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

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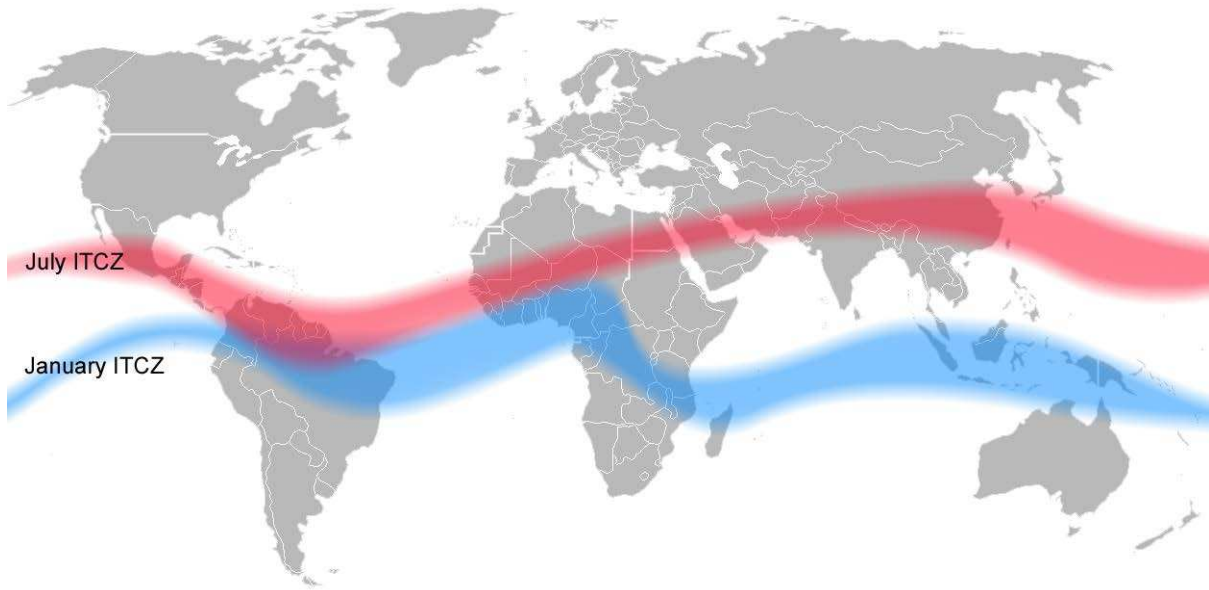
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8   **Abstract:**

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

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

24  
25   **Keywords:** Urban Heat Island (UHI); Tropics; Journal database; Monitoring; Urban compactness;  
26   Comfort strategies; Energy; Green infrastructure; Cool material; Modelling.

27 **1.0 INTRODUCTION AND CONTEXT**



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**Figure 1. Global ‘tropical’ belt (tropics and sub-tropics)**

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Source: Mats Halldin, based on Image: ZICT en janvier.jpg, Image: ZICT en juillet.jpg, and Image: BlankMap-World.png. Licensed under Public Domain via Wikimedia Commons -

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[http://commons.wikimedia.org/wiki/File:ITCZ\\_january-july.png#/media/File:ITCZ\\_january-july.png](http://commons.wikimedia.org/wiki/File:ITCZ_january-july.png#/media/File:ITCZ_january-july.png)

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Much of the 21<sup>st</sup> 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.

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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).

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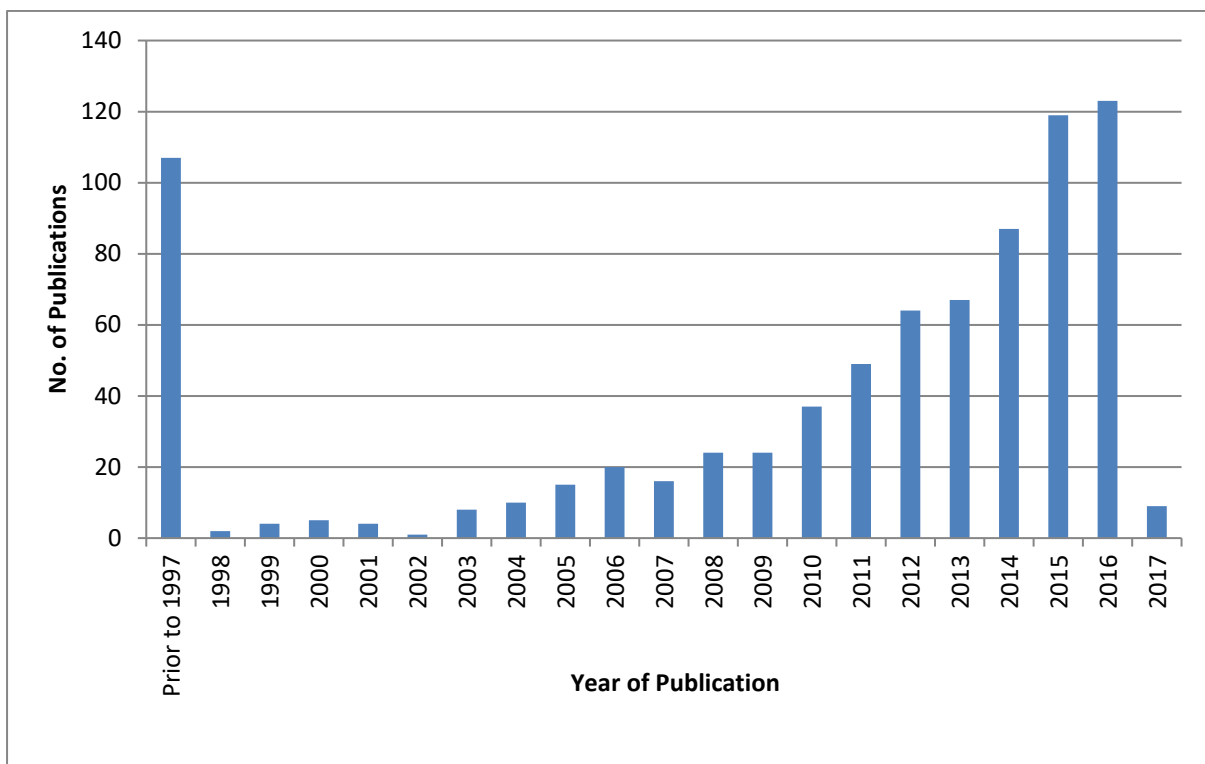
Nevertheless, there is still a concern that Urban Heat Island (UHI) in the tropics is not as well documented as temperate climate (e.g. Rajagopalan, 2014; Gazal, 2008). Further, Eliasson (2000) and Ng (2015) point out the missing link between the technical information and planners’ ability to apply it 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

57 (2016) argued that urbanization in the region of Greater Ho Chi Minh City, Vietnam, was responsible  
58 for approximately half of the observed increases in air temperature since the late 1980's.  
59 Furthermore, there is a 'developmental' shift in disease burden in tropical countries (i.e. a shift from  
60 excess mortality associated with rainfall to excess mortality associated with thermal conditions) that  
61 is exasperated by the UHI phenomenon (Goggins et al., 2016; Burkart et al., 2014).

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

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

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

## 79 2.0 APPROACH AND METHOD

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

- 83 • What is the state of knowledge regarding the uniqueness if any, of tropical UHI  
84 phenomenon?
- 85 • What effects do high density living have on the mitigation approaches to tropical UHI  
86 problem in terms of energy and thermal comfort?
- 87 • What are the emerging approaches to the study of tropical UHI and their future directions?  
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89 The present work is limited to literature review of peer-reviewed journal publications found on four  
90 databases: Web of Science, Scopus, Google Scholar and Science Direct. The following key words  
91 were used: “tropics”, “urban heat island”, “energy consumption” and “urban form.” Search based  
92 on terms “urban heat island” and “tropics” generated 203 and 238 outputs in Web of Science and  
93 Scopus respectively for the period 1997 to 2016. For the same terms and period, Science Direct and  
94 Google Scholar produced 795 (see Figure 2) and 14,100 outputs respectively. For the same period  
95 Boolean search terms “tropical UHI and energy consumption” and “topical UHI and compact urban  
96 form” produced 24 and 9 papers respectively in Web of Science. Similar order of results was  
97 obtained from Scopus as well. Detailed review of the resulting shortlist revealed that while Web of  
98 Science and Scopus were the most focussed and relevant in capturing the most important research  
99 works, they do sometime omit few critical research papers. This is largely due to the use of non-  
100 standard terminology (such as “rise in the outdoor temperature” rather than UHI, for example). A  
101 technique of ‘snowballing’ (where one research subject leads the researcher to another, which in  
102 turn provides a third, and so on, Vogt, 1999) was therefore used to find additional published  
103 resources. These were then added to a common database that was formed by combining outputs  
104 from the Web of Science and Scopus. The total yield from this exercise was 162 research outputs  
105 that report on research from different parts of the topics in terms of UHI trends, technology used in  
106 the experimental and modelling studies, and mitigation strategies. Authors do not claim that the  
107 present review covers all of the tropical urban climate studies conducted in the last two decades, we  
108 are confident that it captures the key literature that emerged from the above mentioned review  
109 process.

## 110 3.0 NATURE OF TROPICAL UHI

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

$$113 \quad Q^* + Q_f = H + LE + \Delta Q_s + \Delta Q_a \text{ (in Watts/m}^2\text{)} \quad \text{(Eq. 1)}$$

114 Two most distinguishing features of tropical urban SEB is the importance of direct solar radiation  
115 within net all-wave radiation ( $Q^*$ ) for daytime urban exchange of momentum, heat and water  
116 vapour (Morris et al., 2016a), and the seasonality of the relationship between Sensible ( $H$ ) and latent  
117 ( $LE$ ) heat. According to Barradas et al. (1999), net radiation was higher during the dry season and  
118 was partitioned between  $H$  and  $LE$  in the order of 69% and 25%, respectively. However, during the  
119 wet season this was reversed to 27 and 70% respectively, and the total was lower. In terms of land

120 cover, Morris et al. (2016b) confirmed that the pattern seen in both temperate and tropical cities is  
121 similar – i.e.  $H$  increases (and  $LE$  decreases) with increase in urban fraction.

122 The instrumentation difficulties, cost and long-term commitment required to maintain and monitor  
123 them have made SEB studies in urban areas relatively uncommon. Of the few, only a handful have  
124 dealt with tropical cities (Park, 2016). We could only find two long term ( $> 1$ yr) SEB studies in a  
125 tropical urban area (Sao Paulo, Brazil in Ferreira et al., 2013 and Singapore in Roth et al, 2017).  
126 According to Ferreria et al.(2013), during daytime, energy flux storage ( $\Delta Q_s$ ) corresponds to  
127 approximately 51% of the net all-wave radiation but drops to 27% when the total daily net all-wave  
128 radiation is included. Overall, 54% and 40% of annual net radiation partitioned into sensible and  
129 latent heat respectively (Roth et al., 2017). The significant diurnal change in the total stored energy  
130 flux could be an important driver of the UHI phenomenon in a tropical city but the relationship  
131 between  $\Delta Q_s$  and UHI is not so clear. The large difference between the day and diurnal storage  
132 (50% vs 27%) might provide an explanation (Ferreira et al., 2013).

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

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

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

161 As a general phenomenon, tropical UHIs are usually smaller in magnitude when compared with  
162 temperate cities. Another feature of tropical UHI is that the urban-rural temperature differences are  
163 often of the same magnitude as the intra-urban temperature differences and this is largely due to

164 the role of vegetation. There is strong evidence for such ‘oasis effect’ in many tropical cities but this  
 165 exists only on a localised basis (Jonsson, 2004).

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

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

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

189 **Table 1: Canopy layer and surface UHI at selected tropical urban areas**

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

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



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

190

## 191 4.0 URBAN COMPACTNESS AND ENERGY

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

### 202 4.1 Impact of urban compactness

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

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

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

$$214 \quad \Delta T_{U-R(\max)} = 0.952 \times \text{median } H:W - 0.021 \quad (\text{Eq.2})$$

215 This relationship (Eq.2) was somewhat weak but statistically significant ( $r=0.53$ , but  $\alpha = 0.05$  with  
 216  $p=0.001$ ). It is likely that the relationship between urban compactness and tropical UHIs are subject  
 217 to a multitude of factors. While it is intuitive to infer urban compactness to reduce daylight, natural  
 218 ventilation and renewable energy potential (cf. Martins et al., 2016), comprehensive studies  
 219 exploring the inter-relationships between these and overheating in the context of humid

220 environments are rare. This is a key research gap that require future consideration in light of the  
221 demand for rapid urban development and affordability of energy to the larger population.

222 In general, the impact of urban compactness on tropical UHI depends on both on-site (urban  
223 geometry) and off-site (large heat sinks) variables in addition to climate/weather variables (Ng et al.,  
224 2012; Lau et al., 2016). While Chow and Roth (2006) reveal that the relationship between urban  
225 geometry and UHI was weak in Singapore, it appears on-site variables are more important than off-  
226 site variables in explaining the differences in intra-urban UHI intensities (Giridharan et al., 2007;  
227 Ignatius et al., 2016).

228 A further problem in urban compactness in the tropics is the lack of standardisation of its  
229 characterisation. This poses problems in deciphering the overall effect of urban compactness on  
230 tropical UHIs. Giridharan et al. (2007) have argued for characterisation of on-site variables and off-  
231 site variables within 15m (i.e. 1000 m<sup>2</sup> area around measurement point) and 300m radius  
232 respectively from the measurement point for Hong Kong while Ignatius et al. (2016) have used 50m  
233 radius to characterise the on-site variables in Singapore. On the other hand, Niu et al. (2015) have  
234 indicated that different thermal conditions prevail within 200m in Hong Kong without explicitly  
235 identifying the boundary conditions. Furthermore, most studies have failed to appreciate the  
236 importance of urban albedo over surface albedo, and limit the investigation only to surface albedo.  
237 Although urban albedo is admittedly more difficult to measure, computer modelling of urban albedo  
238 is possible, but time consuming, considering the number of related surfaces that need to be  
239 modelled to trace the incoming and outgoing solar radiation. Recently Yang & Li (2015) and Qin  
240 (2015) have proposed numerical models but its application in different context needs to be  
241 validated. Vegetation density measurement poses further problems. Although it is generally  
242 represented by means of green area ratio – GAR (e.g. Yang et al., 2010; Giridharan et al., 2008), GAR  
243 does not capture the true influence of vegetation especially the impact of its height and the canopy  
244 structure. In high rise high density environments, disentangling the shading effect of buildings from  
245 vegetation is difficult (Giridharan et al., 2008). Similarly, urban wind too, remains hard to quantify in  
246 the tropics, where macro-level wind speeds are low, thus the influence of roughness elements are  
247 considerable (sharmin et al., 2015; Wong et al., 2010). It is possible to study wind tread using CFD  
248 modelling (Rajagopalan et al., 2014; Emmanuel et al., 2007; Ng et al., 2012), although this is not  
249 extensively used due to cost and computer time constraints.

## 250 **4.2 Energy and environmental effects**

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

258 Emmanuel (2017) highlights five ways in which tropical cooling need is a unique problem that  
259 exacerbated by the superimposing of UHI phenomenon on regional warming. The use of air  
260 conditioners to cool buildings (both as a consequence of global warming as well as to tackle the UHI  
261 effect) leads to dramatic changes in energy demand, which in turn acts as a feed-in mechanism for  
262 further local and regional climate change. This is particularly so in South and South-East Asia, where  
263 energy demand for residential air conditioning could increase more than 40 times in 2100 compared  
264 to 2000, with a 7% growth per year on average (Lundgren & Kjellstrom, 2013). This development is

265 without the additional impacts of climate change, which might add up to an extra 50% in  
266 consumption to this (Isaac and Van Vuuren, 2009).

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

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

288 Apart from the effect on energy consumption, tropical UHIs also lead to thermal discomfort,  
289 morbidity and perhaps even mortality. Evidence for long-term (1921 – 1985) change in bioclimatic  
290 conditions in cities due to the UHI phenomenon was first reported in the sub-tropical Mexico City  
291 nearly 20 years ago (Jauregui et al., 1997). Yan (1997) has shown a rise in mortality and morbidity in  
292 high density compact cities due to heat related stress. In high rise high density environments  
293 variability and intensity of the surface temperature is much higher than air temperature (Nichol,  
294 1996). This has significant impact on thermal comfort in locations where humidity levels are high.  
295 Overall, relationship between energy and UHI in tropics, especially in the residential sector is not  
296 very well captured due lack of accessibility to data and cost implications related to long term  
297 monitoring.

## 298 **5.0 MITIGATION OF TROPICAL UHIs**

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

### 303 **5.1 Shading vs. ventilation in the tropics**

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

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

313 Compact building forms such as standalone towers linked by sky bridges, towers on podium and  
314 blocks with multiple courtyards have great potential to shade the urban environment (Yang et al.,  
315 2010; Giridharan et al., 2008; Lau et al., 2011; Chen et al., 2012). Sharmin et al. (2015) have shown  
316 that compact urban geometry with aspect ratio between 2.4 and 3.5 could provide good thermal  
317 comfort. Giridharan et al. (2007) have outlined in principle the potential of different massing types.  
318 Emmanuel (2017) has proposed 'Shadow Umbrella' that aims to shade public spaces within urban  
319 blocks surrounded by built massing that are themselves optimally positioned to self-shade the  
320 building envelope. However, the impact of compact urban form on shading is not systematically  
321 investigated to generalise the findings from one place to another.

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

$$329 \quad \lambda_f = \frac{A_{facets}}{A_{plane}} \quad (\text{Eq.3})$$

330 In Eq.3,  $\lambda_f$  is the frontal area index,  $A_{facets}$  is the total area of building facades facing the wind  
331 direction, and  $A_{plane}$  is the plane area.

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

342 In the tropics, both shading and ventilation are equally important. Especially in high density settings,  
343 courtyard built forms should be 'connected' to the street (in terms of air passage) at ground level,  
344 while windows and walls should be shaded with 'permanent' ventilation openings (Tablada et al.,  
345 2009). Work done by Qaid et al. (2016) on shading and ventilation in Kuala Lumpur reinforces the  
346 above argument further. However, there are only limited experimental studies which linked both  
347 indoor and outdoor overheating. At the same time, evidence from sub-tropics suggests that at  
348 higher densities, the distributions of wind velocity around the buildings became polarized, and weak  
349 wind regimes begin to dominate. Nevertheless, the cooling effects of building shade become

350 increasingly significant as inter building distance decreases because of the low level of exposure to  
351 strong direct radiation in compact forms. While this combination is beneficial in moderately humid  
352 areas, not ideal for high humid conditions (Xuan et al., 2016).

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

361 A key aspect to keep in mind is the interaction between the many mitigation strategies and air  
362 pollution and internal heat gain. While ventilation is very useful in reducing the cooling load in the  
363 tropics, the ability to benefit from air movement is contingent upon air pollution levels in the  
364 surroundings. The pollution problem in tropical cities is severe – even in the relatively cleaner  
365 Singapore, suburban areas have 15 times more CO<sub>2</sub> than nearby forest cover (Quah & Roth, 2012).  
366 In the absence of good quality air, the windows will be shut, and internal and solar gains will built up.  
367 In this scenario, savings achieved through shading and/or ventilation will be marginal since  
368 elimination of internal and solar gains will solely depend on air-conditioning.

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

## 377 **5.2 Green roofs, walls and other Green Infrastructure (GI) options**

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

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

393 previously pointed out, cooling load reduction benefits to individual buildings in warm climates is  
394 considerable.

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

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

418 In summary, we could conclude that extensive green roofs reduce pedestrian-level air temperature  
419 more moderately than intensive green roofs but this effect is more a function of land cover in the  
420 surrounding. Peng and Jim (2013) found that in sub-tropical Hong Kong, the cooling effect of  
421 extensive green roofs is more visible in open-set low rise sites. Further, coverage by building  
422 footprints and building height dampened lateral and vertical advection of cool air generated by  
423 green roofs (Wong et al., 2010; Peng & Jim, 2013). Similarly, the cooling effect of green parks is also  
424 context-specific. Both large and small parks have influence on urban climate, however the degree  
425 and nature of cooling will vary with the context (Gioia et al, 2014; Ng et al., 2012; Giridharan et al.,  
426 2008; Jamei et al., 2016). Further, Jamei et al. (2016) were of the opinion that the optimum distance  
427 to which the park has influence on changing the temperature is around 300m. There appears to be  
428 consensus that pocket parks in the order of 1000 m<sup>2</sup> at regular intervals is more effective than a  
429 single large park, especially in high-rise high density areas of tropics (Ng et al., 2012; Giridharan et  
430 al., 2008; Jamei et al., 2016).

431 Another GI is the green/living wall and it could reduce the surface temperature in Singapore by 6°C  
432 to 10°C compared to a concrete wall, depending on the type of living wall system (Wong et al.,  
433 2010). At the same time, carbon storage of living wall (0.14 to 0.98 kg C m<sup>2</sup>) is reported to be poor  
434 compared to green roof (0.375 to 30.12 kg C m<sup>2</sup>) due to thickness of substrates (Charoenkit &  
435 Yiemwattana, 2016). However, there are only few studies that report on GI such as green/living  
436 walls. A detailed account of living wall systems and their applications could be found in the work  
437 done by Charoenkit & Yiemwattana (2016) while Jim and Chen (2011), and Pandey et al., (2015)  
438 have outlined variety of plants that could grow on urban surfaces, especially on the vertical surfaces.

### 439 **5.3 Garden cities**

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

### 451 **5.4 Cool roofs, cool pavements and other albedo enhancement approaches**

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

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

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

### 478 **5.5 Albedo vs vegetation deployment**

479 Both albedo and vegetation have the potential to cool an urban environment in tropics. A simulation  
480 exercise in Singapore found that although the city-wide deployment of cool roofs could lead to  
481 daytime temperature reductions but they offer little benefit at night, when tropical UHIs are at their  
482 peak (Li and Norford, 2016). On the other hand, this study showed that vegetation could reduce the

483 near-surface air temperature by more than 1°C across the city. This is due to the higher latent heat  
484 flux and lower heat storage during daytime in green vegetation. Shahidan et al. (2012) have found  
485 that Leaf Area Index (LAI) of 9.7 along with a surface albedo of 0.8 could reduce the average outdoor  
486 temperature by 2.7° C. They were also of the opinion that only a small component of the outdoor  
487 temperature reduction was achieved by albedo enhancement (0.2°C out of 2.7°C). Further sensitivity  
488 analysis is required to establish the relative merits of these two options, especially in the context of  
489 different urban morphological settings. A simulation exercise done by Martins et al. (2016) show that  
490 albedo, aspect ratio and distance between buildings together account for around 80% of the variations  
491 in solar radiation in tropical cities. This could point to potential integrated mitigation strategies  
492 appropriate for the tropics.

493 A way of combining the beneficial effects of various mitigation approaches while avoiding as many  
494 negative effects as is practical is needed for tropical cities. Towards this end, the work of Tan et al.  
495 (2016) offers some clues. Research found that cooling effect of urban trees is highly associated with  
496 SVF. The most significant effect of urban trees in open areas (i.e. those with high SVF) is on air  
497 temperature reduction, while trees in the more built up areas (medium to low SVF) lead to reduction  
498 in MRT. This research also showed that the cooling of air temperature and sensible heat were twice  
499 as high for vegetation arranged along wind corridors than that perpendicular to the prevailing wind.  
500 Thus, a combination of wind flow enhancement approaches boosted by tree planting and other  
501 shade enhancement strategies could be the most effective planning approach to tropical UHI  
502 mitigation.

503 Ultimately, surface cover fractions are key modulators of UHIs in the tropics. In the sub-tropical  
504 Xiamen, China, Xu et al. (2013) have shown that impervious surface is positively and exponentially  
505 correlated with land surface temperature (LST), while vegetation and water are inversely related to  
506 LST. Further, this work shows that impervious surface contribution to regional LST change can be up  
507 to six times greater than the sum of vegetation and water contributions, and an addition of 10%  
508 green or water space for each 10% decrement of impervious surface cover, could lower LST by up to  
509 2.9 or 2.5°C, respectively.

510 A final point to keep in mind in mitigating the tropical UHIs is the importance of combining the many  
511 mitigatory approaches. In this regard, while the evapotranspiratory cooling provided by GI and  
512 waterbodies are useful, they do not provide as much cooling in the high-humidity tropics as when  
513 this is combined with shading (Chow et al., 2016). While shading is a key approach to UHI mitigation  
514 in the tropics, other 'non-thermal' aspects of greenery may be equally important, even if the  
515 'objective' thermal benefit from greens are minimal. At the same time, all mitigatory approaches  
516 need to be mindful of any unintended wind blocking effects that they might create (Algeciras et al.,  
517 2016).

## 518 **6.0 MODELLING OF TROPICAL UHIs**

519 For the purpose of the present review, urban climate modelling is considered to be the energy and  
520 the mass exchange (circulation) in the urban canopy layer (UCL). The urban features that modify the  
521 circulation are the heterogeneity of buildings, impervious and pervious surface materials, release of  
522 anthropogenic heat, release of pollutants, and street geometry. Given the difficulties in obtaining  
523 accurate information of these urban features at fine scales, general Circulation Models usually  
524 ignore the presence of city element (Ooka, 2007). While this may not pose great difficulties in  
525 arriving at global climate projections, ignoring urban land use and land cover has significant impact



526 on the general dynamics of tropical island climates, as shown by Velazquez et al. (2016) for Puerto  
527 Rico. Boehme et al., (2015) have shown that the assumptions surrounding current  
528 micrometeorological models make them unsuited for tropical, especially high-density cities. It  
529 would be necessary to estimate the energy balance accurately, which could in turn enable the  
530 identification of 'hot spots', where computational fluid dynamics (CFD) could be applied for better  
531 accuracy. Rajagopalan et al., (2014) have provided a detailed account of the assumptions for urban  
532 scale CFD modelling.

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

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

554 Numerical models require detailed information on urban morphology and locally measured inputs to  
555 properly define the boundary conditions. Such information is hard to obtain in the developing  
556 regions of the tropics. In this regard the current efforts by the World Urban Database and Access  
557 Portal Tools (WUDAPT) workflow (Ching, 2013; See et al., 2015; Bechtel et al., 2015; Brousse et al.,  
558 2016) is worthy of mention. WUDAPT uses remotely sensed and freely available data for a  
559 supervised classification of Local Climate Zones (LCZs) as detailed by Stewart and Oke (2012) and  
560 Stewart et al. (2014). A demonstration of its applicability to data-poor tropical cities is recently  
561 provided by Perera and Emmanuel (2016).

562 In terms of the most common approach to modelling tropical UHIs, ENVI-met appears to be widely  
563 accepted. Modelling of tropical UHI with ENVI-met is a useful planning approach for assessing air  
564 temperature and daytime extremes in outdoor thermal comfort, but the modeller requires detailed  
565 local information for proper initialization in addition to awareness of its limitations (Roth & Lim,  
566 2017). However, in tropical urban climate studies, the application of climate models taking into  
567 account of surface water and humidity is very weak.

## 568 **7.0 Discussion**

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

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

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

## 604 **8.0 CONCLUSIONS AND FUTURE DIRECTIONS**

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

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

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

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

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