Urban Thermal Environment Under Urban Expansion and Climate Change: A Regional Perspective from Southeast Asian Big Cities

Chapter · September 2023

DOI: 10.1007/978-981-99-3675-5_9

4 authors:

Can Trong Nguyen
Charles University in Prague

Amnat Chidthaisong
King Mongkut's University of Technology Thonburi

Rungnapa Kaewthongrach
King Mongkut's University of Technology Thonburi

Wijitbusaba Marome
Thammasat University

Chapter 9
Urban Thermal Environment Under Urban Expansion and Climate Change: A Regional Perspective from Southeast Asian Big Cities

Can Trong Nguyen, Amnat Chidthaisong, Rungnapa Kaewthongrach, and Wijitbusaba Marome

Abstract Southeast Asia (SEA) is a hotspot of rapid urbanisation and climate change, which is supposed to influence millions of people. They altogether exacerbate urban thermal environments and amplify urban heat islands (UHIs). The chapter provides a comprehensive assessment of urban warming trends in SEA big cities over the past thirty years in a connection with urban expansion and climate changes; of which climate change is represented by temperature extremes as an additional element deteriorating UHIs. It reveals a significant warming trend in nighttime extreme indices across the cities against daytime indices. Manila and Kula Lumpur have confronted the most prominent temperature variations. There were drastic transformations in urban areas, urbanisation patterns, and landscape characteristics during urbanisation. The fastest-growing cities during this period are Jakarta, Bangkok, and Ho Chi Minh City. The degradation of the urban thermal environments was also confirmed via spatiotemporal escalations of land surface temperature (LST) and surface UHI (SUHI) over time. The aggravation in urban thermal environments was mainly driven by urbanisation-related elements and temperature extremes as a background climate factor. The changes in surface characteristics are the main driving factors across the cities. Yet, the stimulations of climate on thermal environment

C. T. Nguyen (✉) · A. Chidthaisong
The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi (KMUTT), Bangkok 10140, Thailand
e-mail: can.nguy@kmutt.ac.th

C. T. Nguyen
Faculty of Engineering, Prince of Songkla University (Hatyai campus), Songkhla 90110, Thailand

C. T. Nguyen · R. Kaewthongrach
Space Technology Research Center, Geo-Informatics and Space Technology Development Agency (GISTDA), Chonburi 20230, Thailand

W. Marome
Thammasat University Research Unit in Urban Futures and Policy, Pathum Thani 12121, Thailand

Faculty of Architecture and Planning, Thammasat University, Pathum Thani 12121, Thailand

A. Cheshmehzangi et al. (eds.), *Climate Change and Cooling Cities*, Urban Sustainability, https://doi.org/10.1007/978-981-99-3675-5_9

degradation are uneven among the cities. Ho Chi Minh City, Jakarta, and Manila are the most vulnerable cities due to combined impacts rather than others. It verifies the integrated impacts of climate change and urbanisation on urban microclimate change, it therefore should have long-term strategies to mitigate the adverse effects of SUHI. The general principle is to reduce horizontal urban expansion, ensure urban spatial planning and urban green spaces, and mainstream climate change adaptation into urban planning.

Keywords Climate changes · Megacities · Southeast Asia · Urban heat island · Urban expansion

1 Introduction

Southeast Asia (SEA) has seen significant urbanisation since the middle of the twentieth century. Along with urban expansion, natural landscapes are increasingly encroached upon by urban features. It causes a difference in temperatures along the urban–rural gradient, called urban heat islands (UHIs) (US EPA, 2008). The urban heat island phenomenon is one of the most concerning problems in urban areas since it causes thermal discomfort, heat-related morbidity, mortality, and high energy consumption for cooling demand (Nguyen et al., 2021a; Santamouris, 2020). With global warming and further urban development, the UHI phenomenon will be likely deteriorated. It means urban thermal environments will be more severe because of the integrated impact of continuing urban expansion and global warming (Fig. 1). However, as indicated by Chapman et al. (2017) only about 14% of the existing studies have assessed urban expansion and climate change interactions on urban thermal environments such as land surface temperature (LST) and UHIs.

1.1 Rapid Urbanisation

After the colonial periods, many Asian countries immediately rebuilt their countries. Most countries have rapidly developed with intensive urbanization, increased population, and industrialisation in the primate cities. However, the outstanding development of the economy in Asian countries only began in the 1980s. Such a transition was even faster than in some western regions (Yamashita, 2017). Mingxing et al. (2014) revealed that the annual growth rate and economic growth rate in SEA from 1980 to 2010 were always higher than that in other regions. An assessment based on population growth and economic development (GPD per capita) indicated that Singapore, Brunei, and Malaysia have a high urbansation level; Cambodia, Timor Leste, Vietnam, Laos, and Myanmar have a less advanced economy with medium–low urbanisation; Thailand, Indonesia, and the Philippines place between these two nation clusters (Yap & Thuzar, 2012).

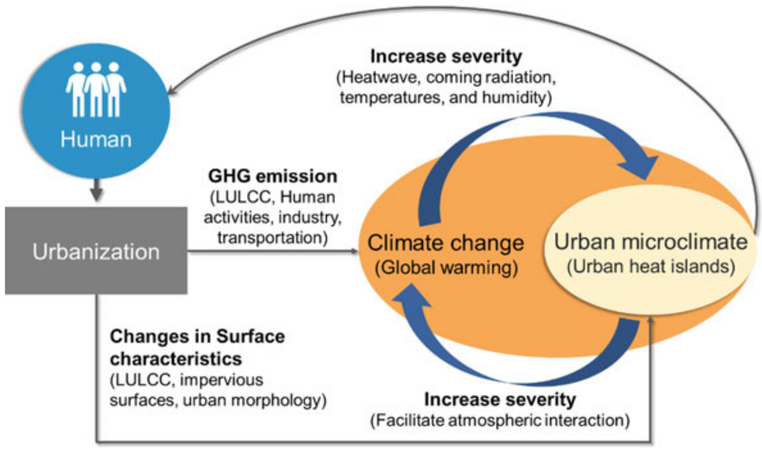

Fig. 1 Conceptual framework about interactions between urbanization, climate change, and urban microclimate change (*Source* Authors' own creation)

SEA is relatively dynamic regarding population growth since this region is the third-highest subregion by population in the Asian continent. Its population was about 662 million in 2019, with half of the population living in urban areas (United Nations, 2019). The urban population is expected to reach 56% in 2030, in which Brunei, Indonesia, Malaysia, Philippines, and Thailand will become spotlights of regional urbanisation in the next ten years. Currently, SEA holds three out of 33 megacities worldwide, including Manila (13.4 million), Jakarta (10.5 million), and Bangkok (10.1 million). The region is also home to 4 of the 48 cities with 5–10 million residents. These cities were Ho Chi Minh city (8.1 million), Kuala Lumpur (7.6 million), Yangon (5.2 million), and Singapore (5.8 million). These are expected to be the next megacities in the future (United Nations, 2019).

Spatial-based assessments on urbanisation (simultaneously or separately) revealed a consistent trend of rapid urban expansion over time. Schneider et al. (2015) confirmed the fast urban sprawl in SEA, in which the built-up expansion was even higher than the regional average (2.0%/year) and Eastern Asia countries, e.g., the Philippines (2.2%/year), Cambodia (2.9%/year), and Laos (3.2%/year). The robust urbanisation was also characterized by nighttime light (NTL), which shows the urban expansion from the centers outwards dominated by the areas of low-intensity NTL (Min et al., 2018, 2020). During the period 1992–2013, NTL data revealed that Thailand, Timor Leste, Myanmar, Vietnam, Laos, and Cambodia developed faster than the entire SEA, in which Cambodia underwent a remarkable rise of approximately 1,800% (Min et al., 2018).

1.2 Climate Change in SEA and Its Impacts on Urban Areas

SEA is among the most vulnerable regions considering global warming and climate change impacts. There is clear evidence of an increase in mean near-surface temperature compared to those observed in 1850–1900 as well as precipitation and extreme events (ASEAN Secretariat, 2021; IPCC, 2021a). In the future, regional climate change will be expected to increase its extremeness. Heat and cold extremes have been detected in two confidences opposing upward and downward trends, respectively. These trends will continue over the coming decades at a high confidence level. Despite the warming trend in SEA being lower than the global average, heat stress impacts are increasingly prominent under the RCP8.5 scenario, especially in Myanmar, Philippines, Thailand, Vietnam, and inland populous cities (IPCC, 2021a).

Moreover, urban areas and cities are the hotspots of global warming since they are mostly warmer than the surrounding areas due to anthropogenic heat sources from human activities, compact urban geometry, and heat trapped in urban materials and impervious surfaces. These factors can accumulatively increase the urban temperature by +3.0 °C to +5.5 °C. Within urban and city areas, there is usually a severe shortage of natural cooling sources, while these landscapes can provide efficient cooling effects, i.e., water bodies (–0.8 °C to –1.2 °C) and vegetation (–1.6 °C to –3.0 °C) (IPCC, 2021a).

Although urbanisation is not the main culprit of warming urban thermal environments, it remarkably contributes to the warming effect in urban areas against surrounding areas. The exacerbation of urbanisation on the total warming is from one-eighth, especially this proportion may reach over a half of the total warming in some cities in the Eurasian continent. Future urban development will amplify the urban air temperature regardless of the cities' background and climate patterns, especially the warming signal on minimum temperature, which will be even more prominent than global effects. There will be far-reaching impacts caused by a synergy between urban expansion and more frequent heatwaves with more hot days and warm nights. It will negatively push the cities into more extreme conditions when urban dwellers' thermal comfort is stressed (IPCC, 2021b).

Therefore, the major research questions leading to this chapter are: How SEA cities have faced local and global changes in urban sprawl, microclimate, and climate extremes over the past three decades? Is there an interaction between climate extremes and urban expansion to urban microclimate change? And, how does this dominance differ across the cities? The chapter begins by monitoring temperature extremes, built-up area expansion, and surface temperature changes from 1990 to 2020 before the interactions among them are then explored to figure out the highlights in each city. Thereby discussing points that should be noted in urban planning for cooler cities.

2 Materials and Methods

This chapter is concerned with five big cities in SEA in terms of population size, including three megacities of Manila (MNL: 13.4 million), Jakarta (JKT: 10.5 million), and Bangkok (BKK: 10.1 million) and two other big cities of Ho Chi Minh City (HCM: 8.1 million) and Kuala Lumpur (KLP: 7.6 million) (Fig. 2). SEA lies around the low latitude, so this physical pattern contributes significantly to forming distinctive regional climates. This region is influenced by two climate systems: the monsoon winds system (i.e., northeast and southwest) and the humid equatorial climate (Gupta, 2006). The seasonal variation increases in higher latitude regions, but the average variation of annual temperature does not exceed 5 °C, while the maritime region's climate tends to be more stable.

Extreme temperature indices represented climate changes, specifically as global warming and temperature increase. Observation data collected from weather stations, especially those placed in urban areas, often face overestimation since it is a result of a complex interaction (Yaung et al., 2021). Therefore, reanalysis data of TerraClimate was adopted to limit this effect in the calculation of seven temperature indices of mean minimum temperature (TNMEAN), minimum of minimum temperature (TNN), maximum of minimum temperature (TNX), mean of maximum temperature (TXMEAN), minimum of maximum temperature (TXN), maximum of maximum

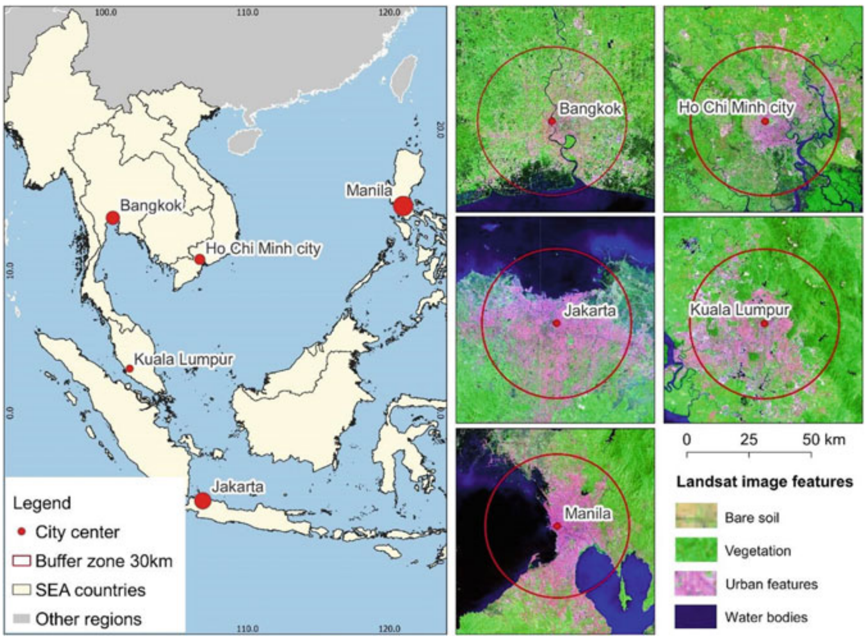

Fig. 2 Location of selected cities in SEA with dot size presenting population scale and false colour composite of Landsat images in 2020 within a 30-km buffer region from the nominal city centers

temperature (TXX), and heat index (HI)—a function between temperature and humidity. The trend of extreme indices was analysed by Mann–Kendall analysis to recognize the monotonic trend (Sein et al., 2018).

Landsat imagery (i.e., Landsat 5-TM, 7-ETM, and 8-OLI) is the core dataset to retrieve land surface temperature (LST), surface urban heat island (SUHI), and delineate urban land use, land cover (LULC) maps. LST was extracted using reflective information from the thermal infrared band and emissivity based on NDVI (Normalised Difference Vegetation Index). SUHI was then identified as LST differences between urban and rural areas, whereas urban–rural boundaries were defined based on LST changes along the urban–rural gradient (Wemegah et al., 2020).

LULC maps in each city were classified from Landsat multispectral bands and spectral indices adopted a classification framework introduced by Nguyen et al. (2022), which releases the dependency of training and validation datasets on field survey data. Specifically, the training and validation datasets were randomly selected based on confident regions, which were detected using spectral indices corresponding to each LULC category (Nguyen et al., 2021b; Tucker, 1979; Xu, 2006). Subsequently, the LULC layers were adopted by using support vector machine classifier (SVM).

Urban features were then extracted for urban expansion analysis to recognise the main urban sprawl trend in each city, which could be infill, extension, or leapfrog patterns. Landscape metrics were calculated for both urban and vegetation features to reflect characteristics of urban and vegetation changes over time, such as AI (aggregation index), ENN (Euclidean nearest neighbor distance), LPI (largest patch index), LSI (landscape shape index), NP (number of patches), PD (patch density), and PLAND (proportion of landscape).

The individual parameter was examined through change detection analysis before they were scrutinised by Partial Least Squared Regression (PLSR) model with dependent variables of LST and SUHI. The PLSR is also a variable reduction method similar to principal component analysis. Yet, it considers independent variables with controls from a/a few dependent variables. Important variables were retained using variable importance on projection criteria (VIP > 1) to reveal the critical controlling factors (Lew et al., 2019).

3 Results and Discussion

3.1 *Manifestations of Climate Change Through Extreme Temperatures*

During 1990–2020, the SEA cities have seen consistent warming and severity trends for extreme temperature indices through significant Mann–Kendall analysis and Thiel-Sen slope (Table 1). The severity is the most evident for heat index and nocturnal temperatures across the cities.

Table 1 Thiel-Sen's slope presents changing magnitude for temperature-based extreme indices over the whole period (°C/decade)

Temperature index	BKK	HCM	JKT	KLP	MNL
HI	0.42*	0.70*	0.43*	0.80*	0.57*
TNMEAN	0.12	0.24*	0.31*	0.35*	0.23*
TNN	0.12	0.30	0.30*	3.70*	0.16
TNX	0.06	0.24*	0.29*	0.33*	0.30*
TXMEAN	0.04	0.05	0.06	0.17*	0.09
TXN	0.04	0.04	0.05	0.19*	0.14
TXX	–0.08	–0.07	0.20*	0.20	0.09

Symbol (*) indicates statistical significance

The changes in TN-based indices were more apparent, which were detected in almost every cities. TNMEAN and TNX are noteworthy regarding the number of detectable cities with significant enlargements (except for BKK), while TNN has a relatively higher increasing magnitude than the other two indicators. The warming trend of TNX was consistently identified across the cities. KLP has experienced the highest warming among other cities for every nocturnal index. However, the warming trend in TNN was rarely found, which was only significant in JKT (+0.3 °C/decade) and KLP (+0.37 °C/decade). The daytime warming was also detected, however, this change is less significant compared to those observed during nighttime. The significant warming was only found in KLP (TXMEAN and TXN) and JKT (TXX).

During the thirty years, there have been critical increasese in the city's daytime and nighttime temperatures and heat index. These variations were observed through changes in extreme indices, which describe different temperature aspects. Nocturnal warming is more apparent compared to daytime warming. However, daytime warming can be detected when considered together with the corresponding relative humidity, reflected via heat index. The severity of extreme indices was recognised in most cities via at least one significant indicator. And, the cities in this region exposed to high heat index were KLP, JKT, and HCM.

3.2 Urban Expansion and Alternations of Surface Characteristics

3.2.1 Urban Expansion Trends from 1990 to 2020

The cities have experienced urbanisation along with LULC changes (LULCC) over the past thirty years to different extents. The primary dynamic is none other than urban expansion, which is observed through urban sprawl and vegetation shrinking. The primate city cores in 1990 have expanded outwards by unique forms depending on each city's characteristics in terms of geographical location and topography, but mainly in the flat plains and valleys along transportation systems. These forms of expansion are prominently observed in BKK, HCM, and JKT (Fig. 3).

In the 1990s, it indicates that BKK held the largest urban areas, about 448 km^2. It was then followed by MNL and JKT, which were approximately a quarter of the urban areas in BKK. The urban areas in HCM and KLP only sealed a relatively small proportion. After thirty years of development, BKK was still the largest metropolitan in terms of urban areas. There were 1,114 km^2 of built-up areas in the buffer zone of the BKK metropolitan. JKT has rapidly expanded its urban areas to gain an extensive area of 1,070 km^2 and to be the second-largest city. The proportion of built-up areas in these two megacities is approaching 50%, i.e., 45.3% in JKT and 39.6% in BKK. Notably, the urbanisation in HCM has considerably developed since the 2010s and became the next largest city with 694 km^2 of urban areas in 2020.

The entire region has experienced rapid urbanisation over the past three decades. Some cities have made enormous strides over this period, which have been witnessed through the annual urbanisation growth rate (AUGR). More explicitly, JKT is the fastest growing city among the others with AUGR = 137%/year. The growth rate was relatively even throughout the whole period, and it was always higher than 100%/year for each ten-year interval. BKK, HCM, and MNL have relatively similar characteristics of urban growth, which underwent a moderate-fast urban expansion with an average AUGR for the whole period of around 75–79%/year. The AUGR gradually augmented over time and achieved the highest rate in the last ten years.

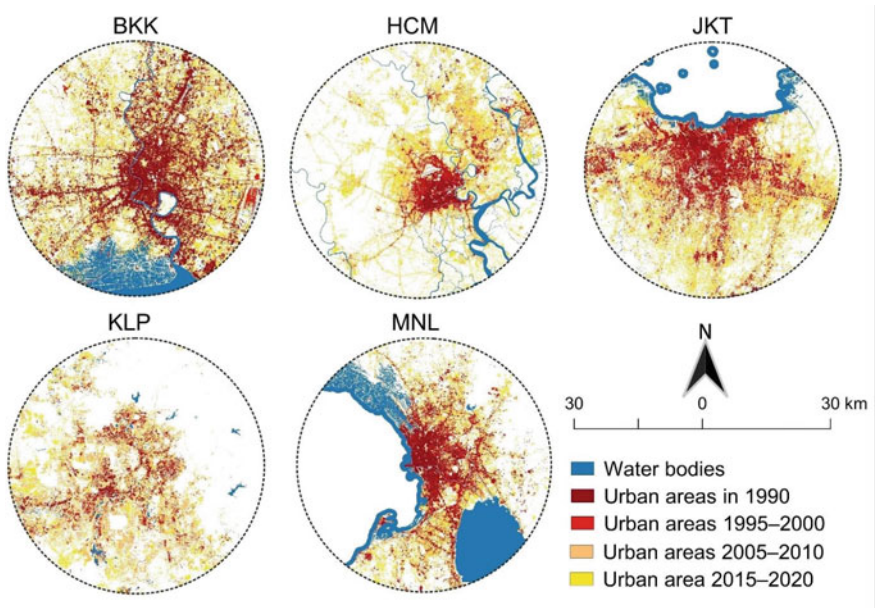

Fig. 3 Spatial distribution of the expended urban areas from 1990 to 2020

Table 2 Proportion of urbanisation patterns in SEA cities over the past thirty years

City	Area (km^2)				Proportion (%)		
	Infill	Extension	Leapfrog	Total	Infill	Extension	Leapfrog
BKK	58.1	555.6	100.0	713.7	8.1	77.8	14.0
HCM	7.8	456.9	181.3	646.0	1.2	70.7	28.1
JKT	12.2	779.3	187.8	979.3	1.3	79.6	19.2
KLP	1.4	334.6	220.6	556.6	0.3	60.1	39.6
MNL	16.7	348.1	75.6	440.3	3.8	79.1	17.2

During the urban expansion, it is similar to others developing cities when the major urbanisation form is the extension—a new urban area developed at the fringe of the already developed urban areas. This form always accounts for more than half of total urbanised areas (Table 2). It even reaches nearly 80% of urbanized areas in the fastest growing city of JKT (79.6%) and the city with limited potential areas for urbanisation like MNL (79.1%). Leapfrog form, which develops separately outside the previous urban areas in the rural areas, is the second main form. Leapfrog is the popular urbanisation form in the newly developed cities or "young cities" as they plan to establish new residential areas independently at potential locations in rural areas (Hong Diep et al., 2021). Then, urban infrastructures connect these "satellite cities" with the primate city to form a great metropolitan. KLP and HCM are the prominent cities with a noticeable proportion of leapfrog patterns, 39.6% and 28.1%, respectively. Infill is the least popular form among the three urbanisation patterns, which is constructed between already developed areas. It intends to be encountered in developed and more mature cities such as BKK (8.1%) and MNL (3.8%).

3.2.2 Alterations in Landscape Characteristics

Along LULCC and urban expansion, landscapes have been profoundly transformed that leading to a significant shift in landscape composition and configuration. The landscape characteristics of built-up and green spaces are the most sensitive quantities during these transformations, which change towards urban agglomeration and vegetation fragmentation. The landscape metrics mainly reflect two focused characteristics of area/edge and aggregation/fragmentation (Table 3). In general, the trends of built-up and green space features are opposite each other.

PLAND and LPI indicate edge and area attributes. It is in line with the findings of urban expansion and increases in city size since urban PLAND was remarkably elevated in all cities, approximately 0.73–1.38%/year. LPI also reveals the enlargement of built-up patches. It is prominent in JKT with PLAND increasing by 1.38%/year and 1.07%/year (LPI). The large urban patch in BKK and MNL grew faster than in HCM and KLP. At the same time, vegetation presented the corresponding shrinking trend over time. JKT, BKK, and KLP have faced considerable degradation in green coverage. The green spaces in almost every city have also been shrunk into

Table 3 Variations in average landscape metrics for urban features and green spaces

Features	Metrics	BKK	HCM	JKT	KLP	MNL
Built-up	AI	−0.03	0.05	0.36*	0.49*	0.2*
	ENN	−1.36*	−3.98*	−1.29*	−1.67*	−1.5*
	LPI	0.81*	0.41*	1.07*	0.26*	0.63*
	LSI	2.31*	3.09*	1.76*	2.52*	1.09*
	NP	265*	496*	174*	327*	86*
	PD	0.09*	0.18*	0.07*	0.12*	0.04
	PLAND	0.78*	0.75*	1.38*	0.75*	0.73*
Green spaces	AI	−0.26*	−0.1	−0.32*	−0.12*	0.05
	ENN	−0.31*	0.14	0.10	0.01	−0.06
	LPI	−0.68*	−0.26*	−2.42*	−0.59*	0.18
	LSI	2.87*	1.27	3.17	1.77	−0.29
	NP	266*	118*	295*	120*	16
	PD	0.09*	0.04*	0.13*	0.04*	0.01
	PLAND	−0.74*	−0.37	−1.24*	−0.50*	0.17

Symbol (*) indicates statistical significance

smaller patches. Notably, the green spaces in MNL have been improved steadily since 2000, this advance is however insignificant during the considered time.

Landscape aggregation and fragmentation were assessed using LSI, ENN, NP, PD, and AI. For urban features, there were consistent trends of increasing LSI and decreasing ENN entire the cities, revealing that built-up patches have developed more closely together and formed more complex shapes. Among the cities, HCM has seen sharp changes in NP, PD, ENN, and LSI for urban features. It implies that HCM is the most dynamic city in terms of quantity, distribution, and shape, becoming more aggregated, compact, and complex. The same trends were found in JKT, BKK, and KLP at a lower rate, while the urban development in MNL was relatively moderate.

The vegetation patterns were significantly changed towards increase in fragmentation. There were increases in the number of green patches (NP) and PD in almost all cities along with the complexity of green spaces (LSI), while LPI declined over time. The extensive green patches are strongly fragmented into smaller discrete patches by constructions and residential areas, which then leads to a compounded landscape with degraded green coverages. JKT, BKK, and KLP have encountered noticeable vegetation shrinking. It was reported that urban green space per capita in BKK and HCM has even much improved compared to the first decade of the century, however, it is still lower than the WHO recommendation (Nguyen & Chidthaisong, 2022). Meanwhile, the vegetation dynamics in MNL tend to be more stable throughout the period than in other cities as a sign of urban reforestation.

3.3 Escalation in Urban Surface Temperatures

Urban thermal environments observed by LST and SUHI showed deterioration in both spatial and temporal aggravations (Fig. 4). All cities have increasingly warming trends and expand the dominated areas occurring in SUHI over the past 30 years. Long-term observation of spatial changes in SUHI indicated that about one-third of the total area in MNL (32.9%) and KLP (31.3%) has confronted the prolonged SUHI (i.e., area with SUHI frequency of higher than 20 years). This region in JKT and BKK also accounts for a significant share of the area, about one-fourth of the total area. Besides, the majority of HCM areas are dominated by the newly formed SUHI with a frequency of fewer than 10 years, about 64.2%. MNL and HCM are the most severe cities within the last three decades because their annual average LST is relatively hot, about 26.0 °C and 25.0 °C.

LST and SUHI have significantly increased over time. A group of three cities, including BKK, JKT, and KLP, has overcome considerable warming in LST, which varies from 1.23 °C/decade to 1.28 °C/decade. MNL and HCM are more modest when their LST have been warmer, about 1.17 °C/decade and 1.08 °C/decade, respectively.

The SUHI has been aggravated at a high significance level ($p < 0.01$) except for HCM ($p < 0.1$). MNL is the harshest city with the most intensive SUHI intensity throughout the time (SUHI ≈ 3.01 °C). The second severe city is KLP with average

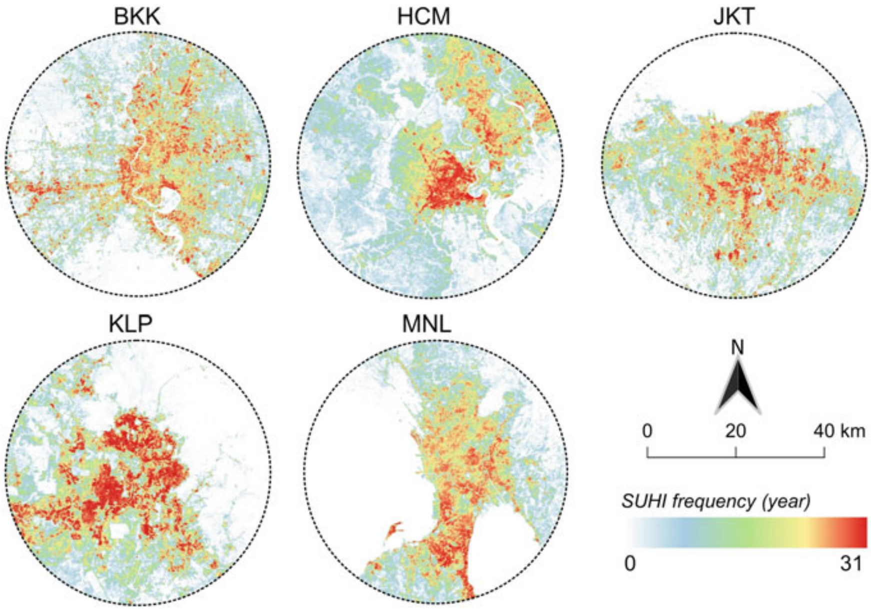

Fig. 4 Spatiotemporal changes in SUHI over the past thirty years observed by SUHI frequency (unit: years), which represents number of SUHI occurrence. Red represents consistent and prolonged SUHI regions, while green and cyan are new and less prolonged SUHI regions

SUHI intensity of about 2.21 °C. These two cities have apparently overcome the fastest-growing SUHI intensity, approximately 0.35 °C/decade (MNL) and 0.37 °C/decade (KLP). They are then followed by JKT (0.23 °C/decade), HCM (0.19 °C/decade), and BKK (0.15 °C/decade).

3.4 Integrated Impacts on Urban Surface Temperatures

Dominant mechanisms of landscape configuration and climate changes for regional urban thermal environments are explained by a significant PLSR model (Fig. 5a–b), with a 62.3% variance of thermal environments described by the first component (Comp1). Specifically, the first component's variations of LST are highly interpreted ($R^2 = 0.68$). The most important variables (VIP > 1) are constituted by landscape patterns of urban features (NP and PD) and green spaces (AI, LPI, LSI, NP, PD, and PLAND). Climate extremes also contribute to changing thermal environments by TNX and TXX. More explicitly, the increases in built-up areas with vegetation fragmentation will warm up the LST in a city, while extreme climate such as an increase in the maximum daytime and nighttime temperatures will exacerbate this severity. Although the SUHI intensity is less characterized by the considered independent variables ($R^2 = 0.22$), it potentially explains the escalation of SUHI intensity by most of the urban features except for LSI and NP, in which urban agglomeration facilitates SUHI deterioration. The fragmentation of vegetation represented by PD will increase SUHI, while increasing the proportion of green spaces is able to diminish the formation of SUHI significantly. Similar to LST, SUHI is also driven by climate change via an increase in the nocturnal temperatures of TNMEAN and TNN.

The unique driving factors of SUHI in each city were depicted by separated PLSR models (Fig. 5c). The SUHI in SEA cities is stimulated by combined impacts from the dynamics in urban expansion and green spaces and climate changes at different extents. Urbanisation was detected to highly exacerbate SUHI in MNL and KLP, reflected by several landscape composition and configuration indicators. This impact is more moderate in JKT and BKK, where changes in urban aggregation and morphology tend to adjust the SUHI escalation significantly. In HCM, the key element controlling its SUHI is the expansion of urban strips. The impact of vegetation dynamics was found to have a less pronounced impact than urban features. For instance, it is invisible in MNL, which means the SUHI growths during the period were not mainly contributed by vegetation changes. In contrast, the increase in SUHI in JKT was caused by a decline in vegetation proportion, while the fragmentation of green spaces was the main culprit inducing SUHI in BKK. Noticeably, HCM and KLP are the places that have encountered SUHI aggravation due to vegetation shrinking and fragmentation. HCM has undergone a quantitative decline, while the vegetation coverage in KLP has degraded proportion and fragmentation. With respect to climate extremes, all cities tend to be influenced by changing climate and ultimately reflecting via SUHI. The most severely affected cities are HCM, JKT, and

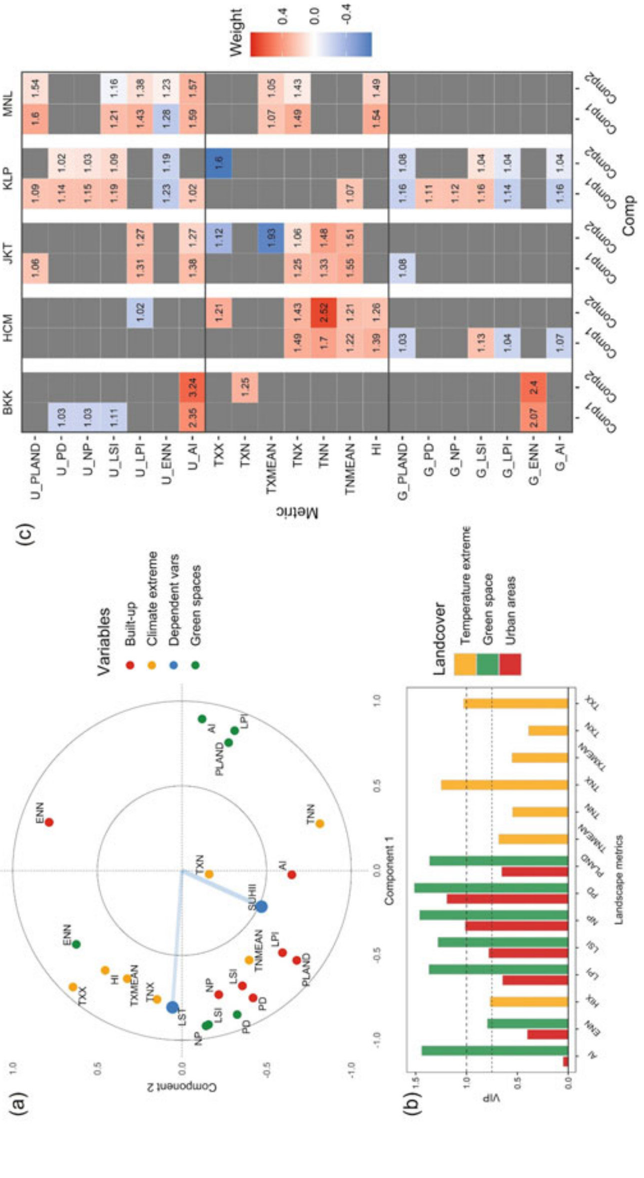

Fig. 5 PLSR analysis shows (a) correlation circle between landscape metrics of built-up and green spaces, climate extreme indices, and thermal environments; (b) important variable selection; and (c) important variables in each PLSR model to characterize SUHI in each city. Numbers show VIP values; color shades represent impact tendency (blue: negative and red: positive), and gray cells are insignificant variables

MNL, where variations in heat index and nighttime temperatures prominently link to SUHI formations.

3.5 Implications for a Long-Run Vision Toward Cooler Cities

SEA cities have been undergoing rapid urbanisation causing urban thermal environment changes throughout the cities. It will worsen due to unceasing urban expansion and the amplification of climate change. Therefore, an insightful understanding and long-term strategies to mitigate UHIs are essential, which could achieve by controlling each corresponding element. In general, the urban sprawl in developing cities in the global South and megacities is dominated by infrastructure-led development (ILD), e.g., built-up mainly expands along the transportation systems in BKK, HCM, and MNL. In addition to its benefits in connecting development nodes and resource frontiers, ILD raises different socioeconomic and environmental issues, such as high land budget demand and daunting land acquisition (Sisson et al., 2018). ILD also causes uncontrolled urban growth because this urban sprawl form often goes beyond the administrative boundary, e.g., the Thailand Eastern Economic Corridor (Can et al., 2021). Therefore, urban and land use plans should be considered at regional levels and cross-boundaries rather than individual counties to better manage urban development and then impede UHI growth. Uniform urban growth among primate and secondary cities should be encouraged to relieve burdens for megacities, especially migration waves for jobs that may lead to unintended development of infrastructures due to shelter demands. It ultimately causes UHIs because of an increase in built-up areas.

Built-up areas in all cities drastically expand horizontally. This expansion will gradually encroach on neighboring areas, especially in green/blue spaces such as forests, agriculture, and wetlands. Besides, the nominal mature cities of BKK, MNL, and KLP expanded mainly by infill form, which is hotter than the other two patterns (Zhang et al., 2021). Therefore, constructions between already urban areas in these cities should be carefully considered as to whether they should be for construction or green space conservation to mitigate UHIs. Compacting urban areas by vertical increase with height-rise buildings, multifunctional stories, and apartments are also a potential solution to prevent further expansion outwards. However, it should be thoroughly considered urban morphology and ventilation to avoid adverse effects. Especially, the severity of nighttime temperatures in HCM, JKT, and KLP is a critical sign implying the problem in urban morphology and compactness, which need prompt attention to avoid accompanying consequences.

There is a scarcity of urban green spaces presently in SEA cities. The reduction rate of green spaces is speedy, and the remaining green spaces are also degraded and severely fragmented. Although the governments have made efforts to improve average green space per capita, it is still lower than the recommendation. Therefore, urban green space areas need to optimize in the downtowns of these cities. Also, the concept of ecosystem services should be strengthened and integrated into land use planning and urban green infrastructure projects to mitigate UHIs.

Presently, it is relatively rare for a developing city to mainstream global warming and climate change into urban planning since it is not a main diver of urbanisation. Yet, climate change along with urbanisation is supposed to influence the urban thermal environments significantly to different extents in each city. It should incorporate climate change into the master plan as an important challenge to address throughout the development of vulnerable cities due to climate changes (e.g., HCM, JKT, and MNL). Subsequently, there is appropriate design planning for temperature changes and SUHI formation and the risk of sea-level rise, urban inundation, and tropical storms to sustainably develop toward more livable cities.

4 Concluding Remarks

Climate change through global warming plays as an additional driver along with urban expansion and alternations in surface characteristics exacerbating urban thermal environmental changes. A warming trend was found in entire SEA cities regardless of daytime and nighttime, of which MNL and KLP have confronted the most prominent noctural variations. All the cities are relatively dynamic in terms of urban development with dramatic transformations in urban areas, urbanisation patterns, and landscapes. The fastest expanding cities are JKT, BKK, and HCM. The degradation of the urban thermal environments was also confirmed via escalations of both LST and SUHI. The aggravation in thermal environments was mainly driven by urbanisation-related elements and climate change as a background climate factor. The surface changes are the main driving factors across the cities. Yet, the stimulations of climate on thermal environment degradation are uneven among the cities. The most affected cities by climate changes are HCM, JKT, and MNL, these cities therefore are supposed to be more vulnerable due to combined impacts than the other cities.

Climate change is considered as a return effect, further amplifying the urban thermal environments, even though the forward effect of urbanisation on near-surface temperature is widely accepted. The urban thermal environments in SEA cities are dramatically affected by the integration of both climate change and local transformations from urban development. Therefore, they should have suitable strategies to mitigate UHIs growth by controlling horizontal urbanisation, introducing ecosystem services of urban green spaces, implementing urban green infrastructure projects, and developing climate change resilience interventions. Yet, it is necessary to adjust flexibly for each city depending on its characteristics and priorities. For example, dense cities need to firstly improve the green space per capita, while climate change-prone cities need to immediately develop adaptation and response strategies.

Acknowledgements This work was supported by the Petchra Pra Jom Klao scholarship of King Mongkut's University of Technology Thonburi (No. 09/2562).

References

ASEAN Secretariat. (2021). ASEAN state of climate change report: Current status and outlook of the ASEAN region toward the ASEAN climate vision 2050.

Can, N. T., Diep, N. T. H., & Iabchoon, S. (2021). Direction of urban expansion in the Bangkok Metropolitan Area, Thailand under the impacts of a national strategy. *Vietnam Journal of Earth Sciences, 43*(3). https://doi.org/10.15625/2615-9783/16313

Chapman, S., Watson, J. E. M., Salazar, A., Thatcher, M., & McAlpine, C. A. (2017). The impact of urbanization and climate change on urban temperatures: A systematic review. *Landscape Ecology, 32*(10), 1921–1935. https://doi.org/10.1007/s10980-017-0561-4

Gupta, A. (2006). *The physical geography of Southeast Asia.* Oxford University Press. https://doi.org/10.1111/j.1467-8306.2006.00492.x

Hong Diep, N. T., Nguyen, C. T., Diem, P. K., Hoang, N. X., Al Kafy, A. (2021). Assessment on controlling factors of urbanization possibility in a newly developing city of the Vietnamese Mekong delta using logistic regression analysis. *Physics and Chemistry of the Earth, Parts A/B/C, 126*, 103065. https://doi.org/10.1016/j.pce.2021.103065

IPCC. (2021a). Climate change 2021a: The physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change.

IPCC. (2021b). Regional fact sheet—Urban areas (Sixth assessment report (AR6)).

Lew, S., Glińska-Lewczuk, K., & Lew, M. (2019). The effects of environmental parameters on the microbial activity in peat-bog lakes. *PLoS ONE, 14*(10), 1–18. https://doi.org/10.1371/journal.pone.0224441

Min, Z., Cheng, W., Zhou, C., Li, M., Huang, K., & Wang, N. (2018). Assessing spatiotemporal characteristics of urbanization dynamics in Southeast Asia using time series of DMSP/OLS nighttime light data. *Remote Sensing, 10*(47), 1–20. https://doi.org/10.3390/rs10010047

Min, Z., Zhou, Y., Li, X., Cheng, W., Zhou, C., Ma, T., Li, M., & Huang, K. (2020). Mapping urban dynamics (1992–2018) in Southeast Asia using consistent nighttime light data from DMSP and VIIRS. *Remote Sensing of Environment, 248*, 111980. https://doi.org/10.1016/j.rse.2020.111980

Mingxing, C., Zhang, H., Liu, W., & Zhang, W. (2014). The global pattern of urbanization and economic growth: Evidence from the last three decades. *PLoS ONE, 9*(8), e103799. https://doi.org/10.1371/journal.pone.0103799

Nguyen, C. T., & Chidthaisong, A. (2022). Urban green space inventory using different spatial resolution satellite images: Practical notes in Bangkok. In *The 11th International Conference on Environmental Engineering, Science and Management* (pp. 333–340). Environmental Engineering Association of Thailand (EEAT).

Nguyen, C. T., Chidthaisong, A., Limsakul, A., Varnakovida, P., Ekkawatpanit, C., Diem, P. K., & Diep, N. T. H. (2022). How do disparate urbanization and climate change imprint on urban thermal variations? A comparison between two dynamic cities in Southeast Asia. *Sustainable Cities and Society, 82*. https://doi.org/10.1016/j.scs.2022.103882

Nguyen, C. T., Diep, N. T. H., & Diem, P. K. (2021a). Factors affecting urban electricity consumption: A case study in the Bangkok Metropolitan Area using an integrated approach of earth observation data and data analysis. *Environmental Science and Pollution Research, 28*, 12056–12066. https://doi.org/10.1007/s11356-020-09157-6

Nguyen, C. T., Chidthaisong, A., Kieu Diem, P., & Huo, L.-Z. (2021b). A modified bare soil index to identify bare land features during agricultural fallow-period in Southeast Asia using Landsat 8. *Land, 10*, 231. https://doi.org/10.3390/land10030231

Santamouris, M. (2020). Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change. *Energy and Buildings, 207*, 109482. https://doi.org/10.1016/j.enbuild.2019.109482

Schneider, A., Mertes, C. M., Tatem, A. J., Tan, B., Sulla-Menashe, D., Graves, S. J., Patel, N. N., Horton, J. A., Gaughan, A. E., Rollo, J. T., Schelly, I. H., Stevens, F. R., & Dastur, A. (2015).

A new urban landscape in East-Southeast Asia, 2000–2010. *Environmental Research Letters, 10*(3). https://doi.org/10.1088/1748-9326/10/3/034002

Sein, K. K., Chidthaisong, A., & Oo, K. L. (2018). Observed trends and changes in temperature and precipitation extreme indices over Myanmar. *Atmosphere, 9*(12). https://doi.org/10.3390/atmos9120477

Sisson, A., Rogers, D., & Gibson, C. R. (2018). Property speculation, global capital, urban planning and financialisation: Sydney Boom, Sydney Bust redux. *Australian Geographer, 50*(1), 1–9. https://ro.uow.edu.au/sspapers/4196

Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment, 8*, 127–150. https://doi.org/10.1016/0034-4257(79)90013-0

United Nations. (2019). World urbanization prospects 2018: Highlights. United Nations, Department of Economic and Social Affairs, Population Division.

US EPA. (2008). Urban heat island basics. In *Reducing urban heat islands: Compendium of strategies*. Washington, DC: U.S. Environmental Protection Agency.

Wemegah, C. S., Yamba, E. I., Aryee, J. N. A., Sam, F., & Amekudzi, L. K. (2020). Assessment of urban heat island warming in the greater accra region. *Scientific African, 8*, e00426. https://doi.org/10.1016/j.sciaf.2020.e00426

Xu, H. (2006). Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. *International Journal of Remote Sensing, 27*, 3025–3033. https://doi.org/10.1080/01431160600589179

Yamashita, A. (2017). Rapid urbanization in developing Asia and Africa. In Y. Murayama, C. Kamusoko, A. Yamashita, & R. C. Estoque (Eds.), *Urban development in Asia and Africa geospatial analysis of metropolises* (pp. 47–61). Springer Nature Singapore. https://doi.org/10.1007/978-981-10-3241-7

Yap, S. K., & Thuzar, M. (2012). Urbanization in Southeast Asia: issues and impacts. ISEAS Publishing (Institute of Southeast Asian Studies).

Yaung, K. L., Chidthaisong, A., Limsakul, A., Varnakovida, P., & Can, N. T. (2021). Land use land cover changes and their effects on surface air temperature in Myanmar and Thailand. *Sustainability, 13*(19), 1–21. https://doi.org/10.3390/su131910942

Zhang, X., Estoque, R. C., Murayama, Y., & Ranagalage, M. (2021). Capturing urban heat island formation in a subtropical city of China based on Landsat images: Implications for sustainable urban development. *Environmental Monitoring and Assessment, 193*(3), 1–13. https://doi.org/10.1007/s10661-021-08890-w