ABSTRACT: This paper presents the historic trends in thermal comfort in the Sri Lankan primate city of Colombo and correlates them with land cover changes. Land cover is calculated from time-series aerial photographs in terms of “hard” cover (buildings, paved areas and roads) and “soft” cover (trees, green areas and bare lands). The period selected for analysis includes pre-rapid (up to 1977) and rapid urban phases (1978 onwards) in the city. Contemporary Sri Lanka’s urbanization is peculiar in that mid to late 20th Century urban rates (approx. 22% of the population) had remained virtually unchanged till the economy was liberalized in 1977, but have recently intensified (currently at about 35%). This offers a unique window of opportunity to look at the thermal comfort transition consequent to urbanization.

An increasing trend in thermal discomfort – particularly at night – is seen especially at the suburban station and it correlates well with hard land cover changes. The relative importance of land cover in city centre vs. rural areas is clearly visible. Hard cover has more effect on thermal discomfort in city centre than in rural areas. Based on these findings, we postulate an outline for a climate-sensitive urban design policy for tropical cities.

Conference Topic: 3 – Comfort and well-being in urban spaces
Keywords: tropical bio-climate, urban heat island, land cover changes, moisture island, THI, RSI

INTRODUCTION

The first ever systematic study of city-induced climate change was carried out by Luke Howard in London in 1833 [1]. Since then studies on urban climate modifications has progressed from descriptive to complex spatial and temporal variability studies, linking climate effects to weather and urban structure [2]. In the recent past, emphasis has shifted to seek the physical basis of urban climate modifications and to develop mitigation strategies [3].

However, from an architectural point of view, the findings of these studies cannot be directly used unless the human consequence of urban climate change is specified. Thus, climate-sensitive architects and urban designers in the recent past have focussed on the human comfort (‘bio-climate’) effect of urbanization [3], [4], [5], [6].

The modification to a city’s climate in contrast to its rural surroundings, known as the Urban Heat Island (UHI) phenomenon, is sparsely studied in the tropics. Early work in the tropics occurred only in the late 1960s [7]. Yet, tropical urbanization remains the largest and the most pressing man-made environmental issue in the world. Almost 90% of the global urbanization between now and 2025 will occur in countries of the developing world located mostly in tropical / subtropical regions [8]. Such statistics underscores the urgency of studying the human consequences of tropical urbanization.

The present study correlates the land cover changes in and around three first order weather stations in the Colombo Metropolitan Region (CMR), the capital city region of Sri Lanka, with the bioclimatic trends during the last 30 years. Land cover is measured in terms of “hard” cover (buildings, paved areas and roads) and “soft” cover (trees, green areas and bare land). Bio-climate is quantified using thermal comfort indices (“Temperature-Humidity Index” – THI and Relative Strain Index – RSI).

2. BACKGROUND

2.1 Urban Bio-climate Quantification

Urban bio-climate quantification is more complicated than indoor comfort due to psychological, physiological and energetic reasons [9].

The quantification of urban thermal comfort is relatively new. Basically, there are three types of approaches to quantify urban bio-climate. The assumption in all these techniques is that human energy balance in the outdoors is influenced by the amount of long-wave radiation loss.

i. Sky-view calculation methods
ii. Shadow calculation methods
iii. Combined methods
2.2 Thermal Comfort Indices Selected for this Study

Temperature-Humidity Index (THI)

Although complex energy balance models provide a more holistic picture of human bio-climate, none can match the potential of the “Temperature Humidity Index” developed by Thom [10], for providing a broad approximation of stress changes in a city over time and for developing useful design guidelines for cities [11]. THI (also known as the “Discomfort Index”) is a variation of ET that combines the wet and dry bulb temperatures into a scale that imitates the thermal sensation of a human being.

\[
\text{THI} = 0.8t + \frac{RH \times t}{500}
\]

where \(t\) is the air temperature (°C) and \(RH\) is the relative humidity (%). By empirically testing the THI values on human subjects, the comfort limits are defined thus:

- \(21 \leq \text{THI} < 24\) = 100% of subjects felt comfortable
- \(24 < \text{THI} \leq 26\) = 50% of subjects felt comfortable.
- \(\text{THI} > 26\) = 100% of subjects felt uncomfortably hot [12].

Relative Strain Index (RSI)

While THI accounts for the thermal comfort effects of air temperature and humidity, the Relative Strain Index (RSI) allows for the effects of clothing insulation and net radiation as well. RSI for a “standard man” (i.e. healthy 25 year old male, un-acclimatized to heat, in business clothing) under specified conditions (i.e. internal heat production = 100 Wm\(^{-2}\), wind speed = 1 ms\(^{-1}\) and no direct solar radiation) is given thus:

\[
\text{RSI} = \frac{(t - 21)}{(58 - e)}
\]

where \(t\) is the air temperature (°C) and \(e\) is the vapour pressure (hPa). At \(\text{RSI} = 0.2\) a quarter of the people will experience some thermal stress while nearly everyone will be uncomfortable at an RSI of 0.3.

Unger [13] mentions that an RSI of 0.2 is the upper limit for comfort for the elderly and those of ill health

- \(\text{RSI} = 0.1\) - 100% unstressed (everyone comfortable)
- \(0.2\) - 75% unstressed
- \(0.3\) - 50% unstressed (upper limit of comfort)
- \(0.4\) - 75% distressed
- \(0.5\) - 100% distressed [13].

3. METHOD

The aim of the present study is to determine the human comfort effects of the CMR’s urban heat island which has previously been shown to be present. Although studies indicate that both the urban morphology and urban land cover are the most important causes for the UHI [14], we focus our attention on land cover changes in the CMR for two reasons. On the one hand, more discernible changes in the CMR relate to land cover changes than the three dimensional form of the city. Secondly, land cover changes are more malleable to public policy initiatives and are therefore more readily controlled by planners and designers.

The study collected historic climate records from the three first-order weather stations in the CMR (Colombo city - CMB, Katunayake - KTN and Ratmalana - RTM) and correlated the climatic changes to land cover changes in and around the three weather stations (Figure 1). It is assumed that the Colombo station (CMB - 6.90°N, 79.87°E, elevation = 7.3m above MSL) indicates the climatic conditions closer to the heart of the city, while the Ratmalana station (RTM - 6.82°N, 79.88°E, elevation = 5.2m above MSL) is more representative of the suburbs. Readings from the Katunayake weather station (KTN - 7.17°N, 79.88°E, elevation = 8.5m above MSL) represent the rural fringes of the CMR.

Land cover was measured in two categories: “hard cover” (build-up & impervious surfaces such as roads, paved surfaces and parking lots) and “soft cover” (trees, grass cover and bare land). The land cover information was digitized from aerial photographs of Colombo. A set of 45-year time series land-use aerial photographs at fine scales (1:1000 or smaller) for an area 0.5km radius around each of the three weather stations was studied.

The outlines of the following land cover categories were digitized from the aerial photographs:

- Buildings (excluding the shadow lines);
- Roads;
- Paved areas (sidewalks, parking lots, airport runways);
- Trees;
- Grass areas (all green areas excluding trees);
- Bare lands (residue of the above).

3.1 Analysis Protocol

The trends in climatic and bio-climatic data were analyzed by fitting a simple linear regression (SLR) equation. Statistical correlation between land cover changes and bio-climate trends were separately calculated for each of the weather stations to determine the relative effects of land cover changes at different urban locations.

It was hypothesized that larger increase in hard land cover would lead to faster deterioration of thermal comfort conditions in the region. The information on correlation, if any, between land use changes and the UHI will be useful for urban designers and planners in devising mitigation strategies to counter the problem of UHI. This will particularly be useful in updating the building and urban design guidelines currently applicable to the CMR. Such an exercise will help guide the city towards a more sustainable development path.

### Table I: “Hard” & “soft” land cover changes around weather stations in the CMR

<table>
<thead>
<tr>
<th>Category</th>
<th>CMB '56 '72 '94 '99</th>
<th>KTN '56 '72 '94 '99</th>
<th>RTM '56 '73 '81 '99</th>
</tr>
</thead>
<tbody>
<tr>
<td>HARD</td>
<td>7.1 14.4 22.2 25.0</td>
<td>9.5 38.6 59.9 60.2</td>
<td>7.4 22.0 32.7 50.8</td>
</tr>
<tr>
<td>SOFT</td>
<td>92.8 85.6 77.8 75.0</td>
<td>95.5 63.4 40.1 39.8</td>
<td>92.6 78.6 67.3 49.2</td>
</tr>
</tbody>
</table>
4. RESULTS & DISCUSSIONS

Table 1 shows the “hard” and “soft” land cover changes around the three weather stations during the last 44 years.

The 30-year air temperature trend (1969 – 1999) in the CMR is presented in Figure 2. Figure 2(a) indicates the daytime trends while the night-time trends are given in Figure 2(b). An SLR fitted to the most statistically significant trend is also shown.

A similar pattern is seen in the RSI trends. Figure 4(a) presents the daytime RSI trends while the night-time trends are shown in Figure 4(b). Figure 4(a) indicates that a daytime climate that was barely
tolerable (hovering at the upper limit of comfort) has now passed the threshold of thermal comfort. This transition seems to have occurred in the late 70’s when the CMR began its accelerated urban growth phase.

The night-time situation offers greater cause for concern (Figure 5(b)). It appears that the nights were reasonably comfortable until very recently (It is now accident that early European settlers considered the nights as winter in tropics [12]. The situation has deteriorated in recent years (mainly in the 1990’s) in the city center and the suburbs, while rural areas continue to exhibit cool conditions at night.

**Figure 4:** RSI trends in the CMR

### 4.1 Moisture Island?

A peculiar phenomenon noted by the study is the increase in wet bulb temperature in the CMR, particularly in the suburbs (Figure 5). The rate of change in the wet bulb temperature is slightly higher during the night (slope of SLR equation = 0.095 deg. C/yr) than during the day (0.073 deg. C/yr) although daytime trend is more significant than the night-time ($R^2$ 0.68 and 0.51 respectively). Such an anomaly was also reported in Pune, India [11].

Causes for the increase in wet bulb temperature are not known. However, some tentative explanations are possible. Deosthali [11] suggested anthropogenic moisture sources (burning of fossil fuel, industrial processes that use water for cooling purposes, etc.). Oke [15] alluded to reduced dewfall, reduced evaporation combined with anthropogenic vapour and stagnant air leading to humid atmosphere in the urban canyon layer. We postulate possibly two reasons for the moisture anomaly in the CMR. On the one hand, the increase in temperature may have caused more moisture to be added to the city environment. It is interesting to note that no significant trends in annual rainfall can be seen in the CMR. In other words, same amount of moisture is available in the city, but more heat facilitates increased evaporation. On the other hand, an increase in water use associated with urbanization may have made more water available in the urban system (typical rural water consumption in Sri Lanka is approximately 50 – 75 litres/person/day; average consumption in the CMR = 185 litres/person/day).

**Figure 5:** 30-yr. moisture trends in the CMR

### 4.2 Land cover Changes

The land cover changes during the last 45 years in the CMR indicate a peculiar development. There appears to be more “soft” land cover around the city weather station than in the rural or the suburban locations. This is not common among world cities where city weather stations are usually surrounded by more hard surfaces than the suburban stations.

The relative changes in the land cover composition among the three weather stations deserve special attention. The hard cover at Colombo increased by three and a half times during the last 44 years. The rate of change in the rural fringe station (Katunayake) is about 600% while that of the...
suburban location (Ratmalana) is nearly 700% during the last 44 years. While the rate of change in hard surface cover at the rural station seems high at first glance, it may be recalled that the station is housed at an international airport where significant changes to the length and number of runways have recently been made. As such, the actual building cover among the “hard” cover at this station is very low. This is borne by Table 2.

Table 2: Land cover changes (m²) at Katunayake

<table>
<thead>
<tr>
<th>Year</th>
<th>Bldgs.</th>
<th>Trees</th>
<th>Green Cover</th>
<th>Roads</th>
<th>Paved</th>
<th>Bare Land</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>6,400</td>
<td>132,940</td>
<td>126,400</td>
<td>67,900</td>
<td>452,074</td>
<td></td>
</tr>
<tr>
<td>1972</td>
<td>20,000</td>
<td>130,126</td>
<td>105,750</td>
<td>267,500</td>
<td>262,338</td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>34,600</td>
<td>129,600</td>
<td>134,700</td>
<td>436,000</td>
<td>50,814</td>
<td></td>
</tr>
<tr>
<td>1999</td>
<td>35,850</td>
<td>134,250</td>
<td>152,580</td>
<td>437,450</td>
<td>25,584</td>
<td></td>
</tr>
</tbody>
</table>

Building cover accounted for only about 4.6% of the land area in the immediate vicinity of the weather station at Katunayake in 1999 while paved areas accounted for nearly 56% of the land cover. Among the “hard” land cover class (buildings + roads/paved areas) in Katunayake in 1999, more than 92% was paved areas.

![Image](image1.png)

Figure 6: Land-cover vs. THI changes in the CMR

Research on UHI suggests that the primary cause for urban climate changes is the building:street geometry which traps the solar heat at day and is slow to release it at night (the so-called “canyon geometry effect” [16]. It is suspected that this effect will be minimal in Katunayake, since most “hard” surfaces in this location are open, devoid of any three-dimensional volume. Hence, a higher percentage of “hard” cover at Katunayake in recent times is somewhat misleading in that, the landscape continues to be “rural” in scope, except for the large paved runway at this site.

That the Katunayake station continues to be in a rural-like setting is borne by the fact that the temperature and THI patterns at this station show the least significant trends. The R² values for the 30-year trends in daytime air temperature and THI is 0.008 and 0.122 respectively. At nights too, Katunayake experienced the least significant THI trend in the last 30 years although the air temperature trend is somewhat more significant than that of Colombo. The R² values for air temperature and THI trends in the last 30 years are given in Table 3.

Table 3: Statistical significance of 30-yr. air temperature & thermal comfort trends in the CMR

<table>
<thead>
<tr>
<th></th>
<th>CMB-AT</th>
<th>KTN-AT</th>
<th>RTM-AT</th>
<th>CMB-THI</th>
<th>KTN-THI</th>
<th>RTM-THI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>0.307</td>
<td>0.288</td>
<td>0.380</td>
<td>0.307</td>
<td>0.288</td>
<td>0.435</td>
</tr>
<tr>
<td>Night</td>
<td>0.380</td>
<td>0.473</td>
<td>0.435</td>
<td>0.380</td>
<td>0.473</td>
<td>0.581</td>
</tr>
</tbody>
</table>

Note: AT = Air Temperature; THI = Temperature-Humidity Index

![Image](image2.png)

Figure 6 presents the land cover / climate change relationship at the three stations. Table 4 shows Pearson’s pair-wise correlation between hard land cover and daytime/night-time comfort conditions at the three stations.

Table 4: Pearson’s correlation matrix – Hard land cover and 30-yr. thermal comfort in the CMR

<table>
<thead>
<tr>
<th></th>
<th>CMB</th>
<th>KTN</th>
<th>RTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>THI – DAYTIME</td>
<td>0.857</td>
<td>0.671</td>
<td>0.998</td>
</tr>
<tr>
<td>THI – NIGHT-TIME</td>
<td>0.956</td>
<td>0.902</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Table 4 bears further evidence to the fact that Katunayake continues to be “rural” in terms of its bioclimatic effect (the weakest correlation between land cover and bio-climate was seen at this station).

The very high degree of correlation between land cover and bio-climate at the suburban station leads one to postulate that a careful control of land cover changes in and around the suburban station would have the greatest effect on bio-climate. While this is unusual from the viewpoint of standard urban climate studies from other regions, it points to a significant urban design/policy initiative that could arrest the negative impact of urbanization on human comfort in the tropics. Unlike in the temperate region, urban design/policy initiatives to control the UHI in tropical cities may have to concentrate their efforts on the suburbs where such efforts are likely to yield more success. This is due to the fact that tropical UHIs are more like a collection of heat islands separated by “cool islands” in-between than a monolithic UHI.

In light of the high degree of correlation between land cover and bio-climate in the CMR, tropical UHI researchers may want to consider the relative importance of the causes for the phenomenon. Although urban morphology is considered to be the most important urban variable controlling the magnitude of UHI [16], it appears that the surface
properties of urban areas play a significant role in tropical UHIs. Since surface properties are more easily amenable to urban policy directives, climate-sensitive tropical planners and architects may wish to concentrate their efforts on regulating land cover to achieve greater improvements to urban bio-climate.

It is clear that the rate of hard cover changes at Colombo and Katunayake is slow and so are the AT and THI trends at these stations. It is also clear that a higher rate of hard cover change had occurred in Ratmalana and the climate change at this station is also the most significant.

It therefore appears that the following may be true for the CMR:

i. There is a statistically significant climatic change in the CMR;
ii. The rate of change varies between the three weather stations in the region;
iii. The rate of change is the highest at the suburban station (Ratmalana);
iv. This is especially the case with respect to bioclimatic (THI & RSI) changes;
v. It is also the case that the suburban station had experienced the fastest increase in “hard” land cover.

At the very minimum, the improvement of urban bio-climate in tropical cities might include the following:

i. Design strategies that improve thermal properties of urban surfaces (more “soft” cover than “hard”);
ii. More concentrated efforts in the suburbs than in the city center;
iii. Strategies that discourage stagnation of water (both storm water and wastewater) in the city system.

CONCLUSION

The present study analyzed the trends in land use changes in the CMR during the last 45 years and attempted to correlate the changes to climatic and bio-climatic changes in the region. It was found that strong and statistically significant trends exist in both cases. The changes in bio-climate appear to be the strongest at the station where “hard” land cover increase is also the most significant.

Based on this result, it is now possible to develop urban design and planning guidelines that encourage soft land cover and specify appropriate thermal properties for the hard cover.

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