Chapter 4
Warming Cities in Pakistan: Evaluating Spatial–Temporal Dynamics of Urban Thermal Field Variance Index Under Rapid Urbanization

Mirza Waleed and Muhammad Sajjad

Abstract With ~57% of the world population living in cities, the global urban population is increasing at an alarming rate, which further stimulates the urbanization process. Consequently, the increasing impervious surfaces in cities and associated variabilities in local/regional climatic characteristics pose several challenges to citizens (i.e., heat-related health issues, higher energy demands, and flooding among many others). Currently, cities contribute 75% of Green House Gases emissions, which is further worsening climate change impacts through global warming. Pakistan, the 6th most populated country globally, with ~220 million people, is among the top 10 most-affected nations vulnerable to climate change. Hence, studies addressing climate variability in local geographical regions have important implications to address the adverse urbanization-associated challenges, such as sustainability of the land resource and mitigating urban heat island (UHI) impacts in the context of climate change mitigation/adaptation. Due to temperature differences between urban, suburban, and rural areas, mapping city zones prone to the UHI effect is essential to provide actionable references. In connection with this, the present study analyses 15 megacities in Pakistan regarding their temperature variability in response to built-up area increment and highlights heat stress zones using the Urban Thermal Field Variance Index (UTFVI). The cloud-computing-based Google Earth Engine platform is employed to explore spatial–temporal variation in Land Surface Temperature (LST), which further leads to the identification of top-15 cities in terms of LST increase and the further evaluation of UTFVI for each city. The findings of this study suggest that the strongest UTFVI zones are concentrated around city-core areas, which are pure impervious surfaces with little or no green space. Moreover, in the last three decades (1990–2020), most of the weak and strong-strength UTFVI areas have been converted into the strongest strength primarily because of a rapid increase in the

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built-up areas. The findings of this study can help urban policymakers to identify priority intervention areas and design/implement strategies to counter the UTFVI and associated challenges. With proper land-use planning and on-time policy implementation, people residing in higher UTFVI zone areas can be safeguarded from noxious heatstroke-like health consequences along with mitigating and adapting to changing environmental conditions in cities.

Keywords Urbanization · Climate change · Urban heat island · Spatial analysis · LULC · LST

1 Introduction

In the last few decades, changing climatic conditions have predominantly affected the living conditions of human beings. Recent studies suggest that those living in metropolitan cities are more prone to the adversities brought by climate change and associated extreme events, such as heat waves and intensifying natural hazards (IPCC, 2021). The changes in land use land cover (LULC) have a direct linkage with changes in climatic conditions of an area, particularly in cities (Faisal et al., 2021). The global population in 2050 is expected to increase by 68% (Nations, 2019). Cities are responsible for three-half (75%) of the world Green House Gases (GHSs) emissions (Masson-Delmotte et al., 2021). According to the IPCC (2021) report, the surface temperature of the earth has increased by ~1.09 °C since 1861, which is primarily due to the increase in impervious surfaces in cities and the reduction of green cover.

Recently, urban sprawl has resulted in several challenges for cities around the world (Alqasemi et al., 2021). According to the European Environmental Agency (EEA), urban sprawl is the low-density conversion of other land-use types, especially nearby vegetative and barren land into urban/built-up (Kafy et al., 2022a). This expansion is a primary consequence of a rapid increase in the population of that particular area due to growth and influx. As a result, cities witness an increase in resource demand (Faisal et al., 2021). Similarly, being a major factor behind the land cover change (Corner et al., 2014), urbanization induces changes in ecology, biodiversity, landscape, and natural habitats as well. The rapid alteration of LULC, especially in developing countries, causes the degradation of essential resources such as water, soil, and vegetation—compromising long-term sustainability (Hassan et al., 2016). Similarly, LULC-induced reduction in green spaces in cities is likely to facilitate the urban heat island effect, which has several consequences in terms of health challenges and higher energy consumption among many other issues (Kafy et al., 2022b). Therefore, supervising LULC alterations is fundamental to proper planning, management, and achieving sustainable development goals through informed decision-making and science-backed policy development (Hua et al., 2021).

Urbanization-led decrease in vegetation and increase in impervious surface results in larger heat retention, and consequently, the urban heat island (UHI) effect takes place. UHI is a phenomenon when the observed surface temperature of core urban regions is higher than the surrounding sub-urban/rural areas (Alqasemi et al., 2021). Though there is no prominent boundary differentiating urban from nearby rural areas, a temperature difference is observed and well-documented around the world (Rahman et al., 2022). Impervious surfaces including roads, tall buildings, and non-vegetative regions (e.g., sandy or barren) within cities are primarily responsible for the UHI effect. The primary contributors to urban warming are a rise in short-wave radiation captivation, heat storage, human-induced heat generation, and reduced evaporation rate (Rajasekar & Weng, 2009). Earth observation data (EOD) is proven to be useful in understanding the urbanization process and associated environmental effects. The use of EOD to evaluate UHI and its effects on spatial distribution, urban vulnerabilities, and health-related risks are widely published globally (Kafy et al., 2022b; Kaplan et al., 2018; Zhou et al., 2018). To evaluate the influence of UHI, the urban thermal field variance index (UTFVI) is usually employed (Tomlinson et al., 2011). Hence, exploring spatial–temporal heterogeneities in UTFVI could provide progressive opportunities to advance our understanding of UHI effects in cities.

The urbanization rate in Pakistan is the highest among all south Asian countries with ~ 37% of people living in cities (UNDP, 2022) In the last five decades, Pakistan has faced rapid urbanization in its metropolitan cities (Waleed & Sajjad, 2022). Punjab, the largest province in Pakistan with respect to population and agricultural productivity, has undergone some noticeable changes in its urban areas. While many researchers (e.g., Dilawar et al., 2021; Hussain et al., 2021; Safder, 2019; Saleem et al., 2020; Tariq et al., 2021; Waleed & Sajjad, 2022) have studied urban LULC patterns in Pakistan, there is still a lack of a systematic investigation of urban regions in terms of LST change and the spatial–temporal evaluation of UTFVI. Furthermore, while such assessments are rare to find in Pakistan, those that are available mostly focus exclusively on the top metropolitan cities (i.e., Lahore, Karachi, and Faisalabad) despite their smaller city area and already highly urbanized nature (Baqa et al., 2021; Imran et al., 2021; Tariq et al., 2021). As a result, the current research focuses on highly populated cities in Punjab and neglects other regions which might have experienced comparable urbanization and associated changes in terms of urban thermal characteristics. This situation represents a significant information gap for other rapidly urbanizing regions and thus hinders informed planning and policy production. In connection with this, the present study evaluates the LST in Punjab province and selects the top 15 cities based on LST change during the past three decades (1990–2020). Based on LST, this study further investigates the spatial–temporal dynamics of UTFVI in these cities. Furthermore, the built-up area increase in these 15 cities is evaluated to discuss urbanization trends along with the increase in the intensity of UTFVI. To do so, the Google Earth Engine (GEE) platform and spatial modelling techniques in ArcGIS Pro. are employed. The results from this study will provide important insights into UTFVI and built-up area dynamics in Pakistan's cities along with providing references for decision-making and designing appropriate action plans in the context of climate change mitigation/adaptation.

2 Data Acquisition and Preparation

The overall work is conducted in various steps, such as data acquisition, built-up area classification, change assessment, LST computation and evaluation, and mapping UTFVI for spatial–temporal inconsistencies evaluation. The data preparation stage starts with filtering the Landsat-5 Thematic Mapper (TM) tier-1 Surface Reflectance (SR), Landsat-8 Operational Land Imager (OLI), and the Thermal Infrared Sensor (TIRS) tier-1 SR data from the GEE data catalogue in the form of image collection. The overall analysis is divided into four periods (i.e., years 1990, 2000, 2010, and 2020) as the LULC change is a slow process. For the years 1990, 2000, and 2010, we use data from the Landsat-5 TM tier-1 collection. For the year 2020, Landsat-8 OLI tier-1 SR data are used. It is noted that we avoid using Landsat-7 data despite its availability for 2000 and 2010 due to scan-line errors since 2007 (Alexandridis et al., 2013). These satellite images for each year are then used to determine urban areas for each period. For this purpose, the machine learning-based random forest (RF) algorithm is utilized due to its robustness and improved LULC classification accuracy compared with other approaches (Waleed & Sajjad, 2022). The obtained classification of built-up area is validated using accuracy assessment indices, such as the Kappa coefficient and Overall Accuracy (Waleed et al., 2022).

3 LST Retrieval Through Earth Observations

As the next step, the Landsat data are used to compute Land Surface Temperature (LST). For this purpose, LST is taken from summer month's satellite images individually for each year. For LST estimation, the Landsat TM and ETM + (Band 6) and Landsat OLI/TIRS (Band 10) thermal bands are used. Landsat 8 (OLI/TIRS) imagery has two thermal bands (10 and 11), but only band 10 is used for the LST estimation because of its more accurate results (Zhou et al., 2018). Equations (3–5) are used to convert digital numbers (DN) into LST as previously used in many studies (Tariq et al., 2021; Waleed & Sajjad, 2022). Firstly, the DN values of each pixel are converted into radiance values (L_λ) using the following equation.

$$L_\lambda = \left(\frac{L_{max\lambda} - L_{min\lambda}}{QCAL_{max} - LQCAL_{min}}\right) + L_{min\lambda} \tag{1}$$

where $L_{max\lambda}$ is the highest radiance value, $L_{min\lambda}$ is the lowest radiance value, $QCAL_{max}$ is the highest quantized adjusted pixel value (consistent to $L_{max\lambda}$ in DN (255)), and $QCAL_{min}$ is the lowest quantized adjusted pixel value (consistent to L_{min} in DN (01)).

All the values used in the above equation are taken from the metadata files that come along with the Landsat images. The radiance values are then converted to surface brightness temperature given as:

$$T_B = \left(\frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)} \right) - 273.15 \tag{2}$$

in which, K_1 and K_2 are the constants, and for reference, their values are available on the United States Geological Survey (USGS) website (https://www.usgs.gov/).

After estimating the at-surface brightness temperature T_B, we compute the pixel-based land surface emissivity (ε). In order to calculate the value of emissivity, we use the pre-defined calibrated values for different Landsat missions along with a particular region's Normalized Difference Vegetation Index (NDVI) as used in recent research (Imran et al., 2021). The LST is computed using Eq. 3, in which T_B is applied with an emissivity correction (ε).

$$T_S = \frac{T_B}{\left[1 + \left[\frac{\lambda T_B}{p}\right]\ln\varepsilon\right]} \tag{3}$$

where T_S is the per-pixel LST value, λ is the wavelength of emitted radiance (value = 11.5 μm), and p is equal to 1.438×10^{-2mk}.

The above procedure is followed to evaluate LST in Punjab province in Pakistan. The derived LST is then used to evaluate the spatial–temporal patterns and trends, if any, in several cities in the study area over the last three decades (1990–2020). In addition, LST is further used to assess UTFVI, which is utilized to map heat stress-affected areas in the top 15 cities in terms of LST change during 1990–2020. It is noted that for simplification, we used a 10-km buffer zone around the central business districts of the cities and quantified changes in the LST, which is then used to select the top 15 cities for further evaluation.

4 UTFVI Estimation and Its Spatial–temporal Heterogeneities

Previously, many researchers have used different techniques to calculate the intensity of UHI specifically in urban and near urban areas (Kaplan et al., 2018; Rahman et al., 2022; Tomlinson et al., 2011). Remote Sensing (RS) techniques have been proven to analyze data in a continuous and cost-effective manner. Using RS techniques, UHI can continuously be monitored with the help of infrared satellite data. Instead of just point readings, the RS-based UHI could show the intensity of heat stress over large geographical areas. According to the literature (i.e., Zhou et al., 2018), the UHI is directly linked to different LULC classes and also to the geographical distribution of vegetation cover. By using RS techniques, the UHI is calculated independently in urban and rural areas following Faisal et al. (2021).

A normalization method is adopted to compare UHI due to observed variations in LST of different seasons within a year. This is given in Eq. 4.

$$UHI_N = \frac{T_s - T_m}{T_{Std}} \quad (4)$$

where UHI_N is the normalized UHI, T_s is the LST, T_m is the mean LST of the study area, and T_{std} is the standard deviation in the LST of the study area.

After computing the UHI, we use the UTFVI to describe its effect. The UTFVI is a quantitative measure to explain UHI in terms of thermal comfort level in a city and is among the most widely used thermal comfort indices (Guha et al., 2017). The index value is quantitatively calculated using the formula given below.

$$UTFVI = \frac{T_s - T_m}{T_s} \quad (5)$$

where the variables are similar to Eq. 4.

The UTFVI is computed for every city for each time period (1990, 2000, 2010, and 2020), and maps are produced to provide spatial references on geographical disparities. This approach is particularly helpful in understanding the distribution of urban thermal comfort across space and time, allowing relevant authorities to take appropriate measures via informed decision-making.

5 Changes in LST, UTFVI, and Built-Up Areas

Figure 1 shows temperature change (LST change) in the top 15 cities of Punjab during 1990–2020. Among 58 cities of Punjab, 15 showed up to 7 °C of temperature change. Among these, Kasur, Chiniot, Sheikhupura, Sahiwal, and Lahore are the ones with surface temperature change greater than 4 °C. Besides, Rawalpindi and Rahim Yar Khan are the ones that experienced the least temperature change (i.e., < 1 °C change). This temperature change (based on LST) provided a base for highlighting cities that underwent noticeable temperature changes in the last thirty years and are investigated further to analyze UTFVI and built-up area variations during 1990–2020.

Once the cities are ranked according to the estimated LST change during the past three decades, the top 15 cities with the largest temperature change are shortlisted to further study the abrupt temperature rise by computing the UTFVI for each city and its dynamics in space and time. For each city, the evaluated UTFVI and its spatial distribution under different periods (1990, 2000, 2010, and 2020) are presented in Fig. 2. To further facilitate the analysis, the cities are grouped based on three regions, including (A) the Central region, (B) the North region, and (C) the South region (Fig. 2). Interestingly, it is observed that most of the cities experiencing increment in LST belong to the central regions of Punjab province in Pakistan, with two cities each from the north and south regions. The location of many large cities in the central areas of Punjab province could be the potential reason behind the rapid urbanization-led change in the LST of these cities. For UTFVI, 11 cities belong to the Central region while 2 to each North and South region.

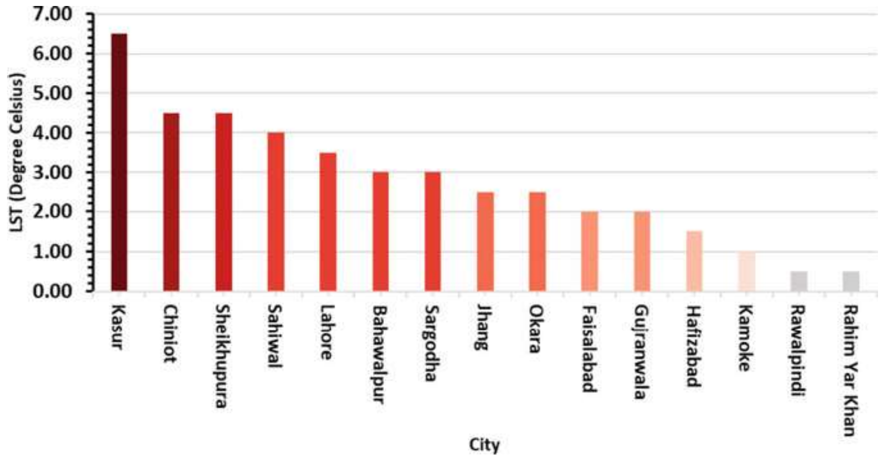

Fig. 1 Ranking of cities of Punjab based on highest temperature change (LST Change in °C)

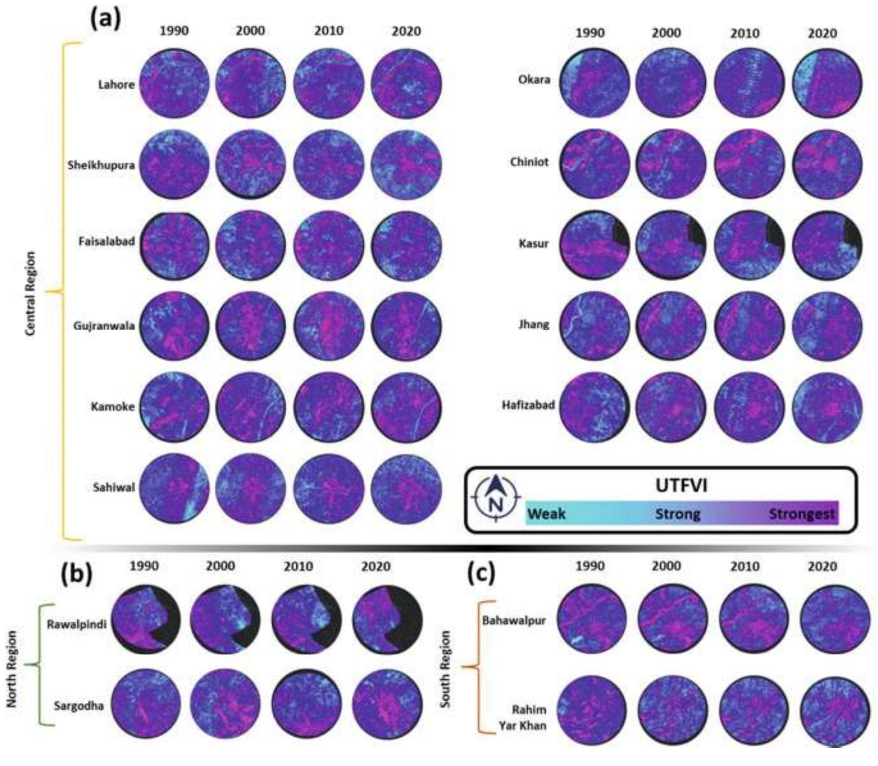

Fig. 2 UTFVI for 15 selected cities based on the change in LST during 1990–2020. The results are visualized using one standard deviation representing how much the value of each 30 m pixel varies from the mean across the overall city

Nearly in all cities, two prominent trends are observed. Some cities, such as Sahiwal, show the strongest UTFVI located in the city core, with UTFVI strength increasing during the past three decades (1990–2020). On the other hand, some cities, such as Hafizabad, show dispersed strongest UTFVI in the surroundings of the city's core area. These dispersed strongest UTFVI areas then experienced a shift toward the city's centre with each passing time period. Besides the strongest UTFVI, weak and strong UTFVI areas are also visible in surrounding regions, and their concentration is reduced by each decade. For example, in Rawalpindi and Sargodha, weak and strong UTFVI areas were prominent in the 1990–2010 duration around the city's centre. Whereas, in the last decade (2010–2020), these weak and strong UTFVI zones are converted into the strongest UTFVI zones. Additionally, it is worth mentioning that although many cities have shown a significant increasing trend of the strongest concentration of UTFVI, there are some cities, such as Lahore, with a minimal increasing trend over the years in the strongest UTFVI. This may be attributed to the fact that metropolitan cities, such as Lahore, are already densely populated and well-urbanized, leaving far lesser space for any new development. In Fig. 2, among the Central region cities, Gujranwala, Faisalabad, Sahiwal, Lahore, and Chiniot showed the highest UTFVI, among which Kasur stands first. For the North and South regions, Sargodha and Bahawalpur are the highest UTFVI concentrated regions, respectively.

To further check the association of the core strongest UTFVI areas of cities with urban development, we evaluated LULC classification for each city, and the results on the sprawl of built-up areas are presented in Fig. 3. In general, Lahore city, which is among the largest cities in Pakistan and accommodates a huge proportion of Pakistan's population, has the highest urban area whereas Bahawalpur has the least urban area. In terms of area change per year, Lahore showed the minimum urban expansion than others between 1990–2020. Also, in Lahore, most of the urban development occurred in the city's core areas, thus, increasing the city's density instead of expanding outwards. This may be due to the fact that the city is already urbanized and can only increase its density in future, which gives minimal space for further expansion unless it is merged with the surrounding smaller cities, such as Sheikhupura and Kasur, or vertical development takes place for future development instead of current horizontal sprawl. Furthermore, an increase in urban development patterns is observed in nearly all the cities (i.e., Faisalabad, Gujranwala, and Kamoke doubled their urban expansion between 1990–2020). It is also evident that nearly all the cities followed a gradual urban expansion process. For instance, Gujranwala followed a city-centric point, in which the urban area expanded with each passing decade in the surrounding core area. Among all the cities, Okara did not show much urban development. On the other hand, among several regional groups of Punjab, Gujranwala in the Central region (Fig. 3a), Rawalpindi in the North region (Fig. 3b), and Rahim Yar Khan in the South region (Fig. 3c) show the highest urbanization during the past three decades (1990–2020).

The statistical evaluation of area changes for each decade and each city's urban area is given in Fig. 4 with percent change (1990–2020) illustrated in Fig. 4a and actual areal change for each city for different time intervals (1990, 2000,

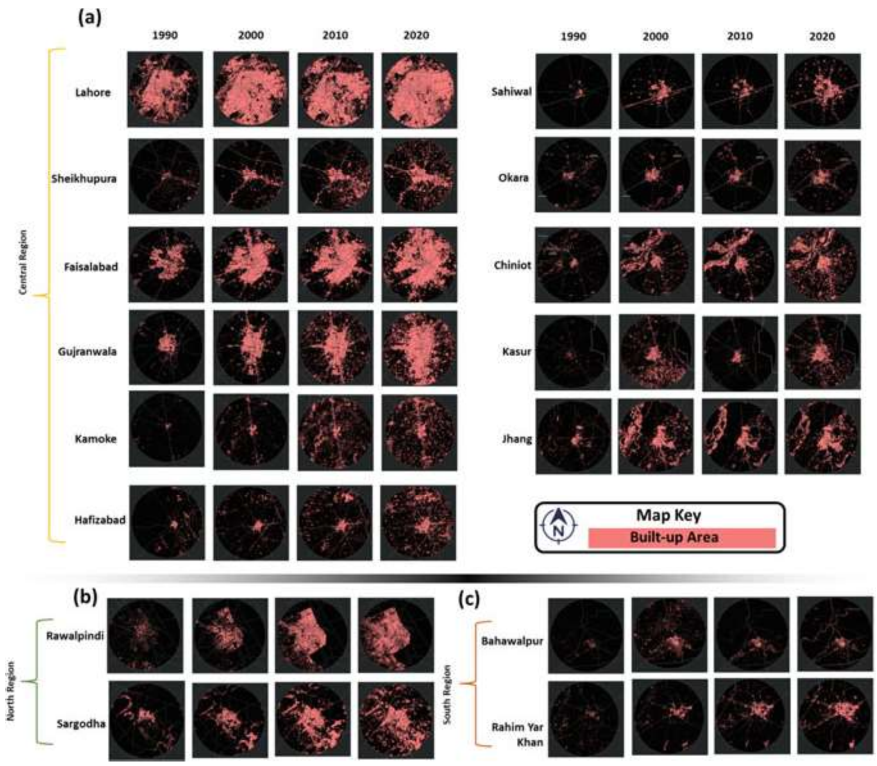

Fig. 3 Urban sprawl for cities between 1990–2020 as estimated using the Landsat Satellite-based earth observation data in Google Earth Engine

2010, and 2020) in Fig. 4b. Notably, area statistics support previous deductions from Fig. 3 that Gujranwala showed the highest urbanization with a 600% change (increase) between 1990–2020. Following Gujranwala, Chiniot, Sargodha, Sahiwal, and Kamoke showed similar urban development trends with percent changes of 405%, 403%, and 333% increase, respectively. Lahore, on the other hand, showed a minor urban increase, with only a change of 47% between 1990–2020. From the perspective of overall percent change, Gujranwala, Chiniot, Sargodha, Sahiwal, and Kamoke are the top five cities in Punjab that show more than 300% change in the last thirty years.

6 Discussions and Implications

While land-use change monitoring is crucial for environmental sustainability, especially addressing development in core urban areas, it is equally important to analyze comfort level by evaluating the thermal conditions within that region. Cities, which

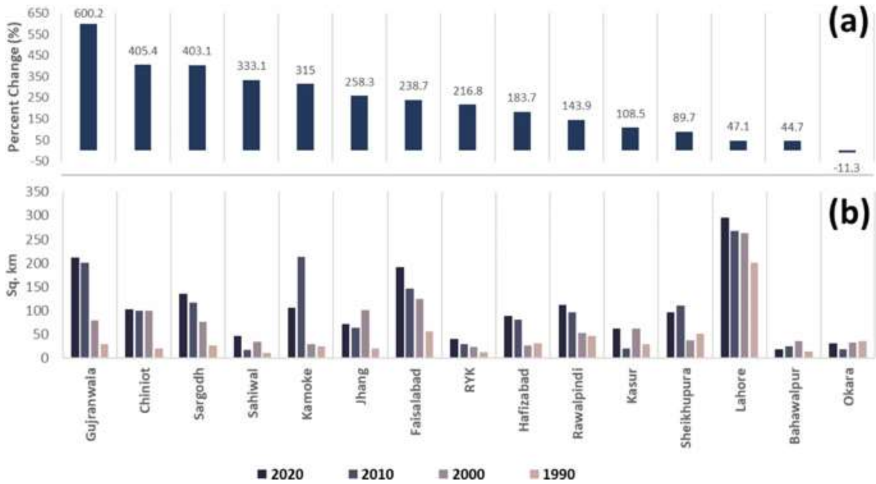

Fig. 4 Urbanization phenomena in top 15 cities. (a) percent change in urban built-up areas (b) actual areal change per decade under the urbanization process during 1990–2020

are the hotspots of global warming, are the most affected regions because of climate change effects. Despite their less than 2% of the earth's surface coverage, they are responsible for more than 70% of GHGs emissions, which is the most significant climate change driver (UN, 2019). Given this situation, the increase in impervious surface, as observed in this study at the cost of natural terrain, reduced the capabilities of cities in terms of carbon sink. As per the available reports, during 1990–2019, the GHGs-based warming induced by anthropogenic activities increased to 45% (IPCC, 2021). Besides GHGs, due to changing landscapes in cities (i.e., the replacement of natural landscapes with the concentration of impermeable pavements, buildings, and other surfaces that influence air and water flows), cities are getting warmer (Dilawar et al., 2021). A similar warming phenomenon is evident in the evaluated cities in Pakistan. This heat that is trapped (also known as the urban heat island effect) results in increased severity of daily weather (i.e., high daytime temperature, low night-time temperature, and high pollution levels), ultimately affecting residents' health, including heat-related mortality and illnesses, such as general discomfort, respiratory difficulties, heat cramps, heat exhaustion, and non-fatal heat stroke (Tomlinson et al., 2011). Hence, managing rising heat in cities with appropriate measures is imperative for healthy and liveable cities, and evaluations, such as this study, provide important insights to direct efforts in the right direction. For instance, the identified top 15 cities (Fig. 1) in terms of LST change during the past three decades should be prioritized for adaptation actions.

As the UHI effect is dependent on land-use surface type, vegetation cover is proved to be effective in UHI mitigation (Kafy et al., 2022b). Therefore, evaluations addressing continuous land-use change and urban comfort analysis are important for improved policy production and smart decision-making to keep a check on the green cover in cities. Ultimately, such efforts ensure higher comfortability in urban areas for the residents. The UHI-based UTFVI disparities in all the studied cities pinpoint zones where the green cover should be prioritized. Although urbanization is directly associated with economic progress and innovation, unsustainable and unplanned growth can cause serious complications for residents. This situation can be worsened with the addition of climatic change-induced uncertainties, which may have long-term effects on human livability.

The United Nations projections show that global urban land will increase by 1.2 million km^2 by 2030 (Vinayak et al., 2021). It is obvious that the urbanization rate of developing countries is much higher than that of developed countries. Hence, the ill-informed urban sprawl resulting in urbanization-induced spatial–temporal changes in their landscapes coupled with unsustainable utilization of land resources put cities at higher risks of looming uncertainties under environmental and climatic changes. Hence, while science-baked development plans should be adopted for the future expansion of cities, other smaller urban areas should not be overshadowed due to the focus of the planners and governments on major cities. Similarly, while the surveillance of smaller urban regions should also be on the agenda of urban planning in Pakistan, the densification of metropolitan cities (i.e., Lahore and Faisalabad) should be monitored and approved under strict policies considering the effects of climate change. For instance, It is also clear from Lahore's percent change (47%) that the city has had minimal urban expansion since 1990, despite being the second largest city in Pakistan after Karachi, as it is already a developed city, and therefore can only increase its core city density as depicted in Fig. 3a. Under this condition, managing green cover in Lahore in the face of future development should be a matter of utmost concern for the relevant authorities. Pakistan being a developing country has faced disastrous climate change consequences over the previous decades. According to the Global Climate Risk Index (2021), Pakistan is among the 10 most affected countries due to global warming. Hence, informed planning and development processes assuring sustainable urbanization (i.e., without compromising the green cover in cities to tackle UHI) are imparative to reduce the impacts of climate change.

The findings of this study ranked 15 cities in Punjab based on LST changes between 1990–2020, in which Kasur, Chiniot, Sheikhupura, Sahiwal, and Lahore are the top five with LST change (i.e., > 4 °C change; Fig. 1). Based on this ranking, UTFVI (Fig. 2) shows increasing trends for all cities with either the strongest UTFVI hotspots localized around the city's centre or dispersed in the surrounding. Either way, UTFVI concentration shows a gradual increment consistent with LST changes (Fig. 1). This increased UTFVI localization can be attributed to landscape changes, including the concentration of impervious surfaces and loss of green cover, as witnessed and documented by recent studies as well (Waleed & Sajjad, 2022). In Pakistan, it is evident from previous studies (Dilawar et al., 2021; Waleed & Sajjad, 2022) that higher resource demand and unsustainable policy management have resulted in negative consequences for the natural landscape. According to Waleed and Sajjad (2022), in the last 30 years in Punjab, the natural landscape has been aggressively used to meet demand resulting in a 250% increase in built-up land, a 10% increase in agricultural land, a 36% reduction in rangeland (vegetative land), and 30% reduction in water bodies (wetlands).

One of the key effects of rising urban heat in the aforementioned cities will be on the energy sector. As per recent studies and governmental reports (Raza et al., 2022), Pakistan has been facing an energy crisis for the last two decades, where the country's demand exceeds 30% of its current production. Thus, the temperature-energy relationship continues to increase, which poses further complications and needs to be addressed through proper investigations. First, the need for air conditioning in summer will put a further burden on the energy sector as well as contribute to additional emissions of hydrofluorocarbons responsible for trapping heat. Second, due to the lack of green energy sources, the energy consumption burden will continue to grow, resulting in contributions toward global warming due to fossil fuel burning (Sajjad, 2020). Hence, it is recommended to prioritize regions in cities for green-cover promotion through different initiatives, such as the recent 10-billion Tree Tsunami (Sabir et al., 2020). The identified cities with increasing LST should be considered under such initiatives to bring back the lost vegetation cover and preserve the remaining through strict no-net-loss policies in future urban planning schemes. For each city, such restoration should be prioritized in the strongest UTFVI zones.

In the context of urban heat mitigation and adaption, this study provides a reference for the top 15 cities in Punjab, Pakistan, for effective planning and design-based policy implementation. In this regard, many existing policy frameworks provided by leading world bodies should be adopted, wherever applicable. For example, the recent report by the Global Alliance for Buildings and Construction (supported by the United Nations Environment Programme) discusses key strategies for mitigating urban heat in cities (Yenneti, 2017). Conclusively, urban greenery, green roofs, water-based cooling technologies, cool roofs, and cool pavements are among the most effective means to reduce urban heat stress. Future policy directions should focus on documenting national benchmarks on heat mitigation measures, emphasize the participation of local municipal governments in the implementation of UHI mitigation strategies, incentives for industry and the public, and encourage community participation for handling localized UHI mitigation projects. Another report by the Energy Sector Management Assistance Program (ESMAP) funded by the World Bank divides urban mitigation solutions into two groups (Energy Sector Management Assistance Program 2020). Firstly, the local authorities should focus on promoting the utilization of reflective surfaces, including solar-reflective green roofs, green walls, and permeable pavements. Secondly, the focus should be towards heat-resistant planning through water infrastructures, urban design (green parks), and reducing human-generated heat.

The findings of this study can act as place-based references to prioritize areas for immediate or gradual actions to take measures for adaptation and mitigation via public participation and enhanced community awareness regarding green spaces. Through informed urban planning, such as initiatives of green roofs, utilization of solar panels for green energy, the introduction of green parking lots, and implementation and sensitization of heat reduction policies, urban comfort can progressively be enhanced in the face of warming cities in Pakistan. In terms of future prospects, it is recommended to simulate future expected urban patterns using cutting-edge approaches (i.e., machine learning) and provide insights into land use land cover dynamics and its association with thermal characteristics in cities. Such important information would further be useful to formulate action plans and guided strategies to cope with the climate change-induced heat stress in cities.

7 Concluding Remarks

Evaluating spatial–temporal inconsistencies in the thermal characteristics of cities provide useful references for urban planning and design in the face of climate change. In this context, this study evaluates the urban thermal field variance index (UTFVI)—also an indicator of urban comfort—in 15 cities in Pakistan, a south Asian country with approximately 220 million people and is often ranked among the ten most vulnerable nations to the impacts of climate change globally. These cities are short-listed based on the changes in their LST during the past three decades (1990–2020). The results show that most of the cities with increasing trends in LST are from the central regions of Punjab province in Pakistan with two cities each from northern and southern Punjab. While the spatial inconsistencies in the UTFVI in each city are evident, there is a clear increase in the higher UTFVI coverage in all the cities during 1990–2020. Connectedly, there has been a significant increase in the built-up areas of all the evaluated cities in response to the ongoing rapid urbanization in Pakistan over the past three decades. Interestingly, it is found that the increase in LST, UTFVI, and built-up area due to urbanization is much higher in mediocre cities rather than in large urban agglomerations, such as Lahore and Faisalabad, which are the second and third largest cities in Pakistan. This could be the potential consequence of higher saturation in terms of built-up areas in larger cities, and now the smaller urban areas in the vicinity are facing a larger increase in urbanization and its impacts on the urban thermal characteristics (i.e., UTFVI). Given the impacts of rising heat in cities on health, as well as energy consumption, there is an immediate need for adaptation measures. For UHI mitigation, policies should emphasize reflective surfaces (green roofs and green walls) in the strongest UTFVI zones. Besides, localized projects should be introduced and handled by local municipal governments, which should ensure public participation by providing them incentives in sustainable conservative initiatives for combating urban heat stress. Since green cover directly influence UHI concentration, policies should be established for a no-net-loss green cover particularly in the strongest UTFVI areas and all the cities in Pakistan in general. Lastly, though Pakistan is among the countries with a minimal proportion of global emissions, heat stress can further be reduced by achieving net zero GHGs emission. The results from this study, such as the areas with higher UTFVI values, can guide pinpointing priority intervention areas for immediate and/or gradual actions to avoid the potential consequences due to the warming of these cities—resulting in enhanced comfort in urban regions.

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