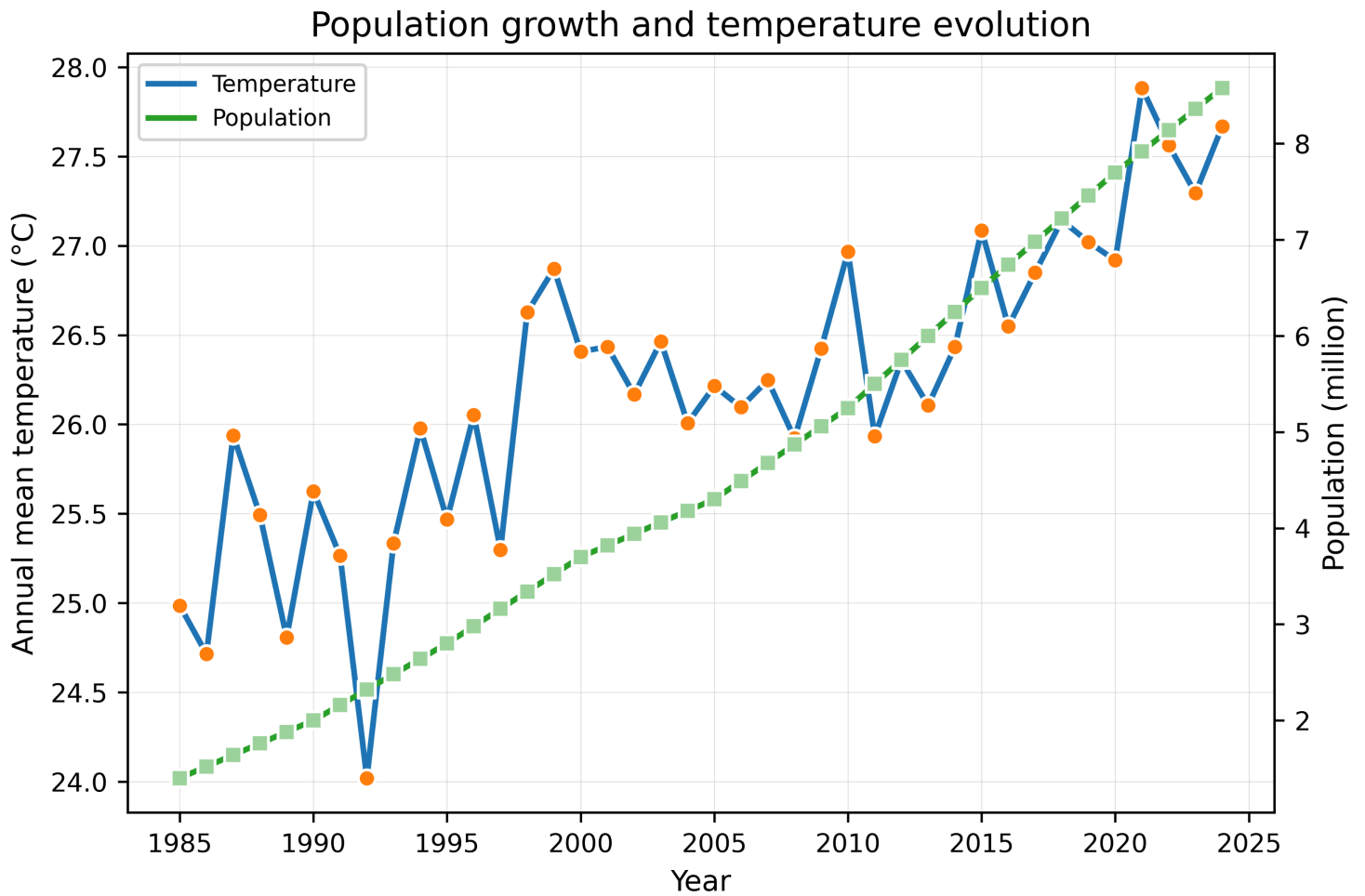


**Figure 6**

Co-evolution of population growth and annual mean temperature in Riyadh. The dual-axis representation highlights the demographic context in which urban thermal amplification developed during 1985-2024.

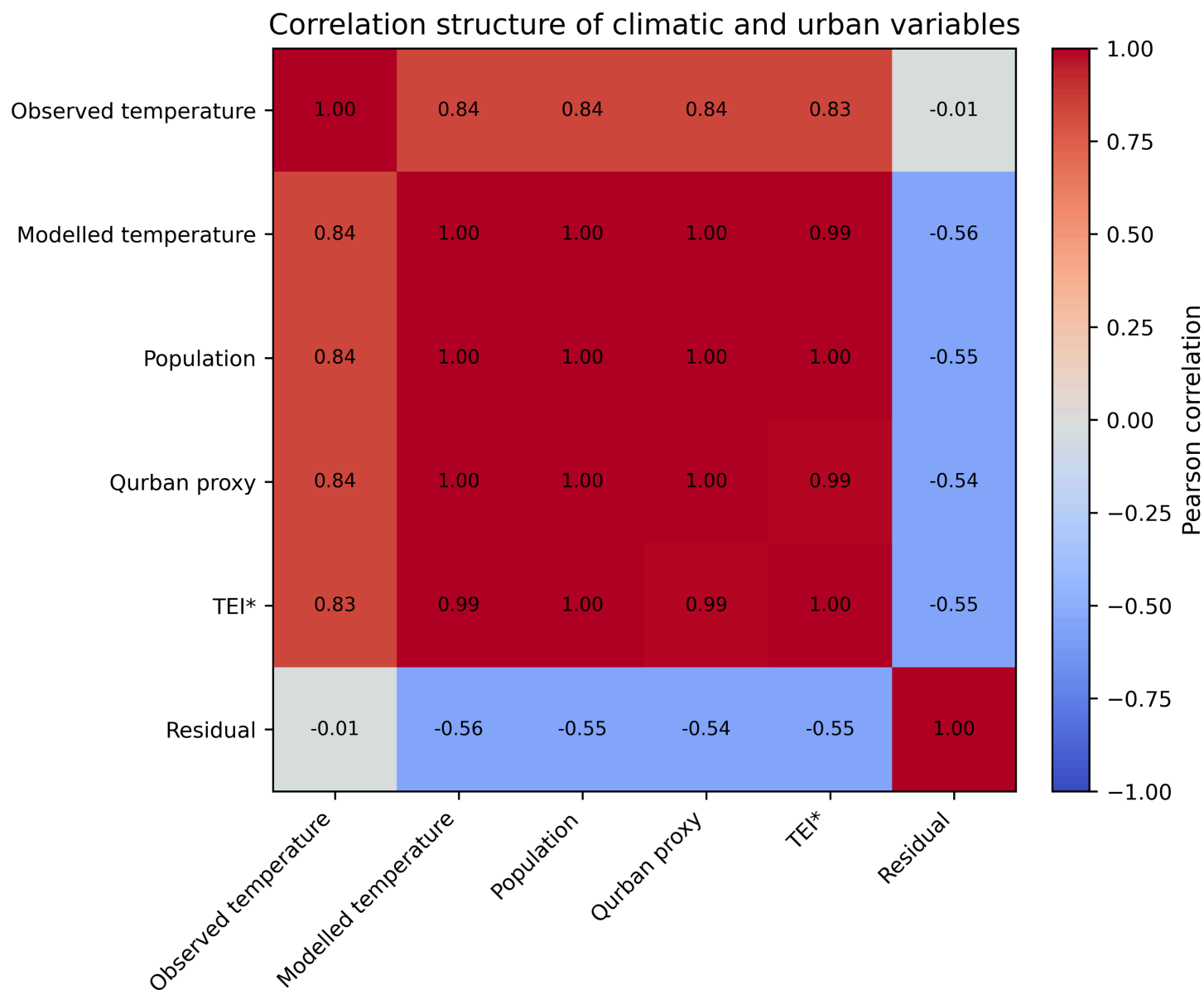


**Figure 7**

Correlation structure among the principal climatic and urban variables. The matrix summarises relationships among observed temperature, modelled temperature, population, anthropogenic heat proxy, TEI\*, and residual variability.

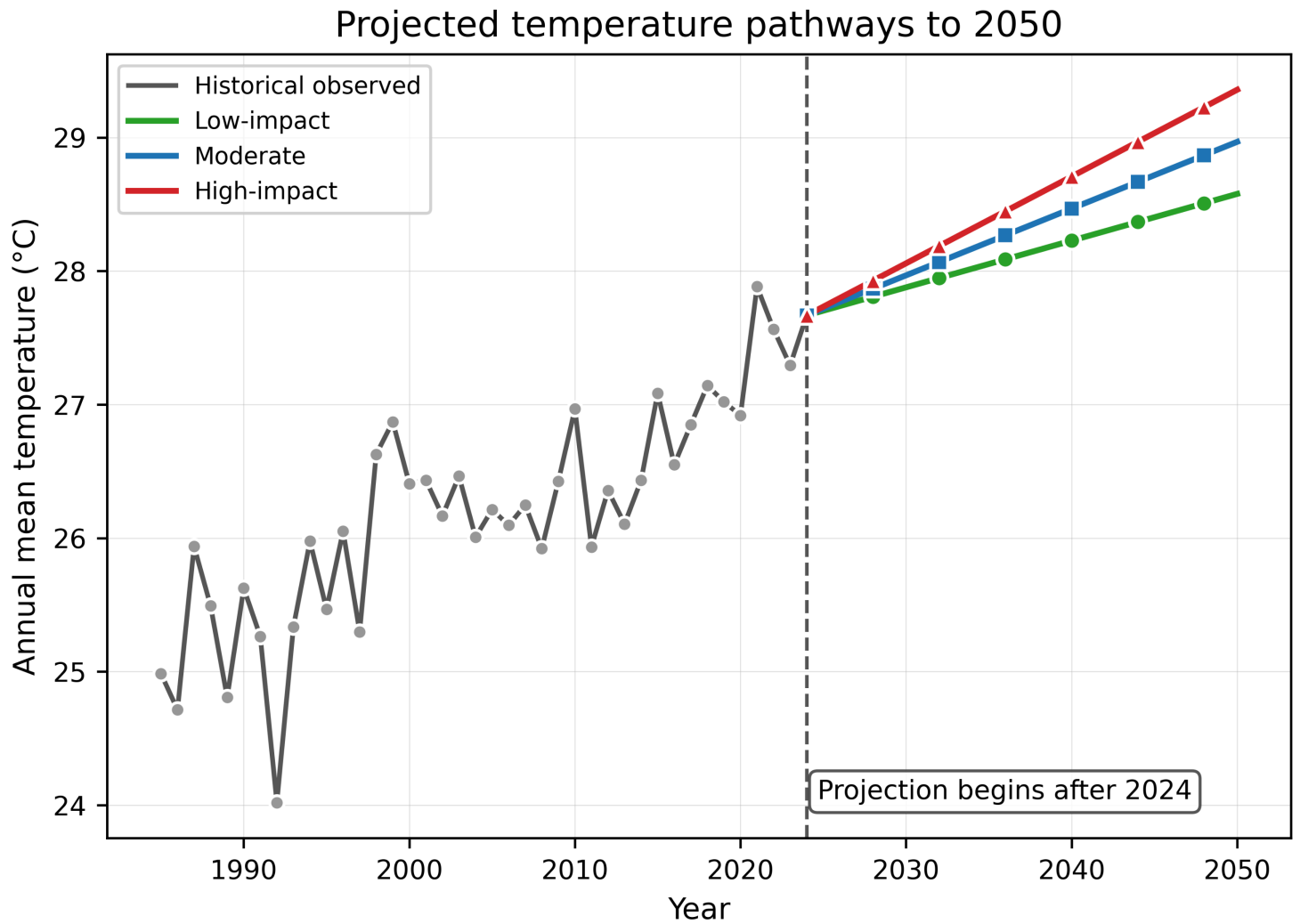


**Figure 8**

Projected temperature evolution in Riyadh under low-impact, moderate, and high-impact urban development pathways to 2050. Scenario divergence after 2024 reflects the increasing role of anthropogenic heat release and population-density coupling under different urban growth assumptions.

## Graphical synthesis of the proposed attribution workflow

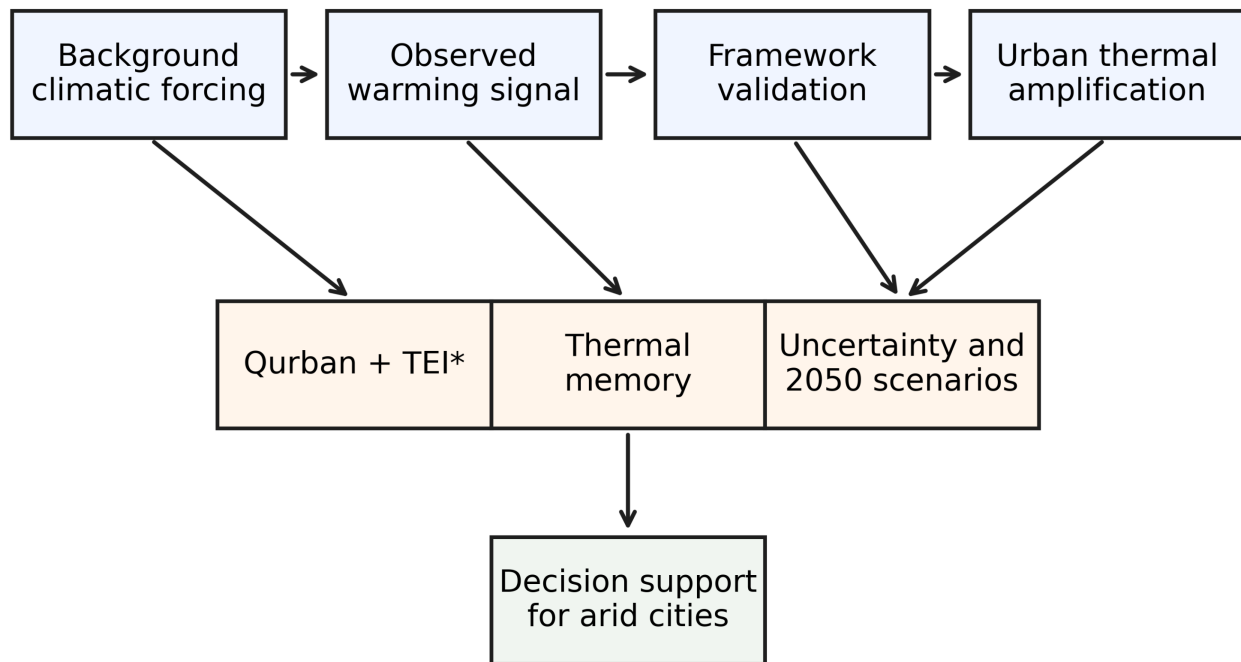


**Figure 9**

Graphical abstract of the proposed attribution workflow. The figure summarises how observations, urban drivers, validation, and future scenarios are integrated to support physically interpretable urban climate attribution and decision support.