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Analysis of Urban Heat Island Effect, Heat Stress and Public Health in Colombo, Sri Lanka and Shenzhen, China

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Abstract: Human health, energy and comfort are determined by the climate that remains in the physical environment. Regarding urban climate, few studies assess the urban heat island effect, heat stress, and public health as geographical representations. This study seeks to fill this gap by selecting Colombo, Sri Lanka, and Shenzhen, China, comparatively, two coastal cities with different climate conditions. We quantified and compared the effects of heat waves and their impacts on public health and the effect of urbanization on urban heat islands (UHI). Heat-related public health issues have been calculated using the Wet-Bulb Globe Temperature (WBGT) index. The Urban Heat Island (UHI) effect was analyzed using Land Surface Temperature (LST), created based on Landsat images obtained in 1997, 2009 and 2019. A rapid increase in temperature and humidity creates an uncomfortable environment in both cities, but apparent differences can be observed in climatic phenomena. During the summer (June to August), the prevailing atmospheric condition in Shenzhen makes a “Very severe stress” with Heatstroke highly likely. Nevertheless, seven months (November to April) are found as “Comfortable” without having any heat-related health injuries. However, Colombo has never been classified as “Comfortable” throughout the year. Out of twelve, five months (April to August) are found as “Very severe stress” with Heatstroke highly likely. When considering the urban expansion and UHI, a fast expansion can be observed in Colombo than in Shenzhen. Consequently, with the more severe heat-related public health and rapid urban heat island expansion, Colombo makes it more stressful than Shenzhen city. Our findings highlight the comparison between heat-related public health and urban heat island between two coastal cities with different climate conditions and under rapid urbanization processes. Therefore, it is imperative to assess these risks and respond effectively.

Keywords: heat stress; human comfort; land surface temperature; public health; heat island

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1. Introduction

The climate is one of the physical sources that is extremely affected not only by thinking of human beings but also by human behaviour and activities [1]. Human health, energy and comfort are determined by climate remaining in the physical environment [2–4]. Climate change refers to significant, long-term changes in the global climate [5]. It directly influences global warming and is projected to affect human health, with primarily negative consequences of increasing the number of excess deaths and hospital admission worldwide [6–8]. Urbanization results in remarked removal and replacement of vegetation cover by various built-up structures, which leads to the urban heat island (UHI) Effect [9,10]. Climate change and urbanization combine to create a perfect disaster of global health risks, such as general discomfort, respiratory issues, heat cramps and strokes, exhaustion, and even heat-related mortality [11–13]. Most of these adverse environmental effects can be minimized by identifying problems and implementing proper urban planning systems with sustainable solutions [14–16]. This study examines the heat waves and their impacts on public health and the effect of urbanization on UHI by selecting the highly urbanized cities of Colombo, Sri Lanka, and Shenzhen, China—comparatively, two coastal cities with different climate conditions.

China is the largest developing country and has a faster increase in surface air temperature than the global average [17,18]. Although the Chinese Government has made increasing efforts to address the impact of climate change, it appears that the health implications have received less attention compared with the energy, economic and agriculture sector [19]. People may adapt to heat stress through modifications in activities, increased use of air conditioning, and alternative building designs. But a vulnerable population may amplify future heat-related health impacts [20]. Shenzhen is a national demonstration zone for sustainable development, with innovation driving China's long-term growth of megacities. Although it is the country's fourth most populous city proper, driven as a global center in technology, research, manufacturing, finance, and transportation, the advancements and sustainable megacity reform initiatives in Shenzhen will be invaluable for other areas [21]. But the trend of increased LST, losses of vegetation, and heat-related health issues from the extreme heat of summer temperatures in the city are increasing, and limited quantified studies have been conducted to analyze them.

Specifically, this research was conducted as a comparative study on the urban heat island effect, heat stress and public health issues in Shenzhen, China, and Colombo, Sri Lanka. Both cities are at high risk of increasing urban heat due to rapid urbanization. Sri Lanka is an island surrounded by the Indian Ocean. The hot weather is dangerously growing [22]. Today Sri Lanka also faced a highly stressful situation with heat stress [23–25]. The trend of mean annual temperatures has been increasing in all meteorological stations in the country. Out of 15 stations, 13 displayed statistically significant ($p < 0.0001$) growing trends [26]. Even traditionally cooler areas are experiencing warmer weather conditions. Also, there have been many hospital admissions because of heat stroke, heat rash (skin), and dehydration [27]. Colombo is the commercial capital and the largest city of Sri Lanka by population [28]. And also it is the administrative capital of the Western Province and the district capital of Colombo District [29,30]. Because of its central location in the Indian Ocean, Colombo port has been one of the most famous in South Asia since ancient times. Due to the high rate of urbanisation, vegetation cover is rapidly diminishing and being replaced by buildings, roads, parking lots, pavements, and other structures.

Furthermore, the region's high vehicle density contributes to the emission of waste heat and pollutant gases. Therefore, previous research has identified Colombo as the most polluted city on the island [31]. As a result of these factors, there is a significant potential for the formation of UHIs within the urban core of Colombo [29].

Both cities of Shenzhen and Colombo are busy with various development projects, business activities and trading. Additionally, the rapid population growth and expansion of urban areas toward the suburban and rural sides address the number of risk cases directly and indirectly combined with urban heat island effects and human health. Although different climatic classifications and research can be seen to identify the various climatic patterns in the cities, attempts to measure heat stress and the urban heat island effect by combining heat-related illnesses are rare and limited to a certain framework. So far, comparing studies addressing all the above issues in spatial and temporal aspects is hard. It seems to be a significant shortcoming in meteorological and urban studies.

This study identifies these issues and their relationships by comparing two coastal cities in tropical and subtropical regions. The results can be used for future urban planning projects to understand the negative impacts of heat stress, UHI effects, and heat-related health issues. At the same time, this research would benefit future studies addressing issues like quantifying the negative heat effect of urban expansion, identifying the population at risk, and identifying the vulnerable sites. And it will also help plan and make policies for various development sectors in both cities.

Conceptual Framework

According to the theoretical framework (Figure 1), a man's thermal comfort mainly depends on four factors. Namely physical activities (indoor and outdoor), climate factors (temperature, humidity, wind, sunshine hours, and Rainfall), clothing pattern (exposure and cover), and internal factors (sweating, metabolic rate, personal adjustment). The specific environmental factors causing heat stress are less movement of air, high humidity, high temperature and radiant heat. Physical works, such as indoor and outdoor activities, also contribute to the total heat stress of a job. In another way, thermal characteristics and the type of clothing worn are also important. Because some clothes are helpful to heat exchange between the skin and the air, but some are stressful for the remaining atmospheric condition.

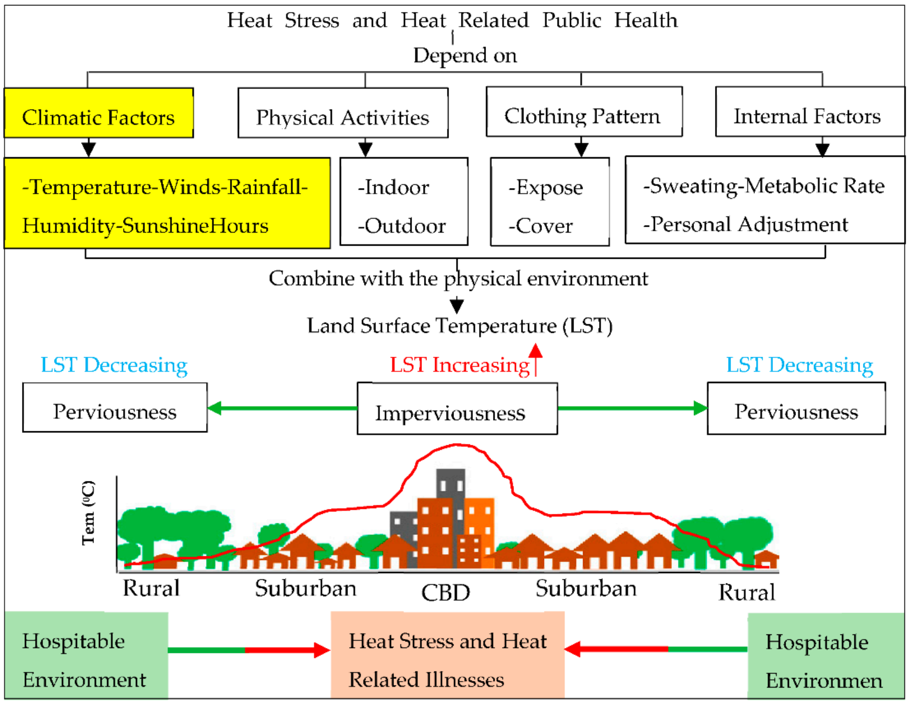

Figure 1. Conceptual framework.

The rapid growth of urbanization leads to multiple diseases, mental and physical stress, and so on. As a result of the development or expansion of cities and towns, significant vegetation loss can be seen. In addition, urban surfaces are covered with buildings, resulting in less shade and less moisture to keep urban areas cool. That caused an increase in the pattern of urban heat patches. Compared to rural surroundings, these conceptual issues warm the urban areas and generate heat-related health issues.

2. Materials and Methods

2.1. Description of the Study Area

Colombo metropolitan area in Sri Lanka and Shenzhen city in China have been selected as study areas for the research (Figure 2). Shenzhen is located in the southeast coastal region of China between 113°46′ E and 114°37′ E and between 2°27′ N and 22°52′ N, with a low altitude in a subtropical region. The city is on the east bank of the Pearl River estuary on the central coast of Guangdong's southern province, with Margin Hong Kong to the south, Dongguan to the north, and Huizhou to the northeast [32]. Its total continental area is 1952 km^2. Shenzhen's climate is highly influenced by the monsoon, with very mild winters and hot, muggy, and rainy summers [33]. In recent decades, the city has evolved from a small border town to a highly urbanized regional economic center. Therefore, it has a solid foundation for exploring the sustainable development of megacities. Therefore, Shenzhen should follow the national sustainable development strategy, formulate distinctive urban sustainable development strategies, and decompose the national sustainable development strategy goals into local goals with specific implementation plans and operability [34,35]. But Shenzhen's urban expansion has nearly reached saturation due to the rapid transformation of urban ecological land into hard urban construction lands. That creates several problems in the city center.

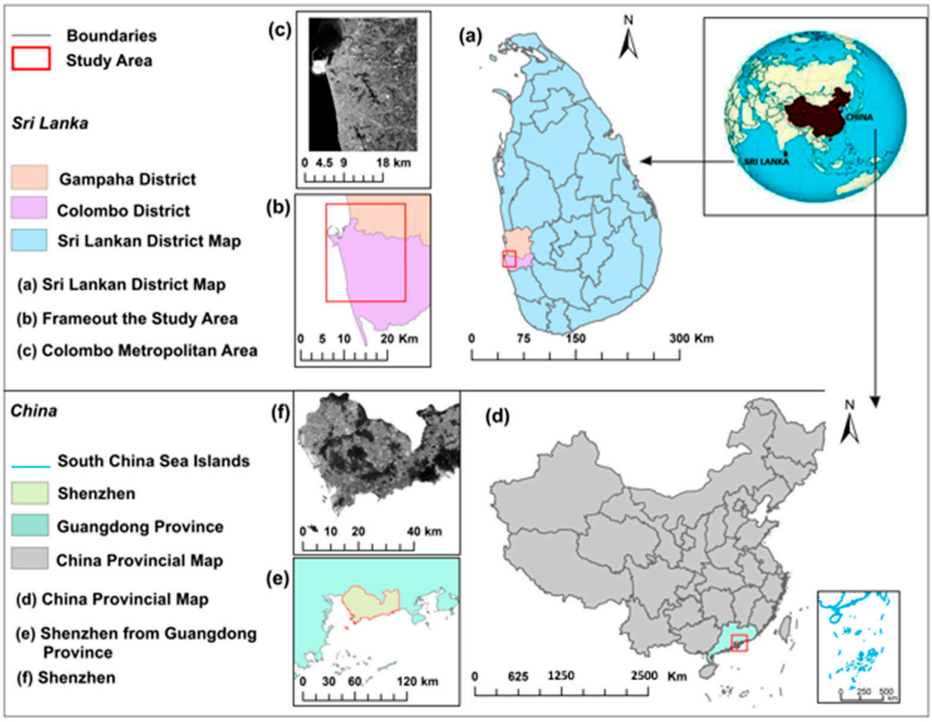

Figure 2. Location of the study area.

Colombo is the commercial capital and the most populous city of Sri Lanka. Due to the location of Sri Lanka, within the tropics between 5°55′ N to 9°51′ N and between 79°42′ E to 81°53′ E, the climate of the island could be characterized as tropical [36]. The city has a warm, humid climate without significant seasonal variations in temperature and humidity [37]. The city has become highly urbanized in the South Asian region due to modern urban development and planning projects. Among the cities of South Asia, the Colombo Metropolitan Area (CMA) is the only one that has seen rapid urban growth and fast changes in surface cover in the last two decades [38]. These massive changes in the urban environment also directly influence the urban heat island hazard and heat-related health problems.

Furthermore, the city is mostly unplanned, and one of the major sources of UHIs is buildings with large footprints roofed with low albedo roofing material such as asbestos or concrete [29]. That creates several heat hazards inside the city. Considering all these issues, this research tried to analyse the urban heat island effect, heat stress and public health issues in Colombo, Sri Lanka and Shenzhen, China, comparatively.

2.2. Heat-Related Illnesses Based on the WBGT Index

They analyzed heat-related illnesses based on the Wet Bulb Global Temperature Index (WBGT) from 2008 to 2018. The Australian Bureau of Meteorology (ABM) has published a simple formula to calculate the WBGT index, and that requires as input only water vapour pressure (ρ) and air temperature (Ta). The website (http://www.bom.gov.au, accessed on

1 March 2023) gives a standard physical science formula to calculate ρ from RH and Ta. The study was based on secondary data from two Meteorology Departments in Colombo, Sri Lanka and Shenzhen, China. Thermal sensation and heat-related health impacts in humans have been classified using the index values of WBGT [39]. The equation to calculate the WBGT index is as follows [40].

$$\text{WBGT}\ (^{\circ}\text{C}) = 0.567\ \text{Ta}\ + 0.393\ \rho\ + 3.94$$

$$\rho\ (\text{hPa}) = \ \text{RH}/100 \times 6.105 \exp(17.27\text{Ta}/(237.7 + \text{Ta}))$$

where Ta—air temperature; ρ—water vapour pressure, RH—Relative Humidity.

The classification was applied for both cities of Colombo and Shenzhen to identify the population at risk monthly and seasonally (Table 1). The WBGT was initially formulated by the United State Navy [41,42] and was developed as a screening tool for analyzing environmental heat stress during industrial, military, sports, and occupational activities. The index has been recommended by the International Organization for Standardization (ISO) certification [40,43]. According to that, WBGT can be taken as a user-friendly and reliable measure of heat stress and health impact assessment. SPSS software and Mann Kendall test [44–46] have been applied for statistical analysis.

Table 1. Heat exposure and associated health effects with WBGT.

WBGT		Thermal Sensation	Health Effects
	≤27.7	Comfortable	—
	27.8–29.4	Partial discomfort	Fatigue
	29.5–31.0	Discomfort	Heat cramps and heat exhaustion are possible
	31.1–32.1	Severe stress	Heat cramps or heat exhaustion likely, and heatstroke is possible
	≥32.2	Very severe stress	Heatstroke highly likely

Source: [39].

2.3. Method of Land Use Classification

There is an interaction between less vegetation, expansion of built-up surfaces and Land Surface Temperature (LST). These combinations, directly and indirectly, lead to the development of an uncomfortable urban environment and making several health hazards. Landsat-5 TM images and Landsat- 8 OLI/TIRS images obtained in 1997, 2009 and 2019 were used for land-use classification and LST calculation in this study (Table A1). Spatial analysis was entirely based on the satellite images downloaded from https://earthexplorer.usgs.gov (accessed on 1 March 2023), and ArcMap 10.7 software was used for the map preparations.

The Normalized Difference Vegetation Index (NDVI) is developed for estimating vegetation cover from the reflective bands of satellite data [47]. NDVI has been one of the most commonly used vegetation indices in remote sensing since its introduction in the 1970s. Moreover, created NDVI images could be used to identify the pattern of land use changes between two different dates [48]. Using Landsat imageries, NDVI values are calculated using the following formula. But the band number of the images changes with the images of Landsat 05 (NDVI = (Band 4 − Band 3)/(Band 4 + Band 3)) and Landsat 08 (NDVI = (Band 5 − Band 4)/(Band 5 + Band 4)) (NDVI, FAQ, 2019). The equation to calculate the NDVI index is as follows [49].

$$\text{NDVI}\ = (\text{NIR}\ -\ \text{RED})/(\text{NIR}\ +\ \text{RED})$$

where, NDVI = Normalized Deference Vegetation Index, NIR = Near Infrared Band, RED = Red Bad

2.4. LST Estimation

Landsat data has been downloaded from the USGS 'Earth Explorer' website. The multispectral bands of the Landsat-5 TM data have a 30 m spatial resolution, while the thermal band (band 6) has a 120 m spatial resolution (https://landsat.usgs.gov, accessed on 1 March 2023). For the Landsat 8 OLI/TIRS data, the multispectral bands also have 30 m spatial resolution, and its thermal bands (band 10 and 11) have 100 m spatial resolution, which has also been resampled to 30 m by the USGS [50]. During the selection of image data, cloud-free images (<10%) have been selected. In addition, radiometric calibration and atmospheric correction have been done for all data sets. The equations to calculate the LST by Landsat Images are as follows [50–52].

Landsat-5 TM data

- Step 1. Thermal Image

$$\text{Band 6.TIF}$$

- Step 2. Conversion DN to Radience

$$\mathrm{L}_\lambda = \left(\frac{\mathrm{LMAX}_\lambda - \mathrm{LMIN}_\lambda}{\mathrm{QCALMAX} - \mathrm{QCALMIN}}\right) \times (\mathrm{BAND6} - \mathrm{CALMIN}) + \mathrm{LMIN}_\lambda$$

- Step 3. Convert Radiance in to BT (in Kelvin)

$$\mathrm{T} = \frac{\mathrm{K2}}{\ln\left(\frac{\mathrm{K1}}{\mathrm{L}_\lambda} + 1\right)}$$

- Step 4. Convert Degree Kelvin in to Degree Celsius

$$\mathrm{C} = \mathrm{K} - 273.15$$

Landsat-8 OLI/TIRS data

- Step 1. Thermal Image

$$\text{Band 10.TIF}$$

- Step 2. Convert DN to Radience

$$\mathrm{L}_\lambda = \mathrm{M}_\mathrm{L} \times \mathrm{Q}_\mathrm{cal} + \mathrm{A}_\mathrm{L}$$

- Step 3. Brightness temperature

$$\mathrm{T}_{10} = \left(\frac{\mathrm{K2}}{\ln\left(\frac{\mathrm{K1}}{\mathrm{L}_\lambda} + 1\right)}\right) - 273.15$$

- Step 4. Calculate NDVI

$$\mathrm{NDVI} = \frac{(\text{Band } 5 - \text{Band } 4)}{(\text{Band } 5 + \text{Band } 4)}$$

- Step 5. Proportion of Vegetation (Pv)

$$\mathrm{Pv} = \mathrm{Square}\,((\mathrm{NDVI} - \mathrm{NDVImin})/(\mathrm{NDVImax} - \mathrm{NDVImin}))$$

- Step 6. Land Surface Emissivity

$$\varepsilon = 0.004 \times \mathrm{Pv} + 0.986$$

- Step 7. Land Surface Temperature (LST)

$$\mathrm{LST} = (\mathrm{BT}/(1 + (0.00115 \times \mathrm{BT}/1.4388) \times \mathrm{Ln}(\varepsilon)))$$

The LST from raw Landsat datasets requires the conversion of the DN values of the thermal bands into radiance values, then which are converted to the satellite brightness temperatures (BT) (in Kelvin) [53]. Finally, convert Kelvin (K) into the degree of Celsius (°C) (Equations above have described the way of LST map preparation by using Landsat 5 TM (Thermal Band 06) and Landsat 8 OLI/TIRS data (Thermal Band 10)). Then, NDVI, Proportion of Vegetation (Pv) and Land Surface Emissivity (ε) must be calculated to obtain the final result of LST in Landsat 8 OLI/TIRS data. Here the brightness temperature is the temperature of a blackbody that would emit an identical amount of radiation at a definite wavelength [54]. Thermal Infrared (TIR) pixel values are firstly converted into radiance from Digital Number (DN) values. Then, radiances for the TIR band of Landsat 5 TM, the LMIN, LMAX, QCALMIN, and QCALMAX values are obtained from the metadata file of the Landsat 5 TM data set.

Their T values are referred as a satellite brightness temperature in Kelvin, K1 (Watts/(m2_srad__m)) and K2 (Kelvin) are the calibration constants, and L is the spectral radiance ((Landsat 5 (Band6); K1 = 607.76 and K2 = 1260.56) (Landsat 8 (Band 10); K1 = 774.89 and K2 = 1321.08)) [50,51]. For Landsat 8 data, calculation of NDVI, Proportion of Vegetation (Pv), and Land Surface Emissivity (LSE) (ε) is essential. In this study, we used m = 0.004 and n = 0.986. Pv is the proportion of vegetation extracted from the NDVI Equation. The NDVImin and NDVImax are the minimum and maximum values of the NDVI, respectively. The Calculation has been done step by step to achieve the final result of LST separately for Landsat-5 and Landsat-8 data sets.

3. Results

3.1. The Temperature Fluctuations of Both Cities

When comparing both cities, apparent differences can be observed in the pattern of climatic phenomena (Table 2). Except from June to September, the temperature in Colombo is higher than in Shenzhen throughout the year. Both cities are located in the coastal belt, and the influence of the sea breeze makes a somewhat comfortable environment. Temperature fluctuation also can be observed as a clear pattern due to the monsoon and seasonal behavior of the cities. This research mainly compares the two cities located in two different climatic zones (Figure 3). Therefore, the temperature transitions from subtropical (Shenzhen, China) to tropical (Colombo, Sri Lanka) can be observed.

Especially the fluctuation of minimum and maximum temperatures of both cities is making a significant pattern throughout the year. During the winter, the maximum temperature of Shenzhen city is below the minimum temperature of Colombo. Except for the period from June to October, throughout the year, the temperature of Shenzhen city is lower than the Colombo city. From January to December, Colombo city's Minimum and Maximum temperatures flow as an equal line. But the curve shape of the pattern in temperature fluctuation can be observed in Shenzhen city due to the seasonal variation (Figure 4).

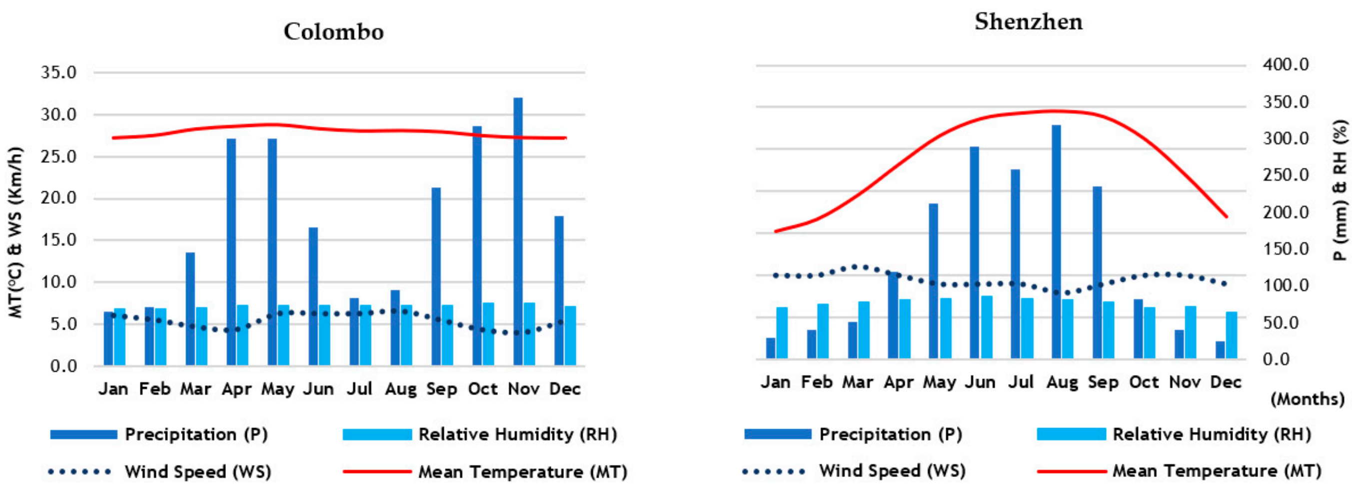

Figure 3. Pattern of climatic variabilities in Colombo and Shenzhen (2008–2018).

Table 2. Summary statistics of temperature and RH (%) fluctuations (2008–2018).

Months	City	Minimum		Maximum		Mean		Std. Deviation		*p*-Value		Sen's Slope	
		T	RH	T	RH	T	RH	T	RH	T	RH	T	RH
Jan	SH	12.0	56.8	18.2	84.0	15.2	71.1	1.6	9.1	0.27	0.08	0.25	1.72
	Co	26.6	72.5	28.3	79.5	27.2	75.3	0.4	2.0	0.39	0.52	0.05	−0.18
Feb	SH	12.6	65.4	21.1	81.7	16.6	75.1	2.3	4.1	0.75	0.43	−0.11	−0.14
	Co	25.7	73.0	28.7	80.0	27.4	76.8	0.8	2.1	0.43	0.26	0.05	−0.25
Mar	SH	17.6	65.5	20.9	87.8	19.5	78.3	1.0	6.9	0.75	0.01	−0.03	1.33
	Co	27.4	77.5	29.5	82.5	28.3	79.2	0.5	1.5	0.23	0.47	0.08	−0.16
Apr	SH	21.6	71.5	24.3	94.8	23.2	81.9	0.7	6.5	0.35	0.03	0.05	1.24
	Co	27.5	77.5	29.9	84.0	28.6	81.5	0.7	2.1	0.13	0.04	0.14	−0.41
May	SH	25.8	73.4	27.9	93.7	26.6	83.0	0.6	5.9	0.06	0.04	0.08	1.33
	Co	28.3	77.0	29.2	85.0	28.9	81.8	0.3	2.3	1.00	0.30	0.00	0.30
Jun	SH	26.9	78.9	29.8	92.9	28.6	85.2	0.8	4.5	0.04	0.08	0.16	0.98
	Co	27.8	81.0	29.0	84.0	28.4	82.7	0.4	1.1	0.29	0.81	0.06	0.00
Jul	SH	28.7	77.3	30.2	89.4	29.3	83.2	0.4	4.2	0.43	0.01	0.02	1.04
	Co	27.4	79.5	29.0	83.5	28.3	81.4	0.5	1.3	0.02	0.05	0.13	−0.31
Aug	SH	28.8	75.3	30.2	90.2	29.5	81.5	0.4	4.8	0.87	0.00	−0.00	1.25
	Co	27.5	78.5	29.1	83.5	28.2	81.3	0.4	1.4	0.58	0.33	0.05	−0.16
Sep	SH	28.2	70.6	29.6	82.7	28.9	77.4	0.5	4.8	0.75	0.02	0.01	1.18
	Co	27.7	79.0	28.6	86.0	28.0	81.7	0.2	2.1	0.13	0.51	0.03	0.07
Oct	SH	25.2	61.0	27.0	81.3	26.2	69.7	0.6	6.4	0.75	0.27	0.04	0.85
	Co	27.2	80.0	28.4	86.0	27.7	83.2	0.3	2.0	0.69	0.11	0.01	0.28
Nov	SH	19.5	58.5	23.9	78.8	21.9	71.1	1.1	6.7	0.27	0.03	0.06	1.52
	Co	27.0	81.5	27.6	85.5	27.3	83.8	0.2	1.5	0.75	0.51	0.00	0.00
Dec	SH	15.0	52.1	19.1	79.1	17.0	63.3	1.1	8.4	0.87	1.00	0.01	0.10
	Co	26.5	76.5	27.9	86.0	27.3	80.1	0.4	2.9	0.18	0.93	0.05	0.00

Note: SH: Shenzhen, Co: Colombo, T: Temperature (°C), RH: Relative Humidity (%). $p < 0.05$ shows a significant trend in the distribution of data.

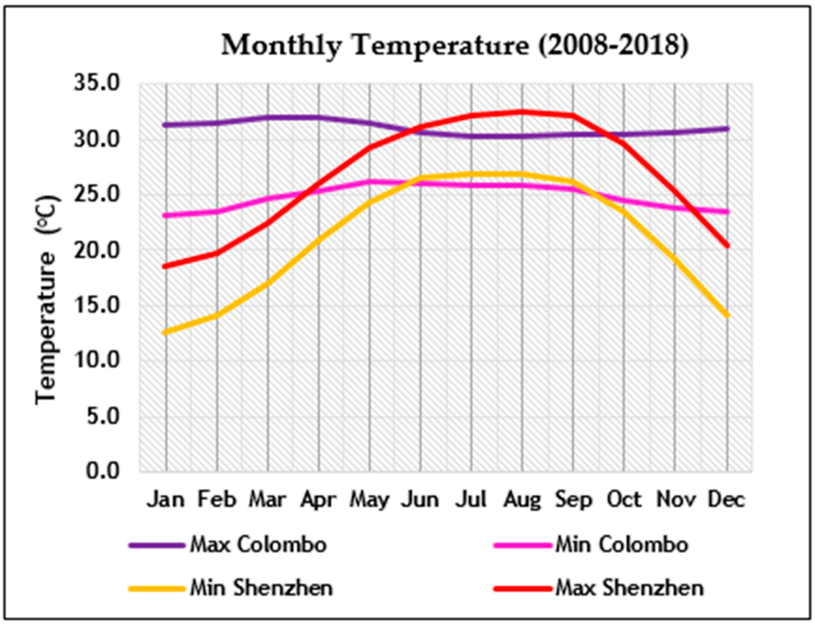

Figure 4. Minimum & Maximum temperature fluctuations.

Only in the summer season, the line of temperature in Shenzhen exceeds rather than the temperature in Colombo. In Shenzhen, the temperature fluctuates from 15 °C to more than 29 °C. As a result, human heat stress and city comfortability also change with the fluctuation of temperature in the city. But significant changes cannot be identified in the pattern of fluctuation of temperature in Colombo. Throughout the year, the temperature of

Colombo has varied from 27 °C to 28 °C. Therefore, the whole year, hot and humid climatic conditions can be observed in the atmosphere. It leads to making stressful conditions inside the city. But other factors, such as wind speeds, amount of rainfall in the year and seasonal behavior are affected to minimize the uncomfortable condition in both cities.

According to the annual rainfall pattern, Colombo receives more than 250 mm of rainfall between April to May and September to November. Shenzhen also receives more than 250 mm from June to September. Therefore, the peak temperatures of both cities are directly related to the highest rainfall months of the year.

3.2. Heat-Related Health Impact Based on the WBGT Index

Increasing humidity and temperature are having a negative effect on human body comfort simultaneously. Therefore, it is clear that there is a mutual relationship between temperature, humidity, and human body comfort, as a comparison study here mainly collected temperature and RH% data for both cities of Shenzhen and Colombo to compare and contrast the thermal sensation and heat-related health effects on the public, based on the WBGT index. A rapid increase in temperature and humidity creates an uncomfortable environment and unfavourable effects on the body's metabolic rate. Therefore, there is a strong interconnection between temperature and RH%. On the other hand, normal air temperature between 25–26 °C and atmospheric RH concentration between 75% and 80% create a comfortable environment (Table 3). Thereby heat stress is minimized, and it leads to a convenient environment for the existence of human beings.

Table 3. Relationship of Temperature, RH% and WBGT index (2008–2018).

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Data
Shenzhen	70	75	78	81	83	85	83	81	77	69	71	64	RH
	15.3	16.7	19.6	23.2	26.6	28.7	29.3	29.5	28.9	26.3	22.0	17.0	MT
	17.4	19.0	22.0	26.2	30.3	33.2	33.8	33.8	32.1	28.1	23.7	18.4	WBGT
Colombo	30.0	30.5	32.0	32.8	33.1	32.7	32.3	32.2	32.0	31.9	31.4	30.8	WBGT
	27.2	27.5	28.4	28.7	28.9	28.5	28.3	28.2	28.1	27.8	27.4	27.3	MT
	75	77	79	82	82	83	81	81	82	83	84	80	RH

Note: RH: Relative Humidity, MT: Mean Temperature, WBGT: Wet Bulb Global Temperature. ≤27.7, 27.8–29.4, 29.5–31.0, 31.1–32.1, ≥32.2.

Seasonal influences are directly affected to determine the pattern of comfortable and uncomfortable thermal sensations in the human body. Especially during the summer, the temperature is higher than 29 °C in Shenzhen city. At the same time, atmospheric RH is also higher than 80%. This particular combination is supposed to increase the values of the WBGT index. Therefore, "Very severe stress" (WBGT: ≥32.2) with "Heatstroke highly likely" condition is created by the above factors in the city of Shenzhen during the period from June to August. Most heat-related health impacts can also be seen in this period. Autumn is "Partial discomfort" (WBGT: 27.8–29.4). But during this period, severe heat-related health impacts cannot be seen. The most common condition is "Fatigue", which everyone feels. But in the winter (December to February), the above process goes the opposite direction. During this season, the temperature is <20 °C and RH is ≤75%. As a result of that, the index value of WBGT is recorded as <27.7. Therefore, the entire season is "comfortable", and heat-related health effects cannot be observed. The same comfortable condition can also be observed in the spring (March to May) without any health effects related to heat stress (Table 4).

Table 4. Monthly and seasonal variation of WBGT index. The classification of WBGT, Thermal Sensation and Heat Effects were referred from the previous research [39].

WBGT	Thermal Sensations	Health Effects	Colombo		Shenzhen	
			Month	Monsoon	Month	Season
≤27.7	Comfortable	–	–	–	January, February, March, April, November, December	Winter, Spring
27.8–29.4	Partial discomfort	Fatigue	–	–	October	Autumn
29.5–31.0	Discomfort	Heat cramps and heat exhaustion are possible	January, February, December	NEM	May	–
31.1–32.1	Severe Stress	Heat cramps or heat exhaustion likely, and heatstroke is possible	March, September, October, November	SIM	September	–
≥32.2	Very severe stress	Heatstroke highly likely	April, May, June, July, August	FIM, SWM	June, July, August	Summer

Note: FIM: First Inter Monsoon, SWM: Southwest Monsoon, SIM: Second Inter Monsoon, NEM: North East Monsoon.

When Colombo and Shenzhen cities are compared, huge differences can be observed in the pattern of monsoons. Throughout the year, Colombo does not come under the “Comfortable” category (WBGT: ≤27.7). Because during the whole year, the temperature does not come down below 27 °C, and RH is also fluctuating between 75% and 84%. As a result, throughout the year, the value of the WBGT index is ≤30.0. Especially in the period of the First Inter Monsoon (FIM) and South West Monsoon (SWM), Colombo city remains under the “Very severe stress” category with “Heatstroke highly likely”. But During the Second Inter Monsoon (SIM) period, the “Severe stress” condition is recorded with a WBGT index score of 31.6, and health effects such as “Heat cramps or heat exhaustion likely and heatstroke are possible”. North East Monsoon (NEM) is better than the other three monsoons in the year. Still, according to the classification, NEM comes under the “Discomfort” category: "Heat cramps and heat exhaustion are possible". Because of the low temperature and RH values recorded during this period, NEM is fairly more comfortable than other monsoons (Table 4).

Apparent differences in the monthly pattern of WBGT can be observed between Colombo and Shenzhen. “Very severe stress” months in Shenzhen are June, July, and August (3 months). But Colombo city comes under “Very severe stress” with “Heatstroke highly likely” during the five months from April to August. “Comfortable” and “Partial discomfort” conditions cannot be observed in Colombo even in one month of the year. But January, February and December are somewhat better than the other months of the year. Generally, throughout the year, Colombo city is in discomfort and stressful condition. But the “Comfortable” condition (WBGT ≤ 27.7) is maintained continuously in Shenzhen city for the six months from November to April. The reason for that is the temperature of Shenzhen city goes down under 23 °C, and RH fluctuates between 64–81% during the above months.

According to the summary statistic of the WBGT index (Table 5), three months (July, September, and October) recorded a significant positive increasing trend of the WBGT index in Colombo city. November is also very close to the significant level (p = 0.05). Throughout the year, all the mean values are recorded as WBGT ≥ 30. When considering the city of Shenzhen, five months (April, May, June, July, and August) recorded a significant positive increasing trend (p < 0.05) in the WBGT index, and many of them are included in the summer season. On the other hand, January and November are very close to a significant level ($p = 0.05$) (Figure 5). From May to September, all the mean values are recorded as WBGT ≥ 30. But December to February Mean values is recorded as WBGT < 20.

Table 5. Summary statistics of WBGT in Shenzhen and Colombo (2008–2018).

Variable	Minimum		Maximum		Mean		Std. Deviation		*p*-Value	
	Co	Sh	Co	Sh	Co	Sh	Co	Sh	Co	Sh
Jan	29.4	14.0	31.4	20.6	30.0	17.4	0.6	1.7	0.87	0.06
Fe	28.6	14.8	32.1	23.4	30.5	19.0	1.0	2.3	0.75	0.87
Mar	31.3	19.1	33.3	23.9	32.0	22.0	0.5	1.2	0.10	0.53
Apr	31.6	24.2	33.9	29.0	32.8	26.2	0.7	1.4	0.11	0.04
May	32.5	28.2	33.5	32.8	33.1	30.4	0.3	1.4	0.53	0.03
Jun	31.8	31.0	33.3	35.8	32.7	33.3	0.5	1.5	0.31	0.00
Jul	31.3	32.7	32.9	35.7	32.3	33.8	0.5	0.9	0.02	0.01
Aug	31.5	32.3	33.0	34.8	32.2	33.8	0.5	0.8	0.43	0.00
Sep	31.4	30.8	32.4	34.0	32.0	32.4	0.3	0.9	0.04	0.21
Oct	31.2	26.1	32.3	30.4	31.9	28.1	0.3	1.2	0.02	0.21
Nov	31.0	20.9	32.0	26.4	31.4	23.7	0.3	1.5	0.05	0.06
Dec	30.1	16.2	31.9	20.5	30.8	18.4	0.5	1.2	0.35	0.76

Note: A common threshold of the *p*-value is 0.05. It is a probability score used in the statistical test to identify the statistical significance of an observed effect; Co: Colombo, Sh: Shenzhen.

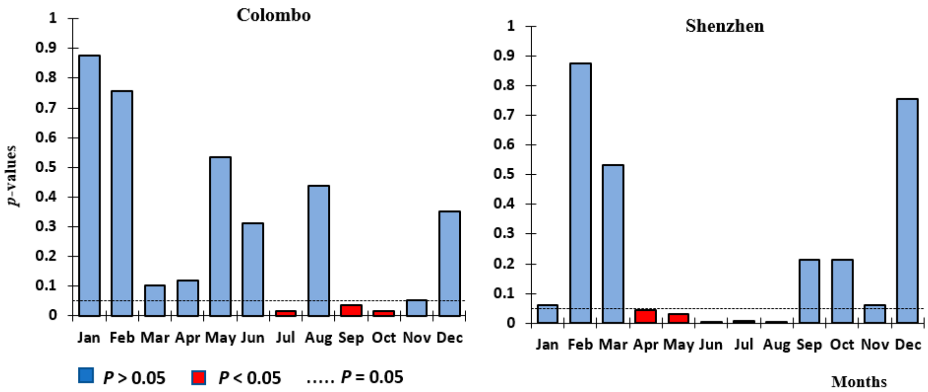

Figure 5. The monthly pattern of *p* values distribution from 2008 to 2018.

Both cities of Colombo and Shenzhen have a positive co-relationship between Temperature–WBGT and RH–WBGT. But it is clear that when Colombo and Shenzhen cities are compared, different distribution ranges of values in temperature, RH and WBGT can be observed. When Colombo city is concerned, no huge difference in values between temperature and WBGT index can be observed. Values of the upper level are gathered in one place when Figure 6 is considered. The main reason for that is temperature, and WBGT index are reached up to 27 °C in Colombo city throughout the year. This condition directly affected the upper distribution of co-relationship in WBGT and the Temperature of the city of Colombo. When Shenzhen city is concerned, different ranges of temperature and WBGT values distribution can be observed throughout the year. The main reason for this distribution is temperature, and WBGT values fluctuate between $\leq$17 and $\leq$33.8 due to seasonal behavior.

Nevertheless, the same pattern of positive co-relationship can be observed between RH and WBGT in Colombo and Shenzhen. When Colombo city is concerned, RH values are established between 75$\leq$ and $\leq$84 in the entire year. In the meantime, values of the WBGT index are moved up to higher ranges. But in Shenzhen city, RH values fluctuate between 65$\leq$ and $\leq$84, and values of WBGT fluctuate between 17.4$\leq$ and $\leq$33.8. As a result of this pattern, the co-relationship of RH and WBGT has been distributed, as indicated in Figure 6.

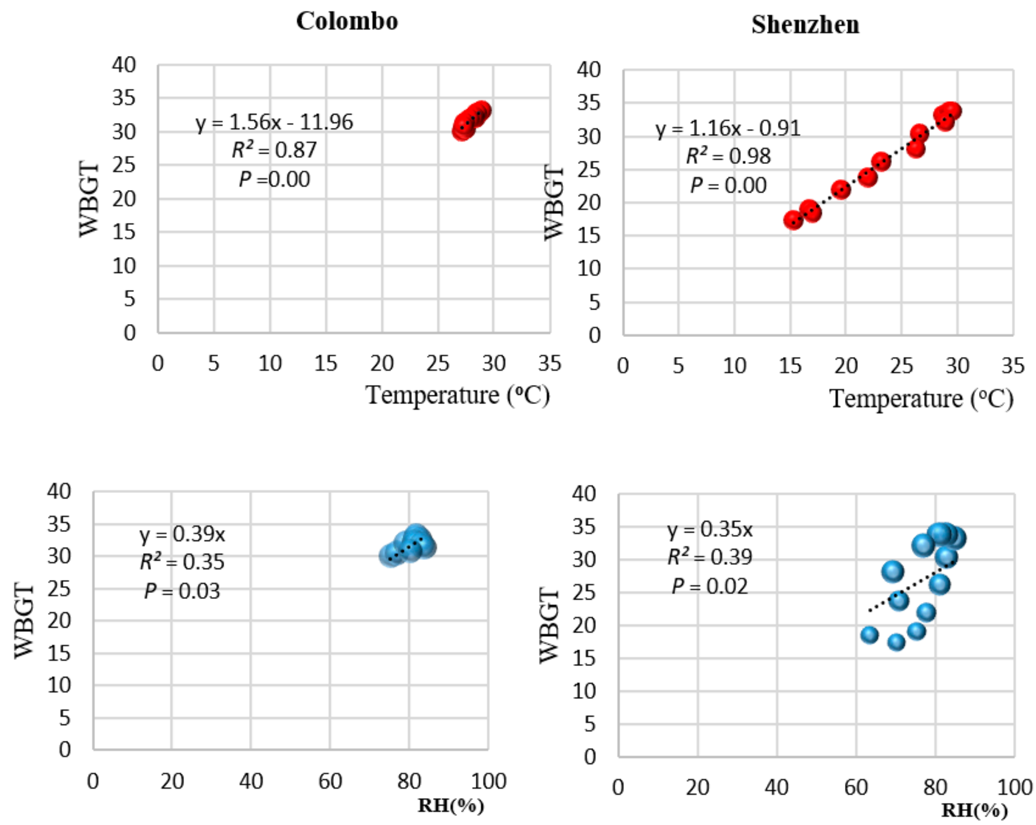

Figure 6. Co-relationship between Temperature—WBGT and RH%—WBGT.

3.3. Land Use Pattern and LST in Colombo Metropolitan Area

When Colombo and Shenzhen cities are concerned, the expansion of built-up areas has been influenced by reducing vegetation cover. Pertaining to that pattern, land surface temperature also can be seen as an increasing trend. When the study was carried on in the Colombo Metropolitan area, extreme expansion of Built-up areas and LST could be observed in the city between 1997 and 2019. Due to the urbanization process, special changes can be visible in areas A, B, C, and D (Figure 7). Fort City and Colombo Harbour are situated in "A" locations, and relatively in 1997 and 2009, Colombo fort city was expanded towards the sea 2019. Colombo municipal council has been symbolized by "D", Biyagama Free Trade Zone is represented by "C" location, and Ratmalana Airport and its surrounding areas are symbolized by "B". All these locations are under the rapid urbanization process.

In 1997, the Thick Vegetation cover was 18 km^2 and was limited to 4 km^2 by 2019. In the same way, Agriculture lands/light vegetation cover also decreased drastically. In 1997 it was 163 km^2, but in 2009 it reduced to 145 km^2 and was limited to 102 km^2 by 2019. But Built-up areas were broadly and rapidly expanded in the city center. In 1997 Built-up areas were 39 km^{2,} and in 2009 it, was increased to 54 km^2; by 2019, it has been further increased to 82 km^2.

With the expansion of Built-up areas, the land surface temperature is also rapidly expanded in Colombo. The areas related to construction works are appeared to be covered with increased LST and decreased LST values can be observed in vegetation lands. The lands belonging to LST: ≥31 °C category was 2 km^2 in 1997. By 2009 and 2019, it gradually increased from 10 km^2 to 21 km^2. This pattern can be observed clearly through the maps (Table 6). From 1997 to 2019, most of the land areas belong to LST: 27–29 °C category. The expansion of the built-up regions on the coastal side can be seen spatially and temporally. Parallel to that, a rapid increase of LST in coastal lines can also be observed.

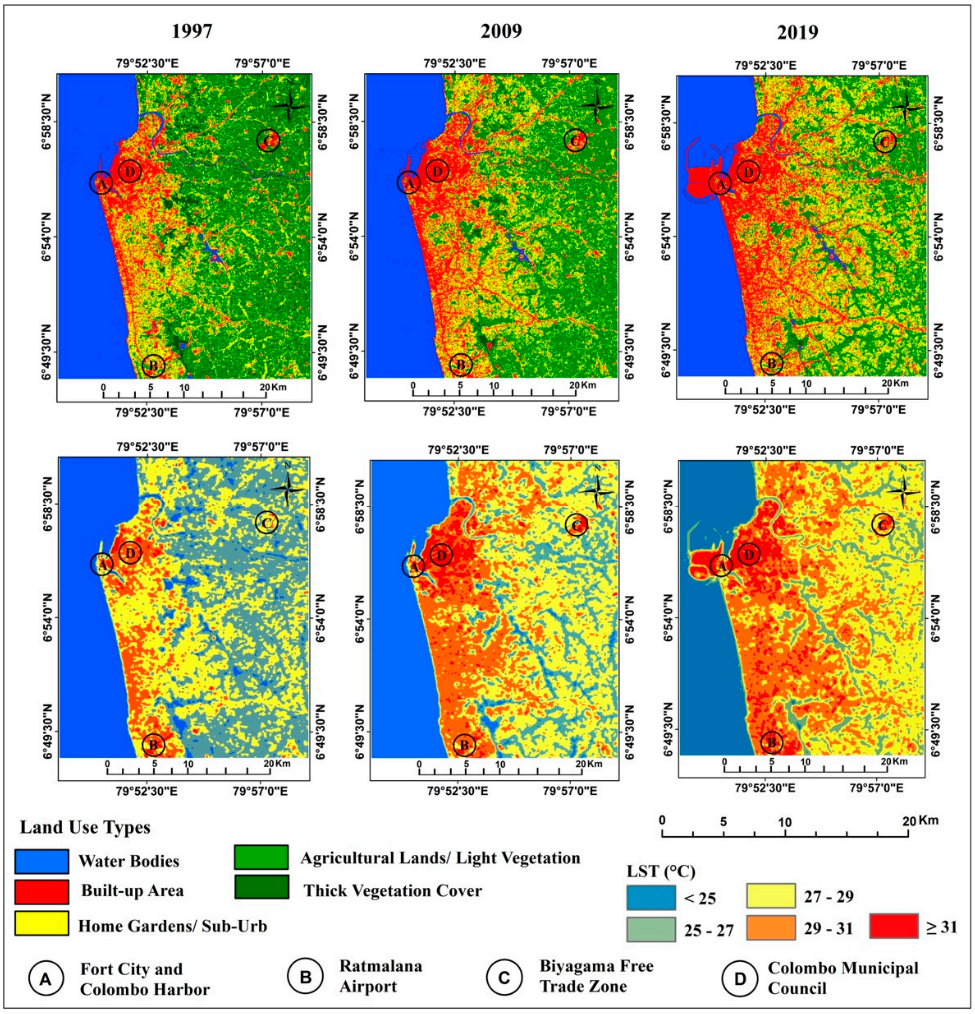

Figure 7. LST and NDVI changes in Colombo.

Table 6. Land use pattern changes and LST expansion in Colombo (Area Km^2).

Years	NDVI				
	Water Bodies	Build-up Areas	Home Gardens/Sub-urban	Agricultural Lands/Light Vegetation	Thick Vegetation Cover
1997	104	39	82	163	18
2009	103	54	97	145	7
2019	98	82	120	102	4
	LST (°C)				
	≤25	25–27	27–29	29–31	31≥
1997	109	137	128	30	2
2009	102	68	145	81	10
2019	92	41	149	103	21

3.4. Land Use Pattern and LST in Shenzhen

Shenzhen city has a vast and clear difference in comparison to Colombo city. A considerable diffusion in Thick Vegetation cover and Agriculture Lands can be observed.

Built-up lands have been rapidly expanded in the A, B, C, and D locations. For example, Shenzhen Bao'an international airport is represented by "A", Mawan Port by "B", Yantian district is symbolized by "C", and the city of Shenzhen is represented by "D" (Figure 8). In 1997, the Thick Vegetation cover was 287 km^2. Gradually it was reduced to 165 km^2 in 2009. Further, it has been reduced to 101 km^2 in 2019. As a result, a vast increase in Built-up areas can be seen. In 1997, Built-up areas were expanded up to 426 km^2. In 2009 it increased to 592 km^2, and by 2019 it increased to 710 km^2 (Table 7).

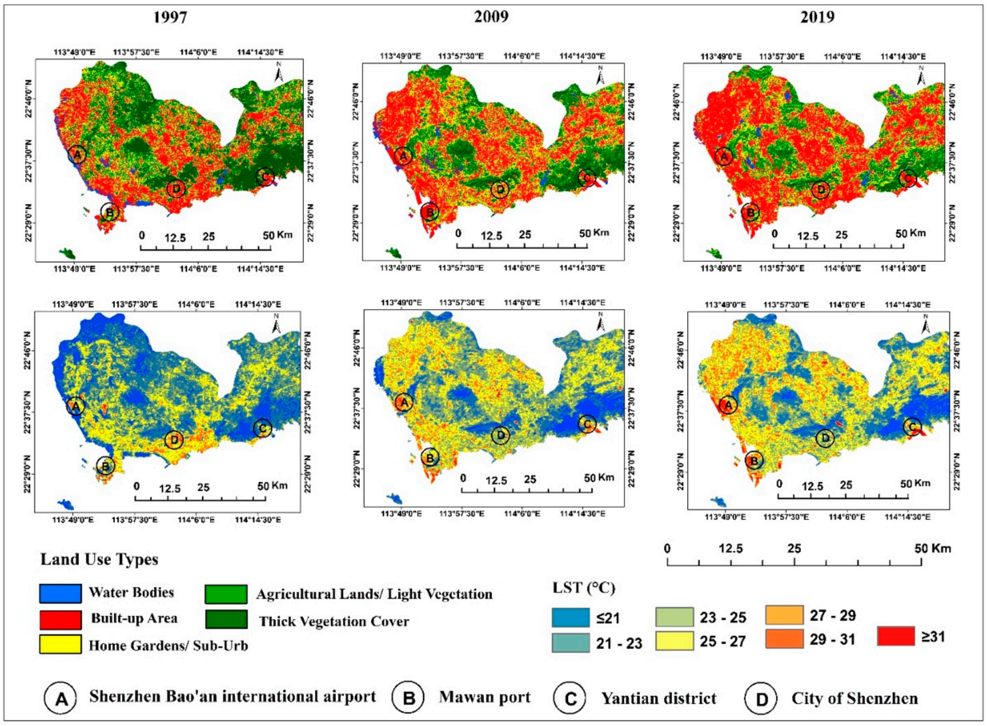

Figure 8. LST and NDVI changes in Shenzhen.

Table 7. Land use pattern changes and LST expansion in Shenzhen (area km^2).

Years	NDVI						
	Water Bodies	Build-up Area	Home Gardens/Sub-urban		Agricultural Lands/Light Vegetation	Thick Vegetation Cover	
1997	35	426	371		395	287	
2009	25	592	440		344	165	
2019	22	710	408		325	101	
	LST (°C)						
	≤21	21–23	23–25	25–27	27–29	29–31	31≥
1997	225	569	384	320	52	5	4
2009	99	304	521	503	120	11	8
2019	78	298	410	568	172	24	16

The broad urbanization process is indicated by these special locations, and urbanization leads to the expansion of LST in the city. The special thing in Shenzhen city is that LST distribution has been slightly controlled owing to broad vegetation cover and agricultural Lands. The pattern is indicated in Figure 8. The lands belonging to LST: ≥31 °C category was 4 km^2 in 1997. By 2019 it had been expanded up to 16 km^2. On the other hand, most of the lands belong to LST: 25–27 °C category. A clear increasing trend has been shown by LST: 29–31 °C category. Under this LST category, 5 km^2 of land was recorded in 1997. In 2009, it was increased to 11 km^2; by 2019, it was expanded to 24 km^2 (Table 7).

Especially in the city of Colombo, minimum LST values are increasing year by year (Figure 9). In 1997 it was recorded as 17 °C. But in 2019, the minimum LST value has grown to 24 °C. When comparing the mean temperature of LST, Colombo consistently outperforms Shenzhen. In both cities, maximum LST values fluctuate between 33 °C to 36 °C. And also, minimum, maximum, and mean LST values are gradually increasing in 2019 compared to 1997 and 2009.

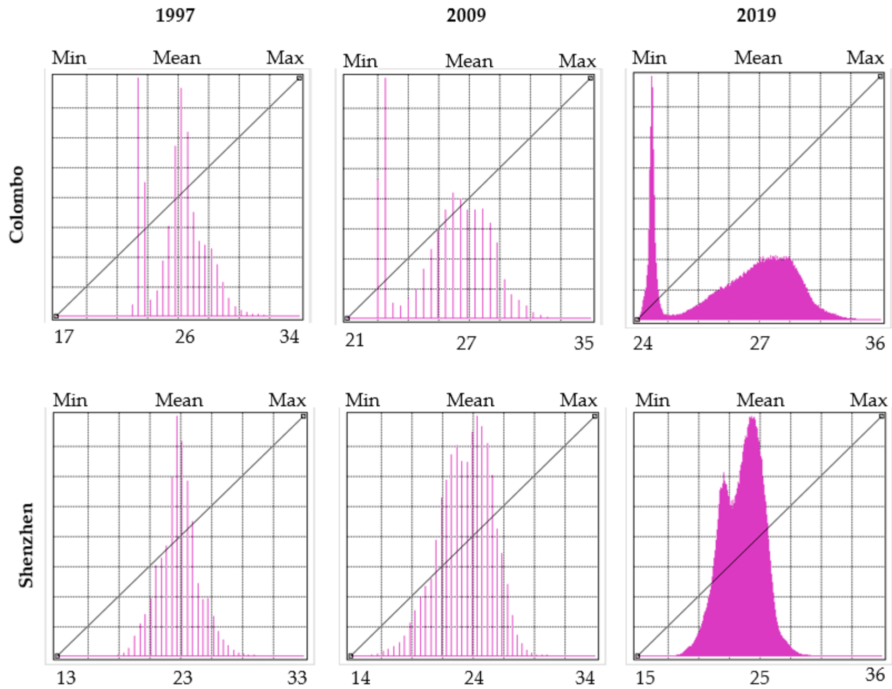

Figure 9. Histograms of LST diffusion in Colombo and Shenzhen.

4. Discussion

Colombo has recorded more WBGT index values, air temperature, and LST annually. When considering the WBGT, from April to June, the index values reached more than 32.5. Several heat-related problems are arising in this period. This is consistent with earlier research found that March and May, when the solar zenith angle is at its lowest, are the most uncomfortable months in Sri Lanka. During this period country was right under the sun—high relative humidity results from low wind speed during ITCZ passage and pre-monsoonal showers [55]. From 1997 to 2019, the LST in the city center also expanded rapidly.

The main reason is the fast land-use changes covered by the unplanned urbanization process. Especially in the west coastline, including the port city area, is identified as the highest-risk area in the city for heat stress and heat-related illnesses. Previous research also showed the same LST pattern in Colombo city. Urban growth in the Colombo Metropolitan Area follows a diffusion pattern, particularly along the western coastal line. Because urban surface materials have higher radiation temperatures, the LST pattern also shows a similar gradient compared with the landscape metrics in the city [31]. There have been considerable and rapidly accelerating changes to the land cover since 2010, with roughly 30% of all new construction occurring between 1990 and 2015 in wetlands and agricultural areas [56].

In the same way, the maximum and minimum LST in the city also shows the same positive increasing trend. The minimum LST values are increasing faster than the maximum LST values. Previous studies also found that the nighttime LST trends show the highest statistically significant trend. It is increasing faster than the daytime trends [25].

When considering the city of Shenzhen, Summer is the most vulnerable period with extreme heat-related injuries. Many researchers found that Summer is the hottest season in China. The daily maximum temperature considerably impacted the number of deaths during this period. The daily death toll slowly rises as the maximum temperature exceeds 35 °C [57]. The city is vulnerable to several heat-related injuries from June to August, and the WBGT index values also exceed 32.1. But all other seasons are in Comfort and Partial discomfort categories considering the summer. The western part of the city shows the fast changes in the land use cover compared to the other areas. Previous researchers also found that the west and central parts had worse climates, which were less comfortable. An ideal climate region with a high wind speed and low temperature is southeast of Shenzhen [58]. This research also observed the same spatial pattern of the LST in the city.

Heat Stress and Heat Related Public health depend on many factors, such as climatic factors, physical activities, clothing patterns and internal factors of the body. But this research only discussed the climatic factors and urban heat environment related to the heat-related health impacts on the human body. This is a certain limitation of this study. In addition, we used land surface temperature data rather than air temperature data to quantify the urban heat island and their relations with urbanization. However, air temperature might be a better variable to characterize the actual thermal conditions, especially to address human perception and comfort issues with heat. However, the limitation of air temperature is that it is generally monitored at only a few meteorological stations. Thus, it is difficult to fully represent the spatial heterogeneity of the urban thermal environment. In our previous studies conducted in Shenzhen, a significant positive relationship between LST and air temperature from the nearest meteorological station was found [59]. We thus used LST as a proxy of the urban thermal environment because it is challenging to derive air temperature with very high spatial resolution. Still, it is also a point to be considered in the future.

5. Conclusions

Urban heat island effect, heat stress and heat-related public health issues can be observed in Colombo, Sri Lanka and Shenzhen, China. When comparing both cities, apparent differences can be observed in the temperature pattern. Colombo experiences higher air temperature throughout the year than Shenzhen City, except in the summer. Human heat stress, thermal sensation and city comfortability are also changed with air temperature fluctuation and relative humidity.

(1) Throughout the year, hot and humid climatic conditions can be observed in Colombo. As a result, Colombo does not come under the "Comfortable" category of the WBGT index. Moreover, nearly half of the year (5 months), the city belongs to the "Very severe stress" category with "Heatstroke highly likely".
(2) But seasonal influences are directly affected to determine the pattern of comfortable and uncomfortable conditions in Shenzhen city. Summer is the only season that recorded the "Very severe stress" condition. Spring and winter create a "Comfortable" environment in the city, and WBGT index values also come down. Both cities of Colombo and Shenzhen have a positive co-relationship between the Temperature–WBGT and RH–WBGT index.
(3) With the rapid growth in Built-up lands, air temperature and LST are also expanded relatively in the city centers. Expansion of LST is a more rapid process in Colombo city than in Shenzhen. Colombo port city and its surrounding areas in the North-Western part along the coast are identified as the most vulnerable locations for LST expansion. In Shenzhen, the urban land along the western coastal line and main roads are expanding faster while the LST patches are increasing.

By comparison of all the factors, this research concludes that Colombo city is more stressful than Shenzhen city. It does not seem like a big issue today. But in the near future, the increasing trend of heat stress, urban heat island effect and heat-related health issues will cause several complications for all nations worldwide. The use of cool and green roofs and the proper distribution of vegetation cover can be applied to the highly vulnerable areas identified in this research. Therefore, it is necessary to assess these risks and respond effectively.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Details of the Landsat data acquired.

	Date Acquired	Satellite	WRS Path	WRS Row	Day/Night Indicator	Sensor Identifier
Shenzhen	29 October 1997	LANDSAT_5	122	044	DAY	TM
	17 October 2009	LANDSAT_5	122	044	DAY	TM
	14 November 2019	LANDSAT_8	122	044	DAY	OLI_TIRS
Colombo	7 February 1997	LANDSAT_5	141	055	DAY	TM
	8 February 2009	LANDSAT_5	141	055	DAY	TM

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