Evaluating Summer Neutral Temperature and Land Surface Temperature Trends Over Three Decades in Tetuan, Morocco Using Thermal Comfort Questionnaires

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Abstract. This study investigates the evolution of summer neutral temperatures and land surface temperature (LST) trends in Tetuan, Morocco, over three decades using data from thermal comfort questionnaires. Integrating subjective assessments with objective temperature data, we identify significant shifts in neutral temperatures influenced by climate change. Analysis of thermal sensation votes from 423 respondents relative to recorded temperatures has allowed for the development of neutral temperature thresholds. These findings contribute to a comprehensive model of urban thermal dynamics, highlighting the impact of temperature variability on urban planning and public health strategies. The unique juxtaposition of subjective thermal perceptions and objective data not only maps the adaptability of urban populations to changing climates but also aids in formulating strategies to enhance thermal comfort in Mediterranean urban settings.

1 Introduction

Thermal comfort is a complex sensation deeply influenced by climatic conditions and is crucial for human health and well-being in outdoor spaces[1]. Individuals in these environments are directly exposed to meteorological elements without the benefits of temperature-modifying devices such as canopies or air conditioning systems. Consequently, they are more susceptible to thermal stress, leading to various discomfort-related issues[2]. Thermal comfort, defined as a state of mental contentment with one's thermal environment[3], has become a critical consideration in urban design due to its direct impact on the quality of urban spaces and, consequently, on public health, space utilization, and social interactions[4]. In the study of thermal comfort, the 'neutral' state is recognized as the optimal condition where individuals neither feel excessively hot nor uncomfortably cold[5], [6].

Recent global research on outdoor thermal comfort has focused on assessing the local populations' thermal sensations, typically represented through the concept of neutral

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temperature. Despite its widespread use, the results often show subtle variations across different regions, an aspect that is frequently overlooked[2].
Thermal comfort research has evolved to address the complexity and variability of human sensations in outdoor environments, with studies increasingly recognizing the need for context-specific assessments.
Multiple studies underscore the importance of tailoring thermal comfort evaluations to local climatic and environmental characteristics. Some have developed new thermal comfort indices that address the limitations of traditional indices under diverse conditions[7], while others have utilized various indices to demonstrate how different urban spaces require unique thermal benchmarks [8]. Collectively, these studies reinforce the necessity of adopting context-specific approaches in thermal comfort research.

Given the observed variations in thermal comfort responses across different regions and climates, this study is particularly pertinent. Few studies have explored these dynamics within Africa[9], and our research focuses on Tetuan, a Mediterranean city in northern Morocco. This geographical focus is crucial as it addresses a significant gap in the existing literature on thermal comfort in African Mediterranean climates and aims to inform effective urban planning and public health strategies. Notably, according to discussions at COP26, although developing African countries contribute minimally to climate change, they are disproportionately affected by severe environmental conditions[10].
Climate change is one of the most pressing challenges of the 21st century, engendering profound social, environmental, and economic impacts[11]. As urbanization intensifies worldwide, natural landscapes are increasingly giving way to impermeable surfaces, altering the urban thermal environment significantly. Land Surface Temperature (LST) plays a pivotal role in evaluating surface warming within these urban thermal systems[12]. By integrating data on land surface temperatures with region-specific neutral temperatures, a more nuanced understanding emerges. This approach provides tailored assessments that reflect the unique characteristics of the local population, enhancing the precision of thermal comfort evaluations. This study aims to calculate the Summer Neutral Temperature for Tetuan, providing crucial insights into the thermal sensations specific to the local population. By understanding these thermal preferences, urban designers can make more informed decisions when planning and developing urban spaces, thereby enhancing outdoor comfort and promoting the well-being of city residents. Research on outdoor thermal comfort has demonstrated that tailored interventions, such as the incorporation of green infrastructure and climate-responsive materials, can significantly mitigate heat stress and improve urban livability[13]. Furthermore, the findings of thermal comfort studies carry significant implications for policymakers, urban planners, and public health officials. Translating research insights into actionable strategies—such as optimizing public space designs, increasing vegetation coverage, and implementing heat-mitigation policies—can make urban areas more climate-resilient and adaptive to the changing environments[14].

2 Materials and Methods

2.1 Study Area Description

Tetuan is located in north-central Morocco, on a rocky plateau just 11 kilometers from the Mediterranean Sea and at the foot of Mount Dersa. The city's geographical coordinates are approximately 35.5889° N and 5.3626° W. Feddan Park, selected for its central location within the ancient medina, is an important urban space for our research.

Tetuan's Mediterranean climate (CSA) is distinguished by mild, wet winters and hot, dry summers, which are typical of coastal North African cities. This climate has a significant impact on the region's thermal comfort studies, particularly how urban residents experience heat and cold.

Fig. 1. Study area: Tetuan city

The city's historical layout, which includes dense building structures and few green spaces such as Feddan Park, has a significant impact on the local microclimate and residents' perceptions of thermal comfort. These urban characteristics are critical to understanding the thermal dynamics in Tetuan's city center.

2.2 Survey Methodology

The survey took place over the entire month of August 2022. In total, 423 questionnaires were administered to randomly selected individuals, ensuring a diverse representation of the population.

2.3 Data Collection

Weather data for the study was meticulously gathered from Wunderground, specifically from the Saniat Ramel Airport Station, which provided detailed meteorological records for both the survey dates and the previous three decades. Temperature, humidity, wind speed, and other factors influencing thermal comfort were among the data collected.

Significant fluctuations in the diurnal temperature range (DTR) and temperature anomalies have been observed in recent decades, posing significant physiological challenges to diverse biota and having a direct impact on human thermal comfort[15].

These variations highlight the critical need to understand both spatial and temporal aspects of DTR, as they play an important role in assessing temperature-induced stress and its broader implications for human health and well-being. To address these issues comprehensively, our study uses Land Surface Temperature (LST) data from NASA's Terra and Aqua satellites' Moderate Resolution Imaging Spectroradiometers (MODIS). MODIS's global coverage and ability to capture twice-daily images provide critical observational data, yielding profound insights into terrestrial changes that affect Earth's ecosystems[16]. This long-term perspective is critical for understanding how sustained changes in temperature patterns over three decades shaped not only environmental and biological responses, but also the thermal comfort levels of urban populations. Our analysis aims to identify the effects of these temperature shifts on urban thermal comfort, informing strategies for mitigating negative effects and improving livability in changing climates.

2.4 Questionnaire Design

The questionnaire was designed to collect personal and environmental data. The survey's core focus was on thermal sensation, with thermal comfort assessed using the ASHRAE[3] seven-point scale. This scale ranges from -3 (cold) to +3 (hot). The responses gathered, known as Thermal Sensation Votes (TSVs), included:

-3 means cold, while -2 means cool.
-1: slightly cool.
0: Comfortable.
1. Slightly warm.
2: Warm.
3: Hot.

This method enabled precise quantification of respondents' thermal sensations and provided a robust dataset for assessing the adequacy of existing neutral temperature thresholds in the context of Tetuan's unique climatic conditions.

2.5 Analytical Methods

This study used a variety of advanced analytical methods to investigate the complex dynamics of thermal comfort in Tetuan, Morocco. Statistical regression analysis was critical in establishing correlations between perceived thermal comfort, measured using ASHRAE's seven-point scale from questionnaire responses, and objective temperature measurements from air and MODIS-derived land surface temperatures. Time series analysis allowed for an examination of long-term temperature trends spanning three decades, providing insights into seasonal and decadal patterns. Geospatial techniques were used to map and visualize the spatial distribution of temperature anomalies, highlighting thermal stress points in urban environments. Furthermore, descriptive statistics provided a fundamental summary of the data, allowing for a clear representation of central tendencies and variability in thermal sensations and temperatures.
Together, these methods provided a comprehensive framework for understanding the effects of urban temperature changes on human comfort levels, allowing for more informed urban planning and public health strategies.

3 Results

This section presents the findings from a comprehensive analysis of thermal comfort trends in Tetuan, Morocco, based on data meticulously collected over three pivotal decades. Each three-year set—2000 to 2002, 2010 to 2012, and 2020 to 2022—provides a snapshot of the evolving climate and its implications on urban thermal environments and human comfort. Weather data for the entire month of August each year was sourced from Wunderground, specifically from the Saniat Ramel Airport Station, ensuring consistent and reliable meteorological insights. Additionally, land surface temperature data were obtained from MODIS, allowing for a deeper understanding of surface heat dynamics.

The combination of these robust datasets enables an intricate exploration of how shifts in diurnal temperature range and other climatic factors have impacted thermal comfort in Tetuan across thirty years. The findings underscore the nuanced ways in which local temperatures have responded to broader environmental changes, with significant implications for urban planning and public health strategies. The following sections detail these trends, providing a clear view of the thermal comfort landscape as it has evolved over the study period.

Initially, the thermal comfort range was established from responses collected through detailed questionnaires, defining a tailored comfort zone based on local perceptions.

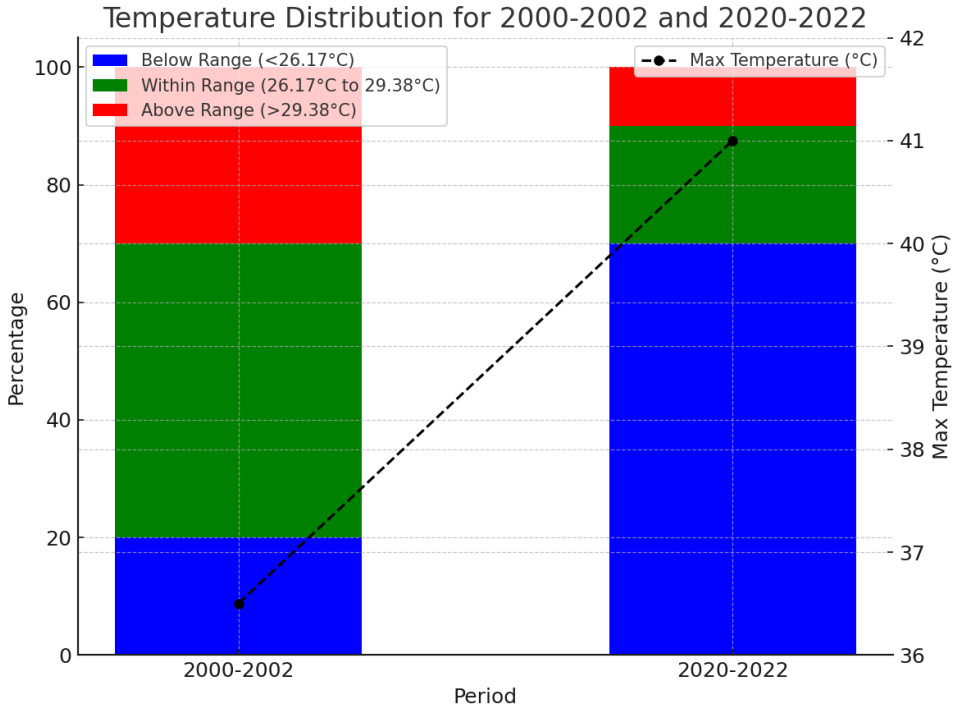

Fig. 2. Analysis of Temperature Extremes and Comfort Zones in Tetuan, 2000-2022

The calculated thermal comfort range, determined to be from 26.17°C to 29.38°C, reflects the temperature band within which the majority of the local population reported optimal comfort. Subsequent analysis of historical temperature data, juxtaposed with these newly established comfort thresholds, led to the creation of Figure 1. This figure reflects the distribution and frequency of days falling within, above, and below the established comfort range over the last three decades, highlighting shifts in temperature patterns and their alignment with human thermal comfort levels. The visualization offers a clear perspective on the changing dynamics of thermal comfort in Tetuan, illustrating how increasingly frequent temperature deviations from this range pose challenges for urban living and public health.

To investigate the evolution of extreme temperature days in August, we examined the

number of days exceeding 30°C, 35°C, and 40°C over three time periods: 2000-2002, 2010-2012, and 2020-2022 as seen in Table 1. The data collected for each period provided information about the frequency and changes in these extreme temperature events over time.

Google Earth Engine was used to calculate average August temperatures in Tetuan, Morocco, using Python code for the years 2000-2002, 2010-2012, and 2020-2022. The code filters data from the MODIS LST dataset (MOD11A2), which contains 8-day composite images, with a focus on the month of August for each selected year.
The code uses a mean function to calculate the average Land Surface Temperature (LST) across all available images during this time period, yielding an aggregated monthly average. Temperatures are initially recorded in Kelvin and then converted to Celsius for practical use.
Finally, the processed data is exported as GeoTIFF files to Google Drive, covering a 5 km radius around Tetuan, allowing for further analysis of temperature trends over the years.

Table 1. Decadal Comparison of Days Exceeding Temperature Thresholds in August for Tetuan (2000-2022)

Years	Days in August > 30°C	Days in August > 35°C	Days in August > 40°C
2000-2002	25	2	0
2010-2012	36	10	1
2020-2022	40	8	2

Fig.2. compares MODIS LST (Land Surface Temperature) data from Tetuan, Morocco, in August 2012 and August 2022. The different colors represent different temperatures, with red indicating higher temperatures and white representing cooler areas.

The comparison reveals possible changes in the region's land surface temperature over the next decade, which could be attributed to factors such as climate change, urbanization, or land use changes.

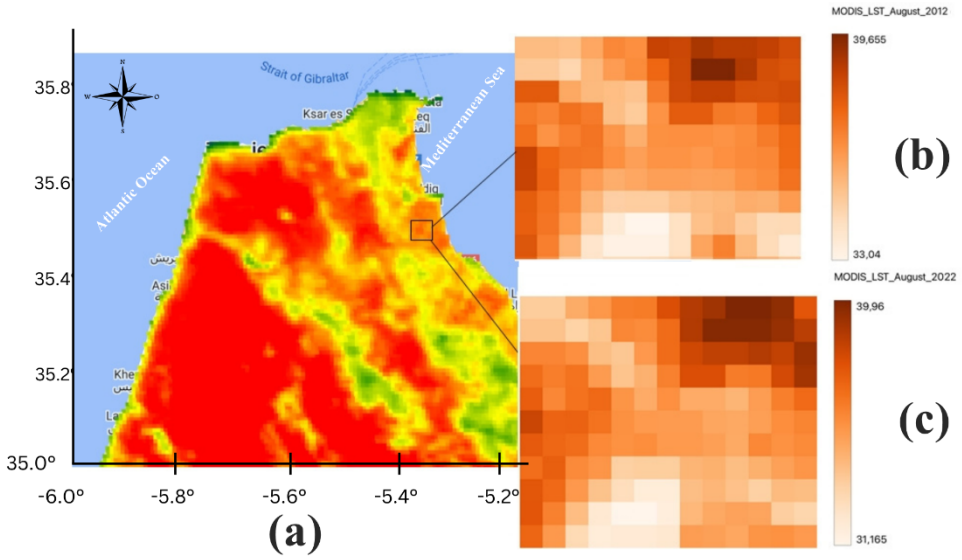

Fig. 3. Land Surface Temperature (LST) Changes in Tetuan, Morocco (2012-2022).
(a): Land surface temperature (August 2010). (b): Land surface temperature (August 2012). (c) Land surface temperature (Agust 2022).

4 Discussion

The findings of this study show a significant increase in extreme temperature events in Tetuan over the last two decades. The data show a notable increase in the number of days in August that exceed various temperature thresholds. Specifically, the number of days above 30°C increased from 25 in 2000-2002 to 40 in 2020-2022. This trend suggests that the frequency of higher temperatures will increase significantly. Similarly, days exceeding 35°C increased from 2 days in 2000-2002 to 8 days in 2020-2022, while days exceeding 40°C increased from zero to 2 days over the same period.

These changes indicate a larger warming pattern that contributes to a shift in the local thermal comfort zone, which is becoming less common. The established thermal comfort range of 26.17°C to 29.38°C is now less frequently encountered, indicating that residents are experiencing increased discomfort as temperatures rise.
The MODIS LST data supports these observations by indicating potential changes in land surface temperature, which are most likely driven by urbanization and climate change. The rise in extreme temperature days raises serious public health concerns, particularly among vulnerable populations like the elderly and young children, who are more susceptible to severe heat-related illnesses.

The long-term impacts of temperature shifts on public health are a growing concern, particularly as climate variability continues to exacerbate extreme heat events. Research

by Shi et al. [17] highlights how exposure to high temperatures can significantly impact physiological health markers, including sleep quality and cognitive performance, which are critical components of overall well-being. These findings emphasize the need for urban environments that minimize heat stress to reduce health risks, especially for vulnerable populations. In response to these challenges, urban planning strategies must evolve to prioritize thermal comfort. For example, Mandic et al.[18] propose the use of adaptive design strategies, such as increasing shading, utilizing reflective materials, and optimizing urban geometry, to create cooler and more comfortable public spaces. Moreover, Zhang et al.'s study [19] suggests that designing urban areas with diverse thermal comfort needs in mind can improve usability and public health outcomes, demonstrating the importance of context-specific solutions. Collectively, these studies highlight how important it is to incorporate public health concerns into urban planning in order to improve climate change resilience.

5 Conclusion

This study found a clear and concerning trend of increasing extreme temperature events in Tetuan over the last two decades. The data show a significant increase in the number of days in August that exceed 30°C, 35°C, and 40°C, indicating a broader warming trend that contributes to a shift away from the established thermal comfort zone. This shift causes increased discomfort for residents and poses serious public health risks, especially for vulnerable groups.

The findings highlight the critical need for adaptive urban planning and climate change strategies to mitigate the effects of rising temperatures. Effective measures, such as incorporating green infrastructure and reflective surfaces, are required to mitigate the urban heat island effect and improve thermal comfort. Furthermore, addressing the underlying causes of climate change through emissions reductions and sustainable practices is critical for long-term resilience.
Continued research is critical for monitoring temperature trends, understanding the impact of socioeconomic factors on heat vulnerability, and developing novel adaptation strategies. By implementing these insights and strategies, Tetuan will be able to better adapt to the challenges posed by climate change, protect public health, and ensure sustainable urban development. This comprehensive approach will be critical for increasing resilience and quality of life in the face of rising temperatures.

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