

Thermodynamic Evaluation of Atmospheric Thermal Energy Based on Climatic Data in Kirkuk City, Iraq

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Abstract

The thermodynamic behavior of the atmosphere is important for understanding climatic stress and sustainability in arid and semi-arid regions. This paper presents a thermodynamic analysis of atmospheric thermal energy in Kirkuk City, Iraq, using observed climatic data from 2016 to 2025. A physically based thermodynamic model was implemented by incorporating a composite thermal energy index comprising sensible heat, latent heat related to atmospheric moisture, and cooling due to rainfall. The index was calculated based on the fundamental principles of thermodynamics, incorporating maximum air temperature, relative humidity, atmospheric pressure, and rainfall. The findings reveal significant interannual variations in atmospheric thermal energy, reflecting a combination of temperature extremes, moisture availability, and precipitation patterns. Higher thermal energy was recorded in years with high temperatures and low rainfall, suggesting that more heat is retained in the atmosphere and that thermal stress is intensified. Conversely, years with greater rainfall exhibited lower thermal energy, owing to enhanced cooling effects and improved heat balance in the atmosphere. The results demonstrate that thermodynamic indicators provide a robust framework for evaluating climatic sustainability, as they capture the physical nature of energy exchange processes in the atmosphere. The proposed method offers a useful resource for assessing thermal stress, informing climate adaptation policies, and supporting sustainable urban and environmental planning in Kirkuk City and other regions with similar climatic characteristics.

Keywords: *Climatic data; Latent heat; Sensible heat; Thermal energy index; Thermodynamics*

1. Introduction

The thermal environment of the atmosphere plays a critical role in determining regional climate behaviour, environmental sustainability, and human well-being in arid and semi-arid areas [1–3]. The rapid change of climatic conditions, rising temperatures, and shifting precipitation patterns have been intensifying heat stress in many cities, posing well-documented challenges to public health, energy consumption, water availability, and ecosystem stability [4]. It is therefore necessary to understand the physical processes that govern atmospheric heat energy in order to assess climatic sustainability and develop effective adaptation strategies [5]. Conventional climate measurements rely primarily on air temperature, but these approaches do not fully account for the thermodynamic complexity of the atmosphere, where moisture content, latent heat cycles, and the cooling effects of precipitation exert a significant influence on the thermal regime [6]. From a thermodynamic perspective, the thermal state of the atmosphere is determined by the balance among sensible heat, latent heat involving water vapour, and energy exchanges driven by hydrometeorological processes [7]. Relative humidity governs the quantity of latent energy in the atmosphere, while precipitation provides a pathway for heat loss through evaporation and convective cooling [8]. Atmospheric pressure

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also exerts an indirect influence on thermal energy storage, air density, and moisture capacity [9]. Failure to consider these mutually reinforcing processes can yield incomplete or misleading assessments of climatic conditions, particularly in environments characterized by extreme temperatures and irregular rainfall [10]. Thermodynamic energy methods therefore offer a more physically meaningful indicator for evaluating atmospheric thermal energy than purely statistical or temperature-specific indices [11–13].

This paper addresses this gap by formulating and implementing a physically based atmospheric thermal energy assessment model incorporating essential climatic parameters: air temperature, relative humidity, precipitation, and atmospheric pressure. The study provides a comprehensive evaluation of the atmospheric thermal behaviour of Kirkuk City during the period 2016–2025 by integrating sensible heat, latent heat, and rainfall-induced cooling into a single thermodynamic thermal index. The proposed methodology goes beyond conventional descriptive analysis and offers a physically grounded indicator capable of capturing interannual thermal variability and its implications for climatic sustainability. The research also contributes to the broader understanding of atmospheric thermodynamics in dry urban environments and supports climate-resilient planning and sustainable environmental management. By linking thermodynamic processes to climatic sustainability, this study provides a robust framework that can be generalized to other settings facing intensifying thermal forces under contemporary climate change.

2. Study Location

Kirkuk City, Iraq, is particularly susceptible to climatic variability owing to its continental climate, frequent heat waves, and fluctuating precipitation patterns. The combination of high temperatures, variable humidity, and intermittent rainfall makes Kirkuk a representative case study for atmospheric thermal energy analysis. The ongoing expansion of urban areas, population growth, and rising energy demand further amplify the effects of thermal stress, underscoring the need for robust tools capable of assessing the climatic sustainability of such urban environments.

Although climate research in Iraq has been growing, there remains a limited body of work that combines thermodynamic principles with long-term climatic observations. Figure 1 shows the location of the study area, Kirkuk City.

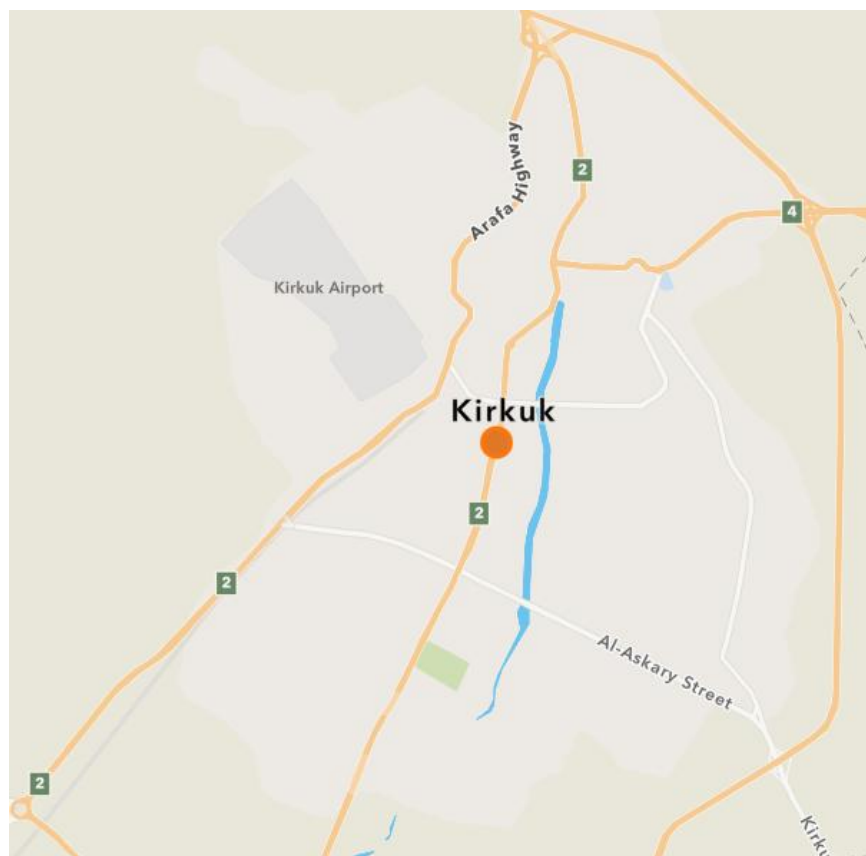
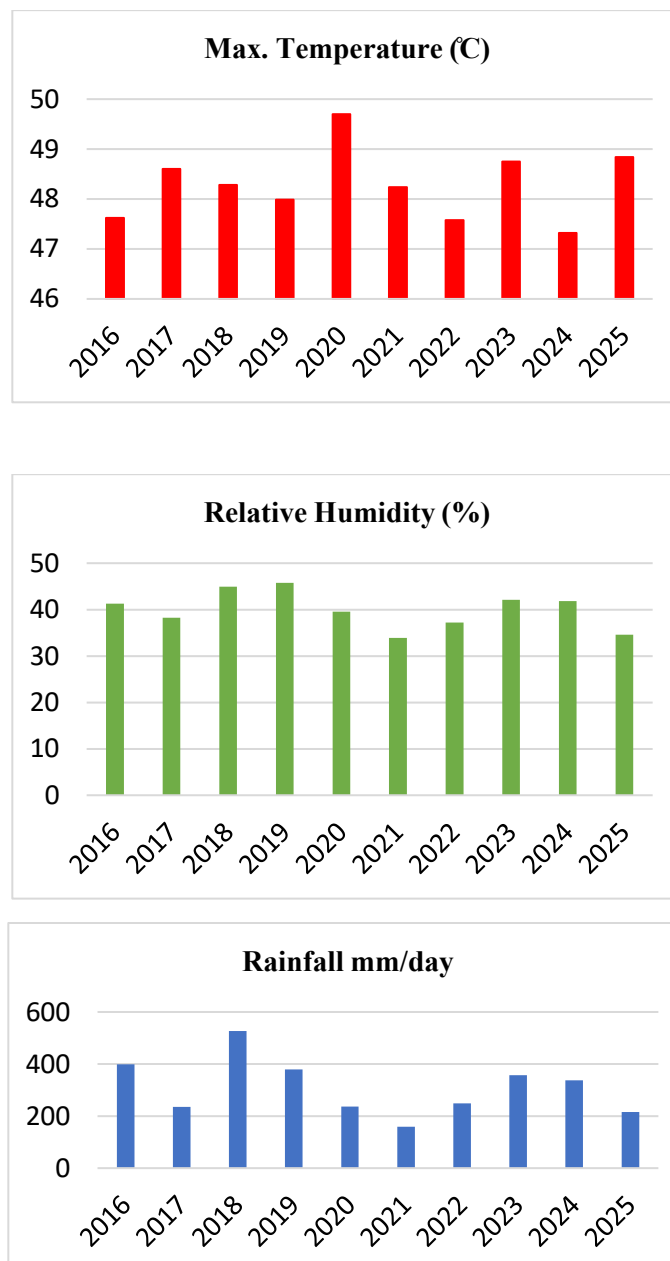


Figure 1. Location of the study area, Kirkuk City, Iraq.

3. Materials and Methods

In this study, long-term climatic records were used to assess the atmospheric thermal energy of Kirkuk City, Iraq, using a thermodynamic framework. Annual weather data for the years 2016 to 2025 were obtained from the NASA POWER Data Access Viewer (DAV), a publicly accessible meteorological database that provides climatic data based on observational records and reanalysis products. These data integrate ground-based meteorological station measurements, satellite observations, and atmospheric model outputs to ensure consistency and quality. The selected variables — maximum air temperature ($^{\circ}\text{C}$), relative humidity (%), rainfall (mm day^{-1}), and atmospheric pressure (kPa) — represent the principal thermodynamic drivers governing heat and energy exchange in the atmosphere.

Prior to analysis, the collected data were organized into a unified database and subjected to a basic screening procedure to ensure completeness and consistency. Annual representative values were computed to smooth short-term fluctuations and to focus the analysis on interannual variations in thermal conditions. Figure 2 presents the annual climatic data used in this study.



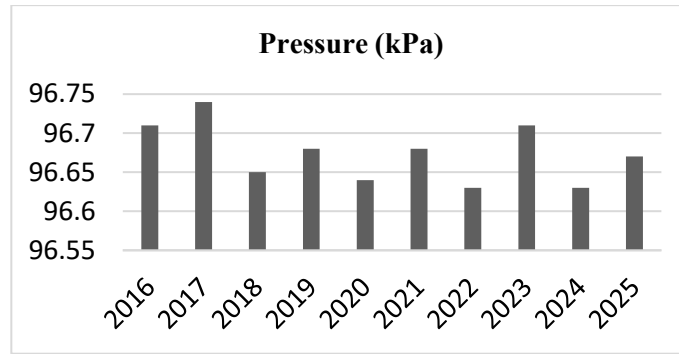


Figure 2. Annual climatic data used in the study.

A thermodynamic framework was adopted to quantify atmospheric thermal energy by summing sensible heat, latent heat, and the cooling effect of rainfall. Sensible heat was calculated using the specific heat capacity of air at constant pressure applied to the air temperature and representative air mass. Latent heat associated with atmospheric moisture was estimated using the latent heat of vaporization and the water vapour mixing ratio. The mixing ratio was calculated from the actual vapour pressure and atmospheric pressure, where saturation vapour pressure was estimated using an exponential temperature-dependent formulation and actual vapour pressure was derived from relative humidity. A proportional coefficient was applied to include the rainfall cooling term, representing evaporative and convective heat loss. These components were combined into a single composite indicator — the Thermodynamic Thermal Index (TI) — expressed in energy per unit mass (kJ kg^{-1}). This physically based methodology enables a comprehensive assessment of the atmospheric thermal state and provides a robust framework for evaluating climatic sustainability in arid cities.

Atmospheric thermal energy was quantified within a thermodynamic framework by summing sensible heat, latent heat, and the cooling effect of rainfall. The governing equation is:

$$TI = C_p T + L_v q - \alpha R \quad (1)$$

where TI is the thermodynamic thermal index (kJ kg^{-1}), T is the maximum air temperature ($^{\circ}\text{C}$), q is the water vapour mixing ratio, R is rainfall (mm day^{-1}), and α is the rainfall cooling coefficient [14]. C_p is the specific heat capacity of air at constant pressure [15], and L_v is the latent heat of vaporization [16]:

$$C_p = 1.005 \text{ kJ kg}^{-1} \text{ K}^{-1} \quad (2)$$

$$L_v = 2501 \text{ kJ kg}^{-1} \quad (3)$$

The actual vapour pressure e (kPa) is calculated from relative humidity RH and saturation vapour pressure e_s [17]:

$$e = (RH / 100) \times e_s \quad (4)$$

Saturation vapour pressure is estimated as a function of temperature [18]:

$$e_s = 0.6112 \exp(17.67T / (T + 243.5)) \quad (5)$$

Sensible heat energy H_s is calculated as [19]:

$$H_s = C_p T \quad (6)$$

These equations form the thermodynamic foundation of the atmospheric thermal energy assessment and enable a physically meaningful evaluation of the climatic conditions and sustainability of Kirkuk City.

4. Results and Discussion

The results of the study are presented in Table 1. The thermodynamic thermal index (TI) was calculated for each year from 2016 to 2025.

Table 1. Thermodynamic Thermal Index (TI) results for Kirkuk City, 2016–2025.

Year	Thermal Energy TI (kJ kg^{-1})
2016	84.62
2017	99.80
2018	82.62
2019	97.46
2020	108.20
2021	97.02
2022	91.61
2023	96.46
2024	90.37
2025	95.52

The findings demonstrate that maximum temperature alone is not the principal determinant of atmospheric thermal energy in Kirkuk; rather, atmospheric thermal energy is also substantially governed by water vapour content (humidity) and the cooling effect of rainfall. The highest thermal energy value was recorded in 2020, attributable to elevated temperatures combined with relatively low rainfall, which reduced rain-induced cooling and amplified both sensible and latent energy. Conversely, 2018 recorded the lowest thermal energy, despite high temperatures, because of significantly increased rainfall that led to substantial heat loss through evaporative and convective cooling.

Table 2. Proposed classification of thermal regime based on TI values.

Thermal Energy (kJ kg^{-1})	Climatic Condition
< 90	Low thermal loading
90 – 100	Moderate thermal loading
> 100	High thermal loading

The atmospheric thermal energy is classified into three categories — low, moderate, and high thermal loading — based on the computed TI values for Kirkuk City over the period 2016–2025. The TI integrates sensible heat, atmospheric latent heat, and rainfall-induced cooling, providing a holistic measure of atmospheric thermal energy per unit mass of air (kJ kg^{-1}). The classification thresholds were determined through analysis of the range of TI values in the dataset. Values below 90 kJ kg^{-1} represent relatively low thermal energy, indicating cooler conditions and reduced thermal stress. The intermediate range of $90\text{--}100 \text{ kJ kg}^{-1}$ signifies moderate thermal loading, reflecting a balanced atmospheric state. Values exceeding 100 kJ kg^{-1} indicate high atmospheric thermal energy with the potential to cause heat stress on human comfort, urban infrastructure, and environmental sustainability. This classification is directly grounded in the calculated thermodynamic energy values, captures interannual variability, and provides an interpretable basis for evaluating climatic sustainability. The thresholds may be adjusted for application in other regions or datasets, provided the connection between thermal energy magnitude and environmental impact is preserved.

5. Conclusion

This paper has presented a thermodynamic assessment of atmospheric thermal energy in Kirkuk City, Iraq, using climatic data from 2016 to 2025. Through a physically based thermodynamic approach, atmospheric thermal energy was quantified using a composite measure of sensible heat, latent heat associated with atmospheric moisture, and

rainfall-induced cooling effects. The thermodynamic thermal index (TI) proved effective in capturing interannual variations in atmospheric thermal conditions, offering a more comprehensive account of the local thermal environment than temperature-based metrics alone. The results show that years with high air temperatures and low rainfall recorded elevated thermal energy values, implying increased thermal stress and reduced climatic sustainability. Conversely, years with greater precipitation exhibited lower thermal energy values, demonstrating the significance of rainfall cooling and moisture-based thermodynamic processes in moderating atmospheric heat. These findings underscore the necessity of incorporating humidity and precipitation into thermal environment assessments, particularly in arid and semi-arid regions where climate variability exerts a pronounced impact on human and environmental systems. Elevated atmospheric thermal energy in Kirkuk City poses implications for urban thermal comfort, public health, water resources, and energy demand. The thermodynamic index introduced in this paper constitutes a practical thermal stress assessment tool that can support climate-resilient urban planning and environmental management. Its physical basis enables direct application in sustainability assessments and climate adaptation strategies. Future studies should expand this model by incorporating additional thermodynamic drivers — such as solar radiation, wind velocity, and surface characteristics — to enhance model realism. Spatial resolution and temporal granularity (e.g., monthly or seasonal analysis) could be improved through integration with remote sensing data. Furthermore, it is recommended to compare the thermal index with established human heat stress indicators and energy consumption records to strengthen its application in sustainability and climate adaptation planning for rapidly warming cities.

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