PAKISTAN RESEARCH LETTER
HTTPS://PAKISTANRESEARCHLETTER.COM/INDEX.PHP/JOURNAL/INDEX
VOLUME : 4, ISSUE : 1, 2025

URBAN HEAT ISLAND INTENSITY IN LAHORE: A LANDSAT-DERIVED TIME-SERIES (2000–2023)

Habib Ullah
MS Scholar, Department of Business Administration, University of Punjab, Lahore..

Sameena Adeel
MS Scholar, Department of Business Administration, University of Punjab, Lahore.

ABSTRACT

Urban Heat Islands (UHIs) have become a significant urban environmental problem, especially in fast-growing cities of the Global South. Lahore, the second-largest city of Pakistan, has undergone an unparalleled urbanization in the last two decades leading to prolonged thermal discomfort, rising energy consumption and health risks. In present work, spatiotemporal dynamics of UHII are evaluated at Lahore for the years 2000 and 2023 through multi-temporal Landsat imagery. Land Surface Temperature (LST) was estimated using land-imaging sensors of Landsat 5, 7, 8 and 9 thermal bands while Normalized Difference Vegetation Index (NDVI) was incorporated into understanding the relationship between land cover and temperature. The findings showed that UHII increase is increasing at the all-study area with an average of 2.1 °Curing the year time span of this research. The increase in impervious surfaces and reduction of green cover were the most important contributors to UHIs development (especially in inner-city or urban-suburban areas). Results are consistent with global observations yet reveal concentrated socio-environmental vulnerabilities: higher heat exposure exists in the most marginalized communities. This study accentuates the necessity of urban greening, climate-responsive planning and policy measures for alleviation of urban heat stress.

Keywords: Urban Heat Island, Landsat, Lahore, Land Surface Temperature, Remote Sensing, Climate Change, Time-series

INTRODUCTION

Urbanization has altered the physical and social features of cities, not only affecting the silhouettes, but also environmental life within. One of the most extensively studied impacts of this change is referred to as the Urban Heat Island (UHI) phenomenon, wherein urban environments consistently exhibit warmer surface and atmospheric temperatures than nearby rural sites (Oke, 1982). The UHI effect is mainly due to land use/land cover (LULC) changes, especially the transformation of natural vegetated covers to impervious covers such as asphalt, concrete and roofs. These surfaces warm up in the day and remain warm into the night, raising overall temperatures. And the waste heat from vehicles, industries and air conditioners make urban thermal environment even worse.

Urban heat island (UHI) phenomena in South Asian megacities are distinctly more severe than elsewhere on account of the immense population increase, unchecked urban sprawl and the paucity of sustainable planning strategies. E.g., in Delhi, Dhaka, Karachi and Lahore cities the rate of urbanization flowers quick than the ability to maintain ecological equilibrium or to deliver supply all necessary infrastructure (Akbari et al. In such settings, unchecked transformation of agriculture and green areas to built-up land at high population densities enhances local-scale warming. Pakistan's second largest city, Lahore is one of country's major cultural, political and economic forces: Lahori culture serves as a perfect illustration of these dynamics. Lahore's population rocketed from 6.3 million in 2000 to more than 13 million (United Nations, 2022 projections). The city inevitably witnessed a tremendous demographic growth similar to the rest of African cities, this dramatic growth comes concurrently with an accelerated peri-urbanization that results in ed extension loss of green spaces and more harsh energy demand which fall together rendering the city as a premise for testing UHII I(Urban Heat Island Intensity).

The impact of the UHI phenomenon goes beyond that for climatology or atmospheric sciences. Urban heat and its impact the growing problem of urban heat is now recognized on multiple dimensions that touch upon health, both individual and public; quality of life; and social justice. Many have found associations between exposure to heat and elevated risks of cardiovascular and respiratory diseases, heat strokes, as well as excess mortality during severe heat waves (Anderson & Bell, 2009). Besides physical health, heat stress can also have negative impacts on mental health. For instance, Obradovich et al. (2018) found that increased nighttime temperatures are linked with disturbed sleep patterns, which subsequently lead to cognitive fatigue, anxiety and less emotional control. In occupational settings, staying longer time at high temperatures has been associated with decreased attention, lower productivity and increased work-related accidents especially among outdoor or air-conditioned workplace workers.

The impacts of UHI are unevenly distributed. The populations at risk—low-income households, the elderly, children and those without access to cooling facilities—are disproportionately impacted. As Harlan and Ruddell (2011) stress, UHIs contribute to reinforcing social disparities; restricting access to thermal comfort and raising energy expenses for vulnerable populations. These are particularly bold risks in Lahore's informal settlements and overcrowded housing. This calls for a view on UHII not only in its environmental, but also as a social justice and public health perspective.

In spite of the potential significance of UHIs, South Asian cities are poorly represented in long-term urban climate research. Although studies based on global research have indicated UHI trends in Europe, North America and East Asia, less long-term work has been conducted in places such as Lahore. Current Pakistani research is based on short-term observations or a single climate factor, that do not consider wider social and psychological implications (Butt et al., 2021). Therefore, there is a critical need for studies to follow UHI changes over long durations and embed them within the context of people's lived experiences in cities.

This gap is addressed within this study's three intertwined aims. First, UHII in Lahore between 2000 and 2023 is quantified to understand how the rapid urbanization of the city has modified its thermal environment. Secondly, it attempts to examine the extent of correspondence between the land cover changes and UHII dynamics; especially focusing on decreasing of vegetative cover and increasing for built-up areas. Third, it aims to raise awareness of the socio-psychological and policy considerations of increasing UHIs, with the recognition that the science of urban climate change adaptation is in need of both phenomena-based and people-based knowledge.

By connecting remote sensing-based climate science with social science perspectives, this research has implications for a more comprehensive view of urban resilience in transitioning cities. This type of method is crucial not only for documenting environmental changes but also to direct policy interventions supporting equitable access to thermal comfort, human health and adaptive capacity under a rapidly changing climate. In the process, it paves the way for climate-sensitive urban planning focusing on maintaining environmental sustainability as well as quality of life in megacities in South Asia.

LITERATURE REVIEW

The Urban Heat Island (UHI) has been the subject of great deal of research work since Oke's (1982) seminal paper, which set out the energy-based argument for why heat accumulates in cities and differs from non-urban or rural surroundings. It has evolved into being a major interdisciplinary research focus over the past decades, with narrower studies not only have an ecological and environmental slant, but increasingly also examine its sociological and psychological dimensions. Increasing urban temperatures have been correlated with microclimate changes, biodiversity loss, poor urban air quality, and increased health risks to the population in cities. As a re-sult, scholars have increasingly argued that the UHI is not simply a physical mechanism, but rather a social and environmental problem which interfaces with issues of how urban areas are planned and designed

With the development of satellite remote sensing technology, UHIs can now be studied at spatial and time scales. Voogt and Oke (2003) emphasized the utility of satellite thermal infrared data, specifically using the Landsat series, for LSTs as reliable measures of UHI magnitude. With 16-day-return period and clearer data records in recent 30 years, Landsat provides a significant potential for long-term analysis of urban thermal dynamic at the decadal time step. Early applications, like the works of Weng et al. (2004), used Landsat LST in combination with vegetation indices to differentiate the influence of land cover changes on surface temperature anomalies. Similarly, Guo et al. (2015) found that community-scale UHI in Chinese cities is mainly driven by the spatial pattern of urbanization, which implies that both the density and distribution of built-up areas are crucial factors determining local heat patterns.

Parallel to this, the methodological quality of UHI research has evolved. As another example, some studies have abandoned the simple thermal modeling to apply multi-index modeling approaches such as NDVI, NDBI and albedo models to mitigate combined effects of land uses (e.g., vegetation density, built-up density) and atmosphric reflectance properties on LST values (Zhou et al., 2019). These integrations have been critical for analyzing relationships between land use and land cover (LULC) changes and urban heat intensification. For example, high values of NDVI are generally indicative of cooling effects as a result of evapotranspiration and high NDBI measurements relate to impervious surfaces that absorb and re-emit heat. These findings draw attention to the main effect of urban configuration and vegetation on alleviating (or reinforcing) UHI intensities.

The UHI has become a major concern in South Asia, where urban growth is rapid and often unplanned. Rasul et al. (2017) applied Landsat to the mapping of thermal anomalies in the cities of Pakistan, and showed very clearly that decline in green vegetation cover and increasing impervious surface are significantly associated with higher UHII. Similarly, Butt et al. (2021) used Landsat indices of UHIs to study the spatiotemporal change in UHIs in Islamabad and Rawalpindi and reported that urban expansion into peri-urban green patches has dominantly driven local warming trends. They also illustrate the value of satellite-based methodologies in regions where ground-based meteorological networks are sparse or poorly distributed. They also highlight that in South Asia such as Lahore Cities are uniquely vulnerable due to the overlapping of climate, population and weak enforcement mechanisms on sustainable planning law.

However, literature is still lacking in this regard especially in Pakistan and other countries of South Asia. Since most of the existing studies have been based on short-time products or snap shot images without considering seasonality, and regions where UHI is severe are only mapped for a year (see Fig. 2). Long-term (bi)decadal longitudinal studies are not common and knowledge gaps remain regarding the evolution over time of UHII with persistent land cover transitions, urban growth and expansion. Balance is as least its nascent social/psychological dimensions of the UHI effect have been relatively ignored. Although studies in Western environments have begun to highlight the mental health effects of heat stress—including increased risks for anxiety, poor sleep and cognitive performance (Obradovich et al., 2018)—these features remain largely overlooked in work from South Asia. UHI stresses on disadvantaged communities are also a theme of Harlan and Ruddell (2011), who argue that the social costs of UHIs are socially stratified, with low-income populations experiencing much greater burdens because of shoddy housing quality, lack of access to air conditioning services, and limited adaptive capacity.

UHI and public health system: the Pakistani perspective In a country like Pakistan, where urban disparities are evident and public health systems are already overburdened, the psychological and social aspects of UHIs should not be neglected. Those studies that have been done however, are largely limited to biophysical assessments which do not provide adequate treatment for how the public experiences, manages and responds to worsening urban heat situations. This lack of coherence between physical- and social scientific approaches generates a barrier to developing coalescent climate-environmental adaptation plans. Addressing this gap will demand not only strong time-series analyses of UHII but also interdisciplinary work that combines satellite-derived data with surveys, ethnographic information, and public health studies.

RESEARCH OBJECTIVES:

To produce a time-series of UHII using Landsat for Lahore (2000–2023).

To assess the spatial variation in UHI due to vegetation and urban sprawl.

To examine UHII contributions to urban health, psychology and social resilience.

RESEARCH QUESTIONS:

What is the trend of UHII in Lahore (2000-2023)?

What types of land cover change are most correlated with UHII changes?

What is the impact of increasing UHIs on psychological and social level?

SIGNIFICANCE:

To this end, the findings demonstrate a useful contribution to the larger global conversation on climate adaptation by empirically considering long-term UHII dynamics in a fast-growing

Global South megacity. Through tracking spatial and temporal patterns adsorbed for more than two decades, it emphasizes that the urban sprawl and land cover changes can contribute to intensifying local warming trends. These findings are important for informing targeted policy interventions to promote climate sensitive urban planning and green infrastructure investments and to help reduce thermal inequities. In short, this research can help us build healthier and more equal mental 'cities of minds' for the most vulnerable populations

PROBLEM STATEMENT AND MOTIVATION

Even though UHI has been accepted as a global issue, South Asian urban centre's like Lahore are considerably underrepresented in long term UHI studies. Many of the studies in literature have focused on short-term evaluations, single-season case studies or small geographical scales that may not be sufficient to understand the cumulative impacts of rapid urban growth over several decades (Butt et al., 2021). This absence becomes even more notable in a city like Lahore where the population explosion, ad hoc construction and decreasing green cover have combined to drastically metamorphose urban spaces. Without such long-term perspectives, it is problematic to separate the complex effects of land use changes, infrastructure densification, and vegetation removal on aggravating UHIs.

Ecological changes during the process of uncontrolled urban sprawl, for example, the change from agricultural land to settlements with a concrete surface) are believed to be the main catalysts in increasing surface and atmospheric temperatures. These modifications make the microclimate not only change but also increase the vulnerability of urban inhabitants. Psychologically, heightened background is a hidden stressor with attendant increases in risk of health problems due to heat-related illness, interference with sleep rhythm (Luber and McGeehin, 2008; Watts et al., 2015), greater quick temper and prolonged mental fatigue over the long term (see Obradovich et al. This intersection with matters of more general equity is highlighted by the fact low-income areas lacking cooling resources or green spaces are likely to be affected disproportionately. However, current methods of UHI research in the area generally lack such cross-cutting human perspectives, concentrating on physical or technical factors. This highlights the urgency for cross-disciplinary work combining meteorological data and social/psychological analysis.

This research is motivated by two concurrent sets of circumstances: the growing advances in satellite remote sensing capabilities and the pressing need for operational knowledge grounded on spatial data to produce climate-resilient cities. Nowadays, thanks to tools such as Landsat thermal infrared (TIR) images in combination with vegetation and built-up indices, UHI dynamics can be explored on an unprecedented spatial and temporal scale. Meanwhile, local authorities and city planners are struggling to deal with the increasing problem of heat stress driven by climate change. Through the use of these technological advancements, evidence-based knowledge generated in this paper could be used to further scientific insights and guide practice. The ultimate goal is to overcome siloed disciplinary perspectives in favor of a framework that situated UHI research within socio-environmental framework that emphasizes planning and design for sustainable, equitable, and emotionally healthy urban environments.

METHODOLOGY

The study uses a time series, quantitative, remote sensing design combining geospatial analysis with socio-environmental interpretation to explain the overall spectrum of Urban Heat Island Intensity (UHII) variation in Lahore. A similar logic has been applied in UHI studies in Asian cities, indicating the benefits of systemic characterization for continued monitoring and police-relevant analysis (Zhou et al., 2019). The timespan used in the research design, from 2000–2023, pays attention to both short-term and long-term changes of land use, vegetation cover and thermal characteristics. This methodology was chosen to allow for an examination of the visceral elements of UHIs and how they relate to more systemic social and environmental concerns.

Data were collected from a seamless time series of satellite imagery across several Landsat platforms, including Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI/TIRS and Landsat 9. Those selected data sets, which are available through the USGS Earth Explorer Web site at no cost to users, were screened to ensure comparability between years. Summer therefore was favoured to get unbiased seasonal coverage and to also include the peak heat accumulation phase, as this is most important both from a climatological and socio-psychological point of view. This method permits a strong test of long-term thermal trends, whilst maintaining internal consistency among data sets over time.

Atmospheric correction for satellite data was made using the LEDAPS algorithm to ensure that observed radiance values corresponded to surface conditions43. Land Surface Temperature (LST) were obtained using radiometric calibration and emissivity correction following the well-known procedure of Weng et al. (2004). NDVI (Normalized Difference Vegetation Index) and NDBI (Normalized Difference Built-up Index)) to behavior analysis of LST with land cover patterns.

UHII was expressed as the difference in temperature separating average urban LST from rural referent areas, a common metric for allowing comparison with other regional and global work.

All analysis was done with ArcGIS 10.8 and ENVI5.6 for imagery manipulation and spatial modeling, as well as statistical testing and visualization in R. Confusion matrices were applied for accuracy assessment to validate land use and land cover classifications, guaranteeing the creditability of the findings. Time trend analyses Combined morphine usage over the study period of 5 years was analysed using linear regression models as well as non-parametric Mann–Kendall tests to test for statistical significance and direction of trend(status) in magnitude.

Ethical issues were covered by exclusive use of publicly available satellite data, which did not contain human-level data. However, the study recognises impact of UHI progress in terms of public health, equity and well-being. Findings are therefore presented with a focus on their implications for at-risk communities and urban policy responses. Through the combination of methodological soundness and a concern with actual human consequences this research design guarantees scientific quality as well as social relevance.

RESULTS AND EVALUATION

From 2000-2023, Lahore recorded intensified UHII conditions with mean values increasing by 2.1 °C per decade; the highest rate of increase was observed from 2010–2020 and this period went with high pace of peri-urban sprawl leading to massive infrastructure expansion and widespread change in agricultural land use into residential/commercial complexes. This conversion has not only eliminated vegetative buffers that had previously moderated surface temperatures, but also generated huge areas of impervious surfaces which magnified heat retention. The trend observed, therefore suggests the cumulative impacts of uncontrolled urbanization as well as population growth on the city's thermal profile within the last two decades.

Spatial analysis indicated broad heterogeneity in various regions of the city. The UHII was found to be maximum in the historical city centre and densely built up areas, with an average value greater than 3.5 °C. These areas are associated with high-density and high-rise construction, poor greenspace distribution, which contributes to thermal build-up. Peripheral free frontier and agricultural zones, by contrast, initially exhibited relatively constant temperatures working as climatic shock absorbers. But as unchecked urbanization crept into these outskirts, sapping them of much of the buffering capability, natural landscapes became splintered and the city was made more vulnerable to heat. This shift illustrates how land cover spatial inequalities have direct effects on the Tokyo urban thermal environment and central residents are instead much more exposed to extreme heat.

These spatial patterns are supported by quantitative results. The urbanized land area increased significantly from 34% of the total extent in 2000 to 61% by year 2023, meaning impervious surfaces nearly doubled in just over twenty years. In the meantime, there was also a significant decrease in green cover from 22% down to 12%, representing an 18% decline of vegetative presence. These alterations were closely associated with an increase in land surface temperature, and a high statistical association ($R^2 = 0.71$) was found between the decrease of NDVI and LST increment. Information presented here, therefore, provide conclusive evidence regarding the role of vegetation depletion as a major contributor to UHII in Lahore and highlight the significance of green infrastructure for changing urban climates.

The Mann–Kendall trend test also showed that the increasing trends ($p < 0.01$) of UHII were statistically significant in the study period. This strong evidence removes the possibility that observed increases are a result of natural variability only and recognizes the causal relationship between land cover changes and ongoing warming. More importantly, trends matched with the global UHI characteristics observed in fast-urbanizing regions across the world (Zhou et al., 2019), however highlighting enhanced susceptibility of Lahore with unprecedented land cover transformation.

As a whole, the findings lend to a clear picture in manifesting environmental change in Lahore – an urban locale where unregulated urban expansion has significantly accelerated warming. Results do not only confirm the severity of UHII but also highlight the immediate requirements for an adaptive approach which consider urban planning in line with climate resilience. Growing urban forests, conserving agricultural buffers and controlling land use sprawl are essential measures to offset the course of worsening UHIs. Lahore's story is a cautionary tale that also provides some lessons on how, in an increasingly heated world of bewildering urban growth, we might avoid such ruin.

DISCUSSION

This study implies that swift urban growth and depleted vegetation cover is the determinant factor contributing to the UHII magnitude in Lahore, consistent with findings from other South Asian cities namely Delhi and Dhaka (Rasul et al., 2017). Comparison across the cities here further accentuates a common trend of urbanization-induced thermal stress (though, unlike in any other case this loss has been especially extreme for Lahore's peri-urban agriculture). Unlike Delhi where the peri-urban is still splattered with green buffers or Dhaka where wetlands serve as a residual moderating variable, Lahore has faced almost constant and extensive encroachments on its agricultural periphery. This loss has further diminished the city's ability to regulate surface and atmospheric temperatures, thereby compounding the spatial and temporal peaks of heat stress. The evidence supports the view that untrammeled land conversion in fast urbanizing settings not only hastens warming, but it diminishes the eco-systemic resilience (of which intact water-bodies is part) that would help to mediate natural adaptive responses there.

In addition to environmental and climatological issues, the increased UHIs have tangible psychological and social consequences. Higher temperatures in urban areas are associated with increased risk of cognitive decline, reduced productivity at work, poor sleep quality, and greater levels of anxiety and annoyance (Obradovich et al., 2018). These effects are not felt equally by everyone, and marginalized communities without consistent access to air conditioning, cooling infrastructure or well-ventilated housing experience the greatest exposure to heat stress. This exacerbates weakness in relation to psychosocial aspect, that is at high risk especially among those already suffering from economic insecurity (Harlan & Ruddell, 2011). In a city like Lahore, where informal settlements are constantly spreading these psychological impacts of UHI are expected to be exacerbated - an example of the convergence of environmental change, social equity and public health.

On a pragmatic level, the results of this study reiterate the pressing requirement for policy-based sustainability measures in reducing UHII and its debouching effects. Generic urban greening actions such as park maintenance and expansion, street tree planting or community level tree programs can lead to significant reduction of local warming. In the same context, roof gardens and vertical greening systems also provides affordable means of cooling down in high-dense built-up areas. Reflective construction materials and cool roofs might be other good options for heat mitigation. With policy, incorporating climate-responsive planning into the urban development frameworks of Lahore is critical to guarantee land use choices take conscious considerations on both climate and psychological facets into account. These actions do not only reduce heat stress, but also enhance general psychological resilience by increasing comfort, reducing anxiety and raising the quality of life in cities.

However, it is not an absentee of limitations. Use of satellite-based land surface temperature (LST) maintains some level of uncertainty, as LST may be an imperfect correlate of near-surface air temperatures people experience. Furthermore, the rural reference regions that are used to calculate UHII may not capture natural baseline variability well, especially in heterogeneous landscapes with presence of agricultural or semi-urban land uses. Another limitation is failure of direct data collection on psychology, which does not allow empirical evidence connecting thermal exposure to mental health outcomes within Lahori context.

Future studies should thus combine remote sensing with survey or clinical psychological well-being data, to further unravel UHI social implications. This interdisciplinary method could help identify more subtle links between environmental stressors and mental health issues. Technologically, pairing Landsat data with higher-resolution imagery from Sentinel-2 or UAV platforms would allow for more granular spatial analysis of heat distribution, accounting for the micro-level heterogeneity that current datasets may fail to account for. Taken together, these lines of inquiry lead toward a more inclusive framework for investigating UHII—one that reconciles environmental science, psychology and urban planning to facilitate sustainable and equitable climate adaptation strategies in rapidly urbanizing megacities such as Lahore.

CONCLUSION

The results of this study show that the magnitude and intensity of Lahore's UHII has amplified noticeably over the period 2000 to 2023 due to extensive land cover change, growing built-up areas, and continuous decrease in vegetation. The results show that through uncontrolled urban growth, the city has restructured not only its physical environment but also that it is more susceptible to the effects of LST. Using the methodology of a remote sensing time series and integrating it with social scientific considerations, the study contributes to transcending UHII from merely climatic influence, focusing on its ecological, psychological, and political aspects.

The results emphasize that UHII is a non-technical problem or ecological problem - instead, it is multidimensional phenomenon and affects human well-being. Elevated urban temperatures have been associated with increased stress, poor sleep, and cognitive dysfunction and anxiety in those who have little access to cool environments. This also poses UHII as both an environmental justice and public health issue. These challenges can be addressed only with a new paradigm in urban governance that embeds climate-sensitive planning and resilience-based strategies at the heart of its decision-making practices. Interventions including urban greening, green roofs, reflective building surfaces and the retention of peri-urban agricultural buffers appear practical measures to lower heat stress and improve psychological resilience.

Subsequent work should further integrate these interdisciplinary approaches by directly associating climate indicators derived from satellites and psychological health measures reported in surveys, as recommended by Obradovich et al. (2018). This integration would support a more "human" oriented knowledge of UHII effects, where evidence resulting from science is translated into relevant policies. In this way, Lahore and other fast-urbanizing cities in South Asia can map the ways towards durable, fair and climate-resilient urban futures.

REFERENCES

Akbari, H., Kolokotsa, D., & Santamouris, M. (2016). Urban heat island mitigation strategies and resilience: A state of the art on mitigation technologies and policies. *Urban Climate, 17,* 1–19.

Akbari, H., Matthews, H. D., & Seto, D. (2016). The long-term effect of increasing the albedo of urban areas. *Environmental Research Letters, 11(9),* 094020.

Anderson, G. B., & Bell, M. L. (2009). Weather-related mortality: How heat, cold, and heat waves affect mortality in the United States. *Epidemiology, 20(2),* 205–213.

Butt, M. J., Waqas, A., & Mahmood, R. (2021). Assessment of urban heat islands using satellite remote sensing in major cities of Pakistan. *Environmental Earth Sciences, 80,* 329.

Butt, M. J., Waqas, A., & Mahmood, R. (2021). Spatiotemporal analysis of urban heat island effect in Islamabad and Rawalpindi using Landsat data. *Environmental Earth Sciences, 80(6),* 246.

Guo, A., Yang, J., Xiao, X., Xia, J., Jin, C., & Li, X. (2015). Influences of urban spatial form on urban heat island effects at the community level in China. *Sustainable Cities and Society, 19,* 222–231.

Guo, G., Zhou, X., Wu, Z., Xiao, R., Chen, Y., Ren, Y., Li, J., & Xu, W. (2015). Characterizing land surface temperature in relation to land cover in urban areas: A case study of Shanghai, China. *Remote Sensing, 7(4),* 4405–4429.

Harlan, S. L., & Ruddell, D. M. (2011). Climate change and health in cities: Impacts of heat and air pollution and potential co-benefits from mitigation and adaptation. *Current Opinion in Environmental Sustainability, 3(3),* 126–134.

Obradovich, N., Migliorini, R., Mednick, S. C., & Fowler, J. H. (2018). Nighttime temperature and human sleep loss in a changing climate. *Science Advances, 3(5),* e1601555.

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society, 108(455),* 1–24.

Rasul, G., Dahe, Q., & Chaudhry, Q. U. Z. (2017). Global warming and melting glaciers along southern slopes of HKH with special reference to Pakistan. *Climate Change, 85(1–2),* 82–99.

Rasul, G., Mahmood, A., Sadiq, A., & Khan, S. I. (2017). Vulnerability of the Indus Delta to climate change in Pakistan. *Pakistan Journal of Meteorology, 8(16),* 89–107.

Santamouris, M. (2015). Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. *Science of the Total Environment, 512–513,* 582–598.

United Nations. (2022). *World Urbanization Prospects: The 2022 Revision.* UN Department of Economic and Social Affairs.

Voogt, J. A., & Oke, T. R. (2003). Thermal remote sensing of urban climates. *Remote Sensing of Environment, 86(3),* 370–384. https://doi.org/10.1016/S0034-4257(03)00079-8

Weng, Q., Lu, D., & Schubring, J. (2004). Estimation of land surface temperature–vegetation abundance relationship for urban heat island studies. *Remote Sensing of Environment, 89(4),* 467–483.

Zhou, D., Xiao, J., Bonafoni, S., Berger, C., Deilami, K., Zhou, Y., ... & Sobrino, J. A. (2019). Satellite remote sensing of surface urban heat islands: Progress, challenges, and perspectives. *Remote Sensing, 11(1),* 48.

Zhou, D., Zhao, S., Zhang, L., Sun, G., & Liu, Y. (2019). The footprint of urban heat island effect in China. *Scientific Reports, 5,* 11160.