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The impact of urban compactness, comfort strategies and energy consumption on tropical urban heat island intensity: a review

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Abstract:

The importance of studying tropical urban climate was recognised by the World Meteorological Organisation (WMO) as early as in 1981 but substantial improvements were seen only in the last two decades. However specific knowledge of tropical urban climate still lags behind that of temperate climate. In this paper, authors review the state of the art in tropical heat island intensity, its influence on building energy consumption and the effect of urban compactness in the tropics. The review is limited to peer-reviewed journal publications found on four databases: Web of Science, Scopus, Google Scholar and Science Direct.

The review indicates that although the tropical belt has large variations in topography, forest cover, land mass and development patterns, much of the current work is confined largely to Far East Asia, South Asia and South America. Future studies should focus on protocol for parameterisation and standardisation of measurement, in depth and scientific understanding of the influence of vegetation, water and topography, survey and monitoring of the context specific relationship between UHI and energy consumption, development of database for numerical model validation and improvement, and the context specific development of LCZ based institutional framework to integrate UHI mitigation strategies with environmental design guidelines.

Keywords: Urban Heat Island (UHI); Tropics; Journal database; Monitoring; Urban compactness; Comfort strategies; Energy; Green infrastructure; Cool material; Modelling.

1.0 INTRODUCTION AND CONTEXT

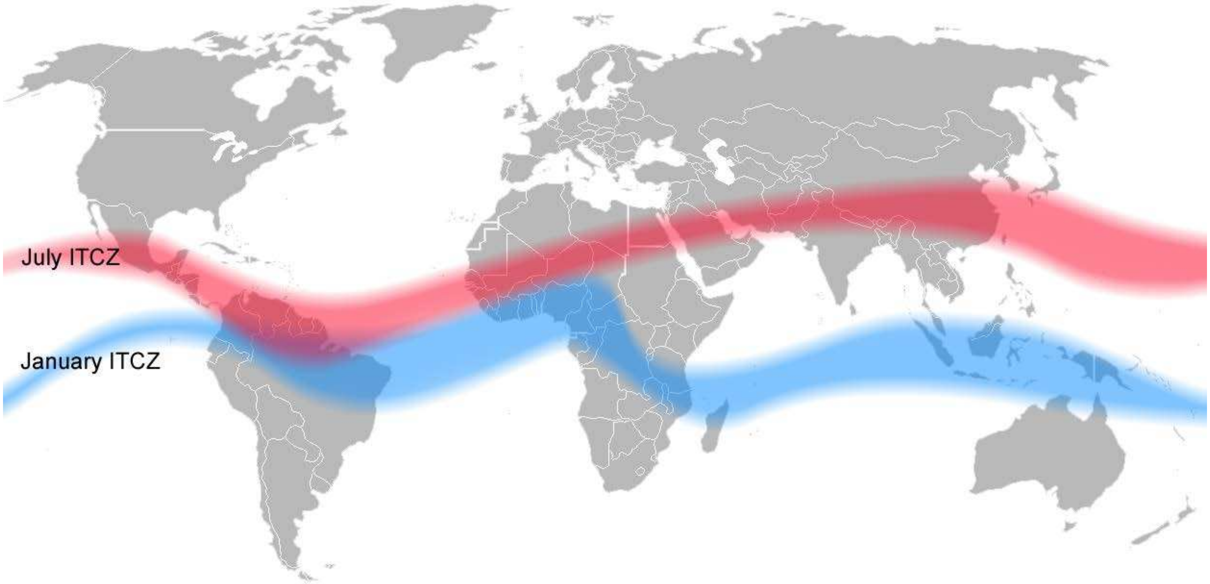

Figure 1. Global 'tropical' belt (tropics and sub-tropics)

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Much of the 21st Century global urbanisation is concentrated in the developing world (Akbari et al., 2016; Roth, 2007; Roth et al., 2017) and a vast swathe of this lies in the Tropical (23.5°N and 23.5° S) and sub-tropical zones (up to 30° N and 30°S), within the three 'tropical' sub-climate types as defined by the Köppen-Geiger climate classification (Rubel and Kottek, 2010): Tropical Rainforest or Equatorial (Af), Tropical Monsoon (Am) and Tropical Wet and Dry or Savannah (Aw).The principal form of climate control in the tropics is the Inter-Tropical Convergence Zone (ITCZ, Figure 1), which despite its wide variations relates closely to solar altitude and the migration of low pressure (and therefore seasonal rains) – two of the most important determinants of tropical climate.

Yet, despite the growing population in the tropics and its rapid urbanisation, the nature of local climate change induced by tropical urban growth is not well studied. The importance of studying tropical urban climate was recognised by the World Meteorological Organisation (WMO) as early as in 1981, with a series of bibliographies commissioned by them in 1993 and 1996 (Jauregui, 1993; Jauregui, 1996). Since then there have been some attempts at reviewing tropical urban climate literature at regional (Africa) or country (Singapore) level (Adebayo, 1990-91; Roth & Chow, 2012). Before 2007 less than 20% urban climate related studies were focused on the tropics (Roth, 2007). But, in last decade there was substantial growth in urban climate studies in the tropics, leading to at least 35 publications per annum (see Figure 2).

Nevertheless, there is still a concern that Urban Heat Island (UHI) in the tropics is not as well documented as temperate climate (e.g. Rajagopalan, 2014; Gazal, 2008). Further, Eliasson (2000) and Ng (2015) point out the missing link between the technical information and planners' ability to apply it in practice. Although this could be a global phenomenon, it is particularly problematic in the tropics, where UHI superimposed on a generally warming climate has serious implications to energy consumption, human health, air pollution and Green House Gas (GHG) emission. For example, Doan

(2016) argued that urbanization in the region of Greater Ho Chi Minh City, Vietnam, was responsible for approximately half of the observed increases in air temperature since the late 1980's. Furthermore, there is a 'developmental' shift in disease burden in tropical countries (i.e. a shift from excess mortality associated with rainfall to excess mortality associated with thermal conditions) that is exasperated by the UHI phenomenon (Goggins et al., 2016; Burkart et al., 2014).

Another concern is the incomplete understanding of the energy needs for building space conditioning (BSC) associated with high-density developments. More importantly, the interaction of urban compactness, thermal comfort and BSC energy needs have significant influence on the changes in the outdoor temperature. In the tropics, this change in outdoor temperature not only has a year-round negative effect but also creates a positive feedback loop with BSC energy demand. Up to date knowledge on this loop is essential to address the environmental issues related to rapid urbanisation and UHI.

The present paper therefore critically reviews the UHI research in the tropics in the last two decades with the focus on urban compactness, comfort strategies and BSC energy need and presents the current state of technical knowledge. Further, the paper identifies challenges and opportunities while highlighting contradictory findings. This paper will not address the social and economic implications of urban climate changes in the tropics. Further, the study is limited to urban canopy layer climate with a focus on near surface Urban Heat Island Intensity (UHII).

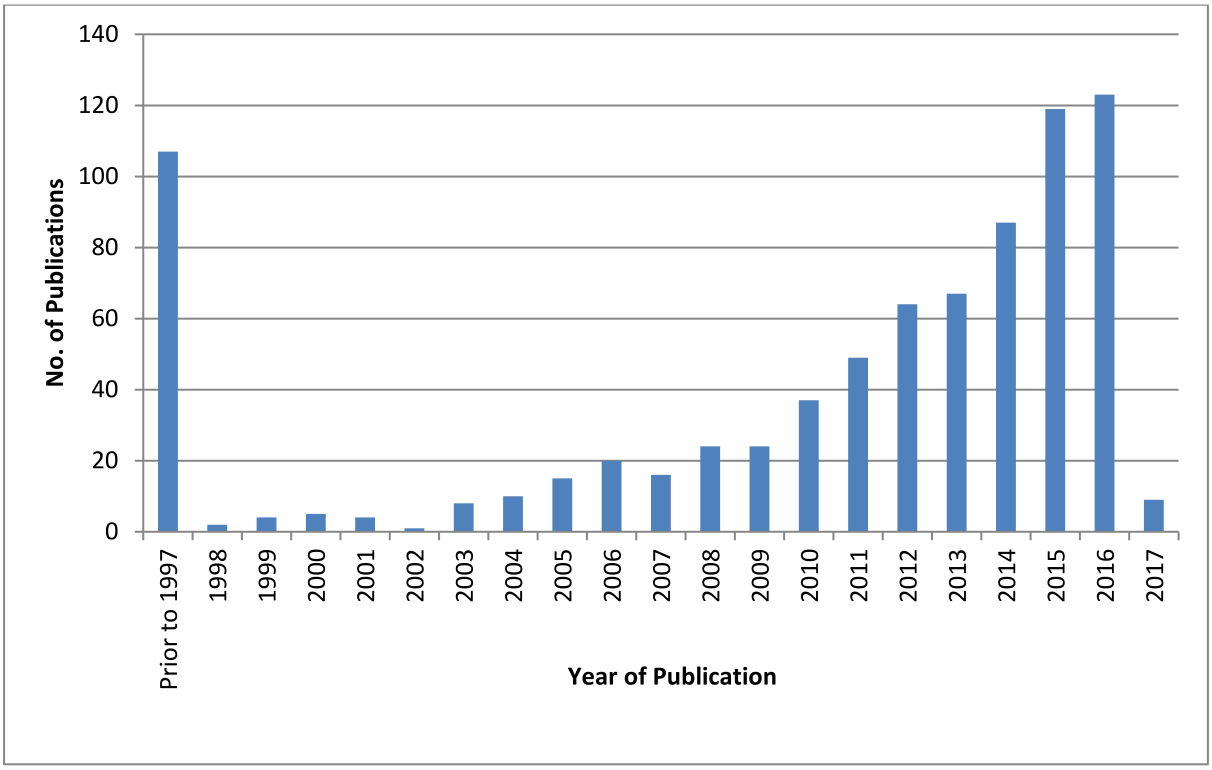

Figure 2. Number of publications listed in Science Direct under search terms 'Urban Heat Island' and 'Tropics

2.0 APPROACH AND METHOD

In light of the early works in reviewing UHI literature in the topics, the present work seeks to explore *new* developments in literature concerning tropical UHI phenomenon in the last two decades with a view to critically evaluating the following:

- What is the state of knowledge regarding the uniqueness if any, of tropical UHI phenomenon?
- What effects do high density living have on the mitigation approaches to tropical UHI problem in terms of energy and thermal comfort?
- What are the emerging approaches to the study of tropical UHI and their future directions?

The present work is limited to literature review of peer-reviewed journal publications found on four databases: Web of Science, Scopus, Google Scholar and Science Direct. The following key words were used: "tropics", "urban heat island", "energy consumption" and "urban form." Search based on terms "urban heat island" and "tropics" generated 203 and 238 outputs in Web of Science and Scopus respectively for the period 1997 to 2016. For the same terms and period, Science Direct and Google Scholar produced 795 (see Figure 2) and 14,100 outputs respectively. For the same period Boolean search terms "tropical UHI and energy consumption" and "topical UHI and compact urban form" produced 24 and 9 papers respectively in Web of Science. Similar order of results was obtained from Scopus as well. Detailed review of the resulting shortlist revealed that while Web of Science and Scopus were the most focussed and relevant in capturing the most important research works, they do sometime omit few critical research papers. This is largely due to the use of non-standard terminology (such as "rise in the outdoor temperature" rather than UHI, for example). A technique of 'snowballing' (where one research subject leads the researcher to another, which in turn provides a third, and so on, Vogt, 1999) was therefore used to find additional published resources. These were then added to a common database that was formed by combining outputs from the Web of Science and Scopus. The total yield from this exercise was 162 research outputs that report on research from different parts of the topics in terms of UHI trends, technology used in the experimental and modelling studies, and mitigation strategies. Authors do not claim that the present review covers all of the tropical urban climate studies conducted in the last two decades, we are confident that it captures the key literature that emerged from the above mentioned review process.

3.0 NATURE OF TROPICAL UHI

Oke (1988) formulated the surface energy balance (SEB) in urban areas that is fundamental to the understanding of UHI in any geographical location:

$$Q^* + Q_f = H + LE + \Delta Q_s + \Delta Q_a \ (in\ Watts/m^2) \qquad \text{(Eq. 1)}$$

Two most distinguishing features of tropical urban SEB is the importance of direct solar radiation within net all-wave radiation (Q*) for daytime urban exchange of momentum, heat and water vapour (Morris et al., 2016a), and the seasonality of the relationship between Sensible (*H*) and latent (*LE*) heat. According to Barradas et al. (1999), net radiation was higher during the dry season and was partitioned between *H* and *LE* in the order of 69% and 25%, respectively. However, during the wet season this was reversed to 27 and 70% respectively, and the total was lower. In terms of land cover, Morris et al. (2016b) confirmed that the pattern seen in both temperate and tropical cities is similar – i.e. *H* increases (and *LE* decreases) with increase in urban fraction.

The instrumentation difficulties, cost and long-term commitment required to maintain and monitor them have made SEB studies in urban areas relatively uncommon. Of the few, only a handful have dealt with tropical cities (Park, 2016). We could only find two long term (> 1yr) SEB studies in a tropical urban area (Sao Paulo, Brazil in Ferreira et al., 2013 and Singapore in Roth et al, 2017). According to Ferreria et al.(2013), during daytime, energy flux storage (ΔQ_s) corresponds to approximately 51% of the net all-wave radiation but drops to 27% when the total daily net all-wave radiation is included. Overall, 54% and 40% of annual net radiation partitioned into sensible and latent heat respectively (Roth et al., 2017). The significant diurnal change in the total stored energy flux could be an important driver of the UHI phenomenon in a tropical city but the relationship between ΔQ_s and UHI is not so clear. The large difference between the day and diurnal storage (50% vs 27%) might provide an explanation (Ferriera et al., 2013).

Estimating Q_f is very difficult in the tropics due to the lack of information on anthropogenic heat. It is customary to either neglect Q_f in tropical cities or use proxy values due to absence of appropriate data. However, there is evidence that this may not be correct, especially in high-density tropical cities such as Singapore, where anthropogenic heat could be locally substantial. In Singapore, the average waste heat density from residential and commercial buildings alone was found to be 27 W/m^2 but the range across the city state varied from 3.1 to 1,500 W/m^2 (Boehme et al., 2015). Similar order of waste heat density could be found in other tropical cities, especially in mega cities. However, it is not being systematically investigated and documented. Theoretically, Q_f is the residual of SEB. However, current techniques used in the monitoring lead to errors in quantifying $Q_{f.}$. In this context, inventory based modelling suggested by Quah and Roth (2012) appears to be a better option than the current monitoring approach. A detailed account of SEB specific to tropics could be found only in a few studies (e.g. Newton et al., 2007; Karam et al., 2010).

When studying the tropics it is more appropriate to refer to sub classifications created by Köppen (Roth, 2007): wet climate (e.g. Singapore), wet/dry climate (e.g. Mumbai), monsoon climate (e.g. Jakarta), highland climate (e.g. Mexico City) subtropical desert (e.g. Muscat) and humid sub-tropical (e.g. Hong Kong). A number of studies affirm the variations in the UHI phenomenon among these sub-classifications and indicate that moisture availability is a key determinant of local climate variations in the tropics (Roth et al., 2017; Chow and Roth, 2006; Quah & Roth, 2012).

Although there were some initial work on the effect of tropical cities on several climate parameters(Jauregui & Romales; 1996) much of the reported work on tropical urban climate is centred on air temperature (e.g. Tso, 1996) with a focus on canopy layer UHI while few reported on surface temperature (e.g. Nichol, 1996). Canopy layer UHI (e.g. Ng et al., 2012) is usually studied at micro (single street canyon) and local (neighbourhoods) scale while surface temperature studies (e.g. Hung et al., 2006) are usually conducted at macro and regional scale. Table 1 captures some of the canopy layer and surface UHI intensities (UHII) in the tropics under specific urban settings. Given the rate and spread of urbanisation in the tropics, it is no longer easy to find 'representative' rural areas near cities for reference (Balogun & Balogun, 2014). Therefore, the reported canopy layer UHI in the tropics are in fact intra urban rather than urban-rural in reality.

As a general phenomenon, tropical UHIs are usually smaller in magnitude when compared with temperate cities. Another feature of tropical UHI is that the urban-rural temperature differences are often of the same magnitude as the intra-urban temperature differences and this is largely due to the role of vegetation. There is strong evidence for such 'oasis effect' in many tropical cities but this exists only on a localised basis (Jonsson, 2004).

The diurnal/seasonal patterns of tropical UHIs are somewhat unique: in terms of air temperature, tropical UHIs are strongest during the pre-monsoon and monsoon nights but surface temperature differences are strongest during the day and during the pre-monsoon only (Chakraborty et al., 2016). The energetic driver for this is the differences in the urban–rural incoming longwave radiative flux, which in turn causes a difference in the outgoing longwave radiative flux. However, advection (ΔQ_a) may also modulate the magnitude of UHI as it happens in other climate regions. But, this diurnal/seasonal pattern has a major impact on the leaf and flowering characteristics of plants (Jochner et al., 2013) which in turn will determine the plant's cooling potential. The literate related to this tropical aspect is very weak.

While the effect of greenery is important in lowering a tropical UHI, the cooling effect is modulated by wetness. This was clearly evident in the research work conducted in Akure and Lagos (Balogun & Balogun, 2014; Ojeh et al., 2016). Differences in evaporative cooling associated with wetness partly explain the fact that tropical UHIs are both day- and night-time phenomena, although nocturnal UHIs are predominate (Jauregui, 1997). Further, wetness changes the magnitude and timing of UHIs (Charabi & Bakhit, 2011). Although the blocking of re-radiation remains the primary cause for tropical night-time UHI, the role of anthropogenic heat and hard surfaces in daytime heat (and cool) islands are poorly explored. One exception could be the work done by Harrison & Amirtham (2016).

The nature of tropical UHIs as presented above is further complicated by climate change. Unlike continental or higher latitude locations, correlations between mean temperature and the frequency of extreme temperatures are stronger in island tropics but weaker in continental tropical locations (Griffiths et al., 2005). For urbanized areas, the dominant change in air temperature is a change in the mean and variance, impacting on one or both extremes, especially for minimum temperature (Griffiths et al., 2005).

Table 1: Canopy layer and surface UHII at selected tropical urban areas

UHI type and location	Occurrence period (day/night)	Intensity in °C	Intensity type	Urban setting	Reference
Canopy layer					
Akure, Nigeria	Night (dry season)	3.5	mean	Low rise low density commercial/residential	Balogun &Balogun, 2014
Akure, Nigeria	Night (wet season)	1.0	mean	Low rise low density commercial/residential	Balogun &Balogun, 2014
Campina Grande, Brazil	Day (dry season)	1.5	Max	High density and low to mid-rise commercial/residential Coastal city	Da Silva et al., 2010
Campina Grande, Brazil	Day (wet season)	0.6	Max	High density and low to mid-rise commercial/residential Coastal city	Da Silva et al., 2010
Colombo	Night	7.0	Max	Low density and commercial/residential	Emmanuel & Johansson, 2010

Delhi	-	8.3	Daily max	High density and commercial	Mohan et al., 2013
Dhaka	Day	1 to 3.8	Mean	Compact mid-rise residential	Sharmin, 2015
Hong Kong	Day (summer)	1.5	Mean	High rise high density coast area residential	Giridharan et al., 2004
Hong Kong	Night (summer)	1.3	Mean	High rise high density coast area residential	Giridharan et al., 2005
Karachi	Night (spring)	13.0	Max	High density and low to mid-rise and industrial/residential	Sajjad, 2015
Maur, Malaysia	Day	4.0	Max	Mid-rise mixed development with colonial buildings.	Rajagopalan et al., 2014
Maur, Malaysia	Night	3.2	Max	Mid-rise mixed development with colonial buildings.	Rajagopalan et al., 2014
Mumbai	Night(winter)	8.5	Mean	High density and mid to high rise commercial/residential	Kumar et al., 2001
Muscat	Day (summer/winter)	1.5/0.25	Max	High density coastal residential	Charabi & Bakhit, 2011
Muscat	Night (summer/winter)	4.25/ 2.0	Max	High density coastal residential	Charabi & Bakhit, 2011
Singapore	Night	7.0	Max	High rise high density commercial/residential	Chow and Roth, 2012
Singapore	Night	4.0	Max	Green areas in High rise high density	Wong & Yu, 2005
Surface					
Bangkok	Day	8.0	Max	High density and mid to high rise	Hung et al., 2006
Bangkok	Night	3.0	Max	High density and mid to high rise	Hung et al., 2006
Ho Chi Min City	Day	5.0	Max	High density and mid to high rise	Hung et al., 2006
Ho Chi Min City	Night	2.0	Max	High density and mid to high rise	Hung et al., 2006
Huston TX	Day (Summer/Winter	5.6/2.0	Mean	Low density and low to mid-rise	Imhoff et al., 2010
Huston TX	Night (summer/Winter	1.9/0.4	Mean	Low density and low to mid-rise	Imhoff et al., 2010

Manila	Day	7.0	Max	High density and mid- to high rise	Hung et al., 2006
Manila	Night	2.0	Max	High density and mid- to high rise	Hung et al., 2006
New Orleans LA	Day (Summer/Winter	5.6/2.0	Mean	Low density and low to mid-rise	Imhoff et al., 2010
New Orleans LA	Night (summer/Winter	1.9/0.4	Mean	Low density and low to mid-rise	Imhoff et al., 2010
Northwestern Argentina	-	1.5 to 2.8	range	Low density and low rise	Gioia et al., 2014
Singapore	Day	7.8	mean	High rise high density	Nichol, 1996

4.0 URBAN COMPACTNESS AND ENERGY

The relationship between building compactness and energy consumption is well researched. However, *urban* compactness and energy are not well understood due to the complexity of the interactions of multiple urban variables and monitoring difficulties. Urban compactness is a function of density, plot ratio, land-use and travel proximity (Gordon and Richardson, 1997; Jenks, 2000; Ganesan & Lau, 2000; Lau et al., 2005). Hong Kong provides a perfect example of a compact city (Jenks, 2000). In tropical compact cities, the feedback mechanism between the rise in outdoor temperature and BSC energy consumption is strongest during the day, while the storage of daytime solar radiation and radiating back into the environment at night is a major concern, especially in high rise high density environments (Martins et al., 2016; Yang et al., 2010; Giridharan et al., 2008; Lau et al., 2011; Chen et al., 2012).

4.1 Impact of urban compactness

There is evidence from heating load-dominated cities that urban compactness is advantageous to reduce heating energy demand (e.g. Rode et al., 2014). Would this hold for tropical cooling loads?

The variables used to characterise compactness in urban climate studies could be summarised as volumetric compactness (building surface area to building volume), aspect ratio (height to width), form factor (building surface area/ building volume, total surface [building plus lot]/volume, sky view factor, aspect ratio, distance to nearest wall, width of the street, built-up area, green areas, albedo, water surface area, roads, open areas, distance to heat sink (Chow and Roth, 2006; Emmanuel & Johansson, 2006; Sharmin et al., 2015; Charabi & Bakhit, 2011; Giridharan et al., 2007; Emmanuel et al., 2007; Yang et al., 2010; Yang et al., 2011; Martins et al., 2016).

An early attempt to link tropical UHIs with the compactness (as given by H:W ratio) was attempted in Singapore (Goh & Chang, 1999).

$$\Delta T_{U-R\,(\mathrm{max})} = 0.952 \times median\ H{:}W - 0.021 \qquad \text{(Eq.2)}$$

This relationship (Eq.2) was somewhat weak but statistically significant (r=0.53, but α = 0.05 with *p*=0.001). It is likely that the relationship between urban compactness and tropical UHIs are subject to a multitude of factors. While it is intuitive to infer urban compactness to reduce daylight, natural ventilation and renewable energy potential (cf. Martins et al., 2016), comprehensive studies exploring the inter-relationships between these and overheating in the context of humid environments are rare. This is a key research gap that require future consideration in light of the demand for rapid urban development and affordability of energy to the larger population.

In general, the impact of urban compactness on tropical UHI depends on both on-site (urban geometry) and off-site (large heat sinks) variables in addition to climate/weather variables (Ng et al., 2012; Lau et al., 2016). While Chow and Roth (2006) reveal that the relationship between urban geometry and UHI was weak in Singapore, it appears on-site variables are more important than off-site variables in explaining the differences in intra-urban UHI intensities (Giridharan et al., 2007; Ignatius et al., 2016).

A further problem in urban compactness in the tropics is the lack of standardisation of its characterisation. This poses problems in deciphering the overall effect of urban compactness on tropical UHIs. Giridharan et al. (2007) have argued for characterisation of on-site variables and off-site variables within 15m (i.e. 1000 m^2 area around measurement point) and 300m radius respectively from the measurement point for Hong Kong while Ignatius et al. (2016) have used 50m radius to characterise the on-site variables in Singapore. On the other hand, Niu et al. (2015) have indicated that different thermal conditions prevail within 200m in Hong Kong without explicitly identifying the boundary conditions. Furthermore, most studies have failed to appreciate the importance of urban albedo over surface albedo, and limit the investigation only to surface albedo. Although urban albedo is admittedly more difficult to measure, computer modelling of urban albedo is possible, but time consuming, considering the number of related surfaces that need to be modelled to trace the incoming and outgoing solar radiation. Recently Yang & Li (2015) and Qin (2015) have proposed numerical models but its application in different context needs to be validated. Vegetation density measurement poses further problems. Although it is generally represented by means of green area ratio – GAR (e.g. Yang et al., 2010; Giridharan et al., 2008), GAR does not capture the true influence of vegetation especially the impact of its height and the canopy structure. In high rise high density environments, disentangling the shading effect of buildings from vegetation is difficult (Giridharan et al., 2008). Similarly, urban wind too, remains hard to quantify in the tropics, where macro-level wind speeds are low, thus the influence of roughness elements are considerable (sharmin et al., 2015; Wong et al., 2010). It is possible to study wind tread using CFD modelling (Rajagopalan et al., 2014; Emmanuel et al., 2007; Ng et al., 2012), although this is not extensively used due to cost and computer time constraints.

4.2 Energy and environmental effects

The effect of UHIs on BSC energy use in the tropics inevitably overlaps with global climate change. Much of the climate change risks in the tropics are concentrated in urban areas. While these are wider than heat stress, increased cooling need has particular implications to both energy use and human health in the tropics. Given the nature of tropical urbanisation, climate change will interact with the urban warming in a variety of ways, some of which will exacerbate the level of climate risk (IPCC, 2013). Furthermore, there are health inequalities, especially in developing tropical cities that further exacerbated by urban warming (cf. Campbell-Lendrum & Corvalan, 2007).

Emmanuel (2017) highlights five ways in which tropical cooling need is a unique problem that exacerbated by the superimposing of UHI phenomenon on regional warming. The use of air conditioners to cool buildings (both as a consequence of global warming as well as to tackle the UHI effect) leads to dramatic changes in energy demand, which in turn acts as a feed-in mechanism for further local and regional climate change. This is particularly so in South and South-East Asia, where energy demand for residential air conditioning could increase more than 40 times in 2100 compared to 2000, with a 7% growth per year on average (Lundgren & Kjellstrom, 2013). This development is without the additional impacts of climate change, which might add up to an extra 50% in consumption to this (Isaac and Van Vuuren, 2009).

Additionally, air conditioning (AC) has a direct effect on the urban heat island effect. A typical office building cluster modelled by Liu et al., (2011) showed that the largest heat island intensity contributed by air conditioning systems can reach 0.7°C at mid-day with a daily average rise of 0.5°C. Hsieh et al., (2007) have pointed that in the sub-tropical Taipei that the heat discharged from AC units has raised the outside temperature between 0.5^{0}C and 2°C during evenings (7 p.m. to 2 a.m.). In general, low set-point temperature of the AC units can increase the anthropogenic heat and raise the outdoor air temperature even further (Liu et al., 2011). The effect is further modified by materials/geometry of buildings and the elevation/positions of AC heat emission points. A low level location of heat ejection will affect the ambient air temperature and cause an additional electricity consumption of up to 11% compared to an area with a high prevalence of window-type AC (Hsieh et al., 2007).

On the other hand, Chow et al. (2013) have shown that for every 0.5^{0}C rise in temperature, cooling load in a typical office building in Hangzhou, China will increase by 10.8%. This could be reduced by shading. Although shading does not reduce air temperature itself, it will reduce the Mean Radiant Temperature (solar gain), which in turn will have a positive impact on energy consumption. In Brazil, Martins et al. (2016) have shown that high values of aspect ratio (thus leading to greater amounts of shading) would result in a solar radiation reduction of 130 kWh/m^2 of roof area while increasing plot ratio could result in a reduction of only 26 kWh/m^2/year. This is an import finding given the weak exploration of the relationship between solar radiation and urban morphology in the tropics. Its relevance could be further enhanced by developing a large dataset covering different latitudes and aspect ratios.

Apart from the effect on energy consumption, tropical UHIs also lead to thermal discomfort, morbidity and perhaps even mortality. Evidence for long-term (1921 – 1985) change in bioclimatic conditions in cities due to the UHI phenomenon was first reported in the sub-tropical Mexico City nearly 20 years ago (Jauregui et al., 1997). Yan (1997) has shown a rise in mortality and morbidity in high density compact cities due to heat related stress. In high rise high density environments variability and intensity of the surface temperature is much higher than air temperature (Nichol, 1996). This has significant impact on thermal comfort in locations where humidity levels are high. Overall, relationship between energy and UHI in tropics, especially in the residential sector is not very well captured due lack of accessibility to data and cost implications related to long term monitoring.

5.0 MITIGATION OF TROPICAL UHIs

Typical approaches to heat island mitigation in the tropics take the one or more form of the following: shading, ventilation, green infrastructure, albedo enhancement and/or urban form manipulation. While the effect varies, these are generally more effective in 'well-designed' buildings than poorly executed ones Luxmoore et al. (2005).

5.1 Shading vs. ventilation in the tropics

Shading is a highly effective means to reduce the daytime heat stress in complex urban environments, especially in high rise high density environments (Lau et al., 2016; Lau et al., 2011;

Shafaghat et al., 2016). The importance of shade is more pronounced in the tropics with the source of shading (whether cast by buildings or trees) being less important than the shade they provide (Emmanuel et al., 2007; Halwatura & Jayasinghe, 2007). Wong et al., (2010) have also showed that although the largest influence on building level energy consumption arises from green plot ratio, the effect was largely due to the shade provided by trees. However, careful arrangement of the nature and scope of shading may be needed to minimise the nighttime heat island effect. An 'intelligent' arrangement of such shading was attempted by Swaid (1992).

Compact building forms such as standalone towers linked by sky bridges, towers on podium and blocks with multiple courtyards have great potential to shade the urban environment (Yang et al., 2010; Giridharan et al., 2008; Lau et al., 2011; Chen et al., 2012). Sharmin et al. (2015) have shown that compact urban geometry with aspect ratio between 2.4 and 3.5 could provide good thermal comfort. Giridharan et al. (2007) have outlined in principle the potential of different massing types. Emmanuel (2017) has proposed 'Shadow Umbrella' that aims to shade public spaces within urban blocks surrounded by built massing that are themselves optimally positioned to self-shade the building envelope. However, the impact of compact urban form on shading is not systematically investigated to generalise the findings from one place to another.

On the other hand, urban ventilation enhancement has received considerably more attention in the tropics than any other mitigation options. Urban ventilation remains a key mechanism for cooling tropical cities. A useful way to map urban ventilation is the concept of "building frontal area index" which could help locate the main ventilation pathways across an urban area (Edussuriya et al., 2011). The frontal area index (λ_f) is calculated as the total area of building facets projected to plane normal facing the particular wind direction (and independent of the angle of the building facets), divided by the plane area (Raupach, 1992).

$$\lambda_f = \frac{A_{facets}}{A_{plane}} \qquad \text{(Eq.3)}$$

In Eq.3, λ_f is the frontal area index, A_{facets} is the total area of building facades facing the wind direction, and A_{plane} is the plane area.

Ventilation in high-rise high density environment largely depends on site coverage, inter building distance, height of the buildings (Yang and Ng, 2012). Rajagopalan et al. (2014) have shown that varying height and massing in the urban environment with scattering of tall buildings give better ventilation at pedestrian level. They also showed that removing few buildings in urban environment (Muar, Malaysia) would not improve the street level wind flow, however it will pave the way for dissipating heat at higher level. On the other hand, Giridharan et al. (2008) have shown that small design details, such as a topographical level change as small as 0.5m along with adequate shading (may be 20-25% tree cover within $1000m^2$) could enhance the cooling potential of ventilation and produce tangible reduction in both daytime and nocturnal UHII in high-rise high density environment.

In the tropics, both shading and ventilation are equally important. Especially in high density settings, courtyard built forms should be 'connected' to the street (in terms of air passage) at ground level, while windows and walls should be shaded with 'permanent' ventilation openings (Tablada et al., 2009). Work done by Qaid et al. (2016) on shading and ventilation in Kuala Lumpur reinforces the above argument further. However, there are only limited experimental studies which linked both indoor and outdoor overheating. At the same time, evidence from sub-tropics suggests that at higher densities, the distributions of wind velocity around the buildings became polarized, and weak wind regimes begin to dominate. Nevertheless, the cooling effects of building shade become increasingly significant as inter building distance decreases because of the low level of exposure to strong direct radiation in compact forms. While this combination is beneficial in moderately humid areas, not ideal for high humid conditions (Xuan et al., 2016).

An opportunity to enhance the combined cooling benefits of both shading and ventilation is provided by solar geometry and monsoonal wind patterns in the tropics. While the effect of street orientation is more pronounced in the tropics (e.g. E-W streets having the worst thermal and comfort conditions compared to N-S streets, Emmanuel et al., 2007), 'traditional' urban form (diverse shapes, setbacks, non-uniform relationship to streets, compactness) performs much better than 'planned' urban areas (characterised by uniform building heights, equal building separation and plot sizes). The latter leads to both harsher thermal comfort conditions and higher air temperatures (Sharmin et al., 2015), a finding also confirmed in a hot, dry climate (Johansson, 2006).

A key aspect to keep in mind is the interaction between the many mitigation strategies and air pollution and internal heat gain. While ventilation is very useful in reducing the cooling load in the tropics, the ability to benefit from air movement is contingent upon air pollution levels in the surroundings. The pollution problem in tropical cities is severe – even in the relatively cleaner Singapore, suburban areas have 15 times more CO_2 than nearby forest cover (Quah & Roth, 2012). In the absence of good quality air, the windows will be shut, and internal and solar gains will built up. In this scenario, savings achieved through shading and/or ventilation will be marginal since elimination of internal and solar gains will solely depend on air-conditioning.

Another caveat is cooling load reductions achieved by simulating a sample location cannot be extrapolated citywide due to the diverse nature of building typology and occupancy pattern (Miller et al., 2015). Further, per capita energy consumption influences the magnitude of latent heat fluxes (Quah & Roth, 2006). This process increases the anthropogenic heat in the urban area and has significant impact on both day and night time UHI. As noted earlier, in the context of UHI studies, one of the most difficult parameter to quantify is the anthropogenic heat and it is very important to consider this when attempting to estimate the cooling potential of shading and/or ventilation in tropical cities. Future research should explore the use of drones to profile the waste heat release.

5.2 Green roofs, walls and other Green Infrastructure (GI) options

The energy saving benefits of Green Roof (GR) to individual buildings is regularly reported (Wong et al., 2003; Morau et al., 2012) but evidence to the direct pedestrian-level cooling benefit due to GR is mixed. Peng and Jim (2013) simulated pedestrian level air temperature effect of extensive green roofs (EGR) and intensive green roof (IGR). The results showed that EGR reduced pedestrian-level air temperature by 0.4–0.7°C, and IGR by 0.5–1.7°C, in Hong Kong but the distribution of such cooling effect was limited to immediate vicinities of buildings, particularly so, in high density settings. Although of limited value, there is a role of GR in high density settings where land for green infrastructure is limited.

Additional claimed benefits of GRs include reduced GHG emissions, sustainability, biodiversity and UHI mitigation. At the same time, negative consequences include sediment and nutrient concentration from storm water runoff from green roof. This could be up to ten times higher than what could be on conventional bare roofs (Chen & Kang, 2016). Furthermore, reductions in runoff from green roofs are not as high as expected because retention and detention are affected by high rainfall intensity, which is typical of tropical areas. Without additional maintenance, green roofs can contribute to nonpoint source pollution in hot, humid tropical cities (Chen, 2013). However, as previously pointed out, cooling load reduction benefits to individual buildings in warm climates is considerable.

The cooling benefit of GRs depends on the type of vegetation cover, nature and thickness of the growth media, and moisture availability and retention in the GR system. Morau et al. (2012) have found that in Reunion Island, green roof of 120 mmm thickness (substrate and drainage) could reduce the temperature by 6^{0}C at the bottom of drainage layer. However, porous media with high water-storage capacity could lead to high thermal mass that in turn could act as a heat sink and eventually create fluxes downwards to warm indoor air and increase the building cooling load. The research on different plants and substrate materials, and its implication on cooling potentials are very limited. Jim (2015) has provided a very useful summary of 'best practices' in GR for tropical locations while indicating that thick foliage growth could prevent the beneficial cooling due to evapotranspiration from reaching downwards. Thus, care is needed to carefully design and execute GRs in warm, humid locations.

However, cooling benefits of individual and clusters of trees at the pedestrian level is well known. Abreu-Harbich et al. (2015) have found 0-15^{o}C reduction under trees in a tropical setting (Campinas, Brazil). In these conditions, thermal comfort improvements as measured on the PET scale were even higher. In Singapore, air temperature in urban parks was on an average 1.3^{0} C lower than the areas closer to the parks (Ca et al., 1998). In Taipei, during summer, the urban parks showed 0.8^{0} C cooler than the surrounding area at noon (Chang et al, 2007). However, the large variation in the cooling effect of trees indicate that several factors of tree physiognomy are critical - features such as tree height, foliage cover, shape and permeability of the crown can influence the thermal environment (Abreu-Harbich et al., 2015). Additionally, trunk and branching structure, and size and shape of leaves, influence the level and nature of shading (and therefore the cooling effect). However, for tropical cities, it is recommended to plant monsoonal dry forest species which are tolerant to high heat and drought (Kjelgren et al., 2011).

In summary, we could conclude that extensive green roofs reduce pedestrian-level air temperature more moderately than intensive green roofs but this effect is more a function of land cover in the surrounding. Peng and Jim (2013) found that in sub-tropical Hong Kong, the cooling effect of extensive green roofs is more visible in open-set low rise sites. Further, coverage by building footprints and building height dampened lateral and vertical advection of cool air generated by green roofs (Wong et al., 2010; Peng & Jim, 2013). Similarly, the cooling effect of green parks is also context-specific. Both large and small parks have influence on urban climate, however the degree and nature of cooling will vary with the context (Gioia et al, 2014; Ng et al., 2012; Giridharan et al., 2008; Jamei et al., 2016). Further, Jamei et al. (2016) were of the opinion that the optimum distance to which the park has influence on changing the temperature is around 300m. There appears to be consensus that pocket parks in the order of 1000 m^{2} at regular intervals is more effective than a single large park, especially in high-rise high density areas of tropics (Ng et at., 2012; Giridharan et al., 2008; Jamei et al., 2016).

Another GI is the green/living wall and it could reduce the surface temperature in Singapore by 6^{0} C to 10^{0} C compared to a concrete wall, depending on the type of living wall system (wong et al., 2010). At the same time, carbon storage of living wall (0.14 to 0.98 kg C m^{2}) is reported to be poor compared to green roof (0.375 to 30.12 kg C m^{2}) due to thickness of substrates (Charoenkit & Yiemwattana, 2016). However, there are only few studies that report on GI such as green/living walls. A detailed account of living wall systems and their applications could be found in the work done by Charoenkit & Yiemwattana (2016) while Jim and Chen (2011), and Pandey et al., (2015) have outlined variety of plants that could grow on urban surfaces, especially on the vertical surfaces.

5.3 Garden cities

Another mitigatory option is based on the 'Garden city' concept developed in the 19th Century Britain by Ebenezer Howard. This combines green belts and waterbodies both on the fringes of urban areas as well as within urbanised areas as corridors of greenery. Tropical examples of the application of these principles include Maringa, Brazil (Macedo & Maringa, 2011) and Putra Jaya, Malaysia (Moser, 2010). In the case of Putra Jaya, Morris et al. (2016b) have found that the reduction in overheating due to the use of vegetation and water bodies were 0.04 and 0.02°C per km^2 of vegetation and waterbody respectively. Overall, the garden city approach contributed to approx. 0.5°C cooling over Putrajaya City (Morris et al., 2016b). The drawback of this concept is that the extent of soft area (un-built) required is substantial and may not be viable for tropical cities with chronic land scarcity. Further, there is not enough research to suggest the optimum size of the garden city for a given density to achieve thermal comfort.

5.4 Cool roofs, cool pavements and other albedo enhancement approaches

The albedo is the proportion of the radiation reflected by a surface (reflection coefficient), defined as the ratio of incoming to outgoing radiation. As such, surface with an albedo of 0 absorb 100% of the incoming radiation and have no reflection, while those with an albedo of 1 reflect 100% of the incoming radiation back to the environment. Santamouris (2014) has provided an overview and critique of cool roof/cool pavement applications in mitigating the UHI problem. However, issues specific to the tropics are poorly studied. These include excessive glare from the usual overcast/mostly cloudy skies in the tropics, maintenance of cool paints in high humidity environments. Furthermore, the actual effectiveness in reducing thermal discomfort in the already stressed tropical environments needs empirical validation.

An experimental study conducted in Malaysia on five types of cool pavements (high albedo) showed that porcelain tiles could reduce the surface temperature by 6.4°C compared to asphalt (Antiga et al., 2017). High albedo on vertical surfaces could increase the incoming radiation on vertical surfaces due inter reflections, for example an albedo of 0.8 could result in an increase of 259 kWh/m^2/year solar gain on east façade compared to 67 kWh/m^2/year on the roof (Martins et al., 2016). However, in low rise compact development, solar gain will largely occur via roof and the application of cool material (0.9 albedo) could result in reduction of peak cooling load varying between 5% to 35% depending on type of fabric system (Miller et al., 2015). The reduction in the peak cooling load could have significant impact on the anthropogenic heat released.

Another albedo enhancement option is to use different types of glass on building surfaces since reflection depends on the character of glazing system. On most occasions, lower 'G' (solar factor) value glazing is recommended to reduce the cooling load in the tropics (Bui et al., 2017). Although this could reduce air conditioning load (and thus the anthropogenic heat) the wisdom of using low 'G' glazing in high density tropical settings is questionable. It would be more appropriate to reduce the use of glass in the first place, especially in compact urban settings in the tropics. The impact of glass on urban environment is not well researched in tropics, especially in the form of field experiments.

5.5 Albedo vs vegetation deployment

Both albedo and vegetation have the potential to cool an urban environment in tropics. A simulation exercise in Singapore found that although the city-wide deployment of cool roofs could lead to daytime temperature reductions but they offer little benefit at night, when tropical UHIs are at their peak (Li and Norford, 2016). On the other hand, this study showed that vegetation could reduce the near-surface air temperature by more than 1^{o}C across the city. This is due to the higher latent heat flux and lower heat storage during daytime in green vegetation. Shahidan et al. (2012) have found that Leaf Area Index (LAI) of 9.7 along with a surface albedo of 0.8 could reduce the average outdoor temperature by 2.7^{o} C. They were also of the opinion that only a small component of the outdoor temperature reduction was achieved by albedo enhancement (0.2^{o}C out of 2.7^{o}C). Further sensitivity analysis is required to establish the relative merits of these two options, especially in the context of different urban morphological settings. A simulation exercise done by Martins et al. (2016) show that albedo, aspect ratio and distance between buildings together account for around 80% of the variations in solar radiation in tropical cities. This could point to potential integrated mitigation strategies appropriate for the tropics.

A way of combining the beneficial effects of various mitigation approaches while avoiding as many negative effects as is practical is needed for tropical cities. Towards this end, the work of Tan et al. (2016) offers some clues. Research found that cooling effect of urban trees is highly associated with SVF. The most significant effect of urban trees in open areas (i.e. those with high SVF) is on air temperature reduction, while trees in the more built up areas (medium to low SVF) lead to reduction in MRT. This research also showed that the cooling of air temperature and sensible heat were twice as high for vegetation arranged along wind corridors than that perpendicular to the prevailing wind. Thus, a combination of wind flow enhancement approaches boosted by tree planting and other shade enhancement strategies could be the most effective planning approach to tropical UHI mitigation.

Ultimately, surface cover fractions are key modulators of UHIs in the tropics. In the sub-tropical Xiamen, China, Xu et al. (2013) have shown that impervious surface is positively and exponentially correlated with land surface temperature (LST), while vegetation and water are inversely related to LST. Further, this work shows that impervious surface contribution to regional LST change can be up to six times greater than the sum of vegetation and water contributions, and an addition of 10% green or water space for each 10% decrement of impervious surface cover, could lower LST by up to 2.9 or 2.5°C, respectively.

A final point to keep in mind in mitigating the tropical UHIs is the importance of combining the many mitigatory approaches. In this regard, while the evapotranspiratory cooling provided by GI and waterbodies are useful, they do not provide as much cooling in the high-humidity tropics as when this is combined with shading (Chow et al., 2016). While shading is a key approach to UHI mitigation in the tropics, other 'non-thermal' aspects of greenery may be equally important, even if the 'objective' thermal benefit from greens are minimal. At the same time, all mitigatory approaches need to be mindful of any unintended wind blocking effects that they might create (Algeciras et al., 2016).

6.0 MODELLING OF TROPICAL UHIs

For the purpose of the present review, urban climate modelling is considered to be the energy and the mass exchange (circulation) in the urban canopy layer (UCL). The urban features that modify the circulation are the heterogeneity of buildings, impervious and pervious surface materials, release of anthropogenic heat, release of pollutants, and street geometry. Given the difficulties in obtaining accurate information of these urban features at fine scales, general Circulation Models usually ignore the presence of city element (Ooka, 2007). While this may not pose great difficulties in arriving at global climate projections, ignoring urban land use and land cover has significant impact on the general dynamics of tropical island climates, as shown by Velazquez et al. (2016) for Puerto Rico. Boehme et al., (2015) have shown that the assumptions surrounding current micrometeorological models make them unsuited for tropical, especially high-density cities. It would be necessary to estimate the energy balance accurately, which could in turn enable the identification of 'hot spots', where computational fluid dynamics (CFD) could be applied for better accuracy. Rajagopalan et al., (2014) have provided a detailed account of the assumptions for urban scale CFD modelling.

A more common approach to studying the impact of urban variables on UHI is to use statistical models (Da Silva et al., 2010; Giridharan et al., 2007; Yang et al., 2010; Wang et al., 2016). Use of numerical models to assess the UHI impact is limited. Lau et al., 2016 have used SOLWEIG numerical model to assess the impact of mean radiant temperature on high density (compact) environment. SOLWEIG model is an efficient method to assess the mean radiant temperature across wide spatial variation. This model also generates the sky view factor and shadow patterns. Karam et al. (2010) have used tropical Town Energy Budget (TEB) numerical model to compute the surface fluxes, air temperature and humidity. This model crucially takes into account the surface water capacity and drainage time scale which are critical component in tropical urban thermal balance. Therefore, in terms of urban energy budgeting TEB is better than SOLWEIG.

In contrast to statistical models, numerical models explain the physical process and they are classified as one, two and three dimensional. One and two dimensional models are not appropriate to study the micro and macro scale UHI impact due to their inability to capture the variations in urban geometry. They may also introduce errors in the estimation of short-wave radiation and turbulence due to lack of validation and calibration. As per Martilli (2007) these models also under-estimate the outdoor temperature predictions due to absence of proper representation of sea breeze and its inland penetration. Although Martilli's research does not focus on the tropics, some of the comments are relevant to tropics. Another aspect found in that research is the representation of vegetation, i.e. heat fluxes from vegetation and urban surfaces, is calculated separately and the area weighted average is used to assess the effective fluxes. However, in reality, vegetation has an influence on both latent and sensible heat fluxes released into an environment.

Numerical models require detailed information on urban morphology and locally measured inputs to properly define the boundary conditions. Such information is hard to obtain in the developing regions of the tropics. In this regard the current efforts by the World Urban Database and Access Portal Tools (WUDAPT) workflow (Ching, 2013; See et al., 2015; Bechtel et al., 2015; Brousse et al., 2016) is worthy of mention. WUDAPT uses remotely sensed and freely available data for a supervised classification of Local Climate Zones (LCZs) as detailed by Stewart and Oke (2012) and Stewat et al. (2014). A demonstration of its applicability to data-poor tropical cities is recently provided by Perera and Emmanuel (2016).

In terms of the most common approach to modelling tropical UHIs, ENVI-met appears to be widely accepted. Modelling of tropical UHI with ENVI-met is a useful planning approach for assessing air temperature and daytime extremes in outdoor thermal comfort, but the modeller requires detailed local information for proper initialization in addition to awareness of its limitations (Roth & Lim, 2017). However, in tropical urban climate studies, the application of climate models taking into account of surface water and humidity is very weak.

7.0 Discussion

In common with other regions, canopy layer tropical UHIs are mostly studied using field measurements with mobile and/or fixed weather stations. However, there are wide variations in reporting the results in terms of interval of measurement, duration of the study period, classification of day and night, height of measurement, and number of measurement points. The call for more standardisation of UHI measurements issued by the WMO in 2004 thus remains unheeded and inter-comparisons are difficult to make. A promising approach to overcome this could be seen in the classification of measurement locations by their key micro-climate influencing features through the so-called ‘Local Climate Zone’ (LCZ).

SEB and its relationship to UHI is not well understood in tropics. Further, the tropical UHI issues are complex and place sensitive, and available experimental and modelling methods do not capture the complete variations of the geography and its impact on UHI. However, in the recent years, improvements in sensors and temporal resolution of remote sensing have advanced its application in the UHI studies, especially for surface temperatures. This technique has potential in the context of rapid urbanisation if it is combined with micro and macro on-site measurements. A detailed account of data collection and the error correction process for remote sensing studies with special reference to tropical UHI is reported by Quah & Roth (2012), Nichol (1996), Nichol (1998), and Nichol & Wong (2005). Given that the remote sensing is biased towards horizontal surfaces, its applicability to high density settings is limited, but Nichol & Wong (2005) have highlighted that issues related to the depth of the canyon in high-rise high density environments could be managed by combining satellite images with geometrical data derived from photogrammetry or digitised geometrical data. Although in principle this approach sounds effective, its application in various tropical context needs to be validated. Use of drones could compliment this approach. The sky view factor, albedo, vegetation density and wind velocity are critical ‘urban compactness’ variables in the tropics but the effect is hard to isolate. Therefore, compact forms defined in terms of height to width ratio is not adequate enough to capture the impact on UHI and energy. Recently, the relationship between compactness and air quality in China has been studied using compact index as function of urban area and perimeter (Lu & Liu; 2016). We are of the opinion that this index has a potential application in UHI studies along with indices such as fractal dimension and Boyce Clarke shape since they are sensitive to massing as well as extend of the development.

Ultimately, the embedding of UHI mitigation in practical planning in tropical cities requires supportive institutional framework. Here again LCZs could be used as Zoning precincts, by defining a LCZ specific morphology and future maximum development. The development of LCZ-based urban form/material thresholds is technically possible. However, the interpretation of these in the context of a specific city could create many issues (Stewart & Oke, 2012). Therefore many context specific research is needed to resolve these issues.

8.0 CONCLUSIONS AND FUTURE DIRECTIONS

Although studies on tropical UHIs remain numerically inferior to temperate UHI studies, there appears to be a considerably rich and diverse knowledge base built upon in the recent past.

Nevertheless, additional work is needed in the following areas: The application of advanced material for urban surfaces of tropics is not well researched. Considering the huge variations in topography, research on tropic-specific plants for appropriate cooling to mitigate UHI is also needed.

Furthermore, adequate research is needed to identify the nature of the link between global climate change and tropical UHI, especially taking into account the anthropogenic heat. The implications of UHI to space conditioning energy load, especially in the residential sector, is not well captured. At micro level, there has to be focused and structured research on vegetation, surface material and energy consumption such that the database could be used for both validation and calibration of climate models. Further, LCZ's should be used as templates field experiments.

Finally, UHI mitigation in the tropics requires consideration of equity (i.e. who benefits from UHI mitigation and who pays for it?) but this is beyond the scope of the present review. Nevertheless, such considerations are important in the further development and deployment of the many technical approaches advocated in the present review.

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