Projected urban development, changing 'Local Climate Zones' and relative warming effects in Colombo, Sri Lanka

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Abstract

Colombo is rapidly developing. This factor is further highlighted by the projected urban growth outlined by the Sri Lanka Urban Development Authority, "Zoning Plan 2020 for the City of Colombo".

The background climate of Colombo is found to be affected by the 'Urban Heat Island' (UHI) phenomenon. Together with the projected urbanisation, ensuing changes to land use patterns and building morphology, local climate changes are deemed to make the already barely-tolerable thermal conditions within the city more intolerable.

This study quantifies and compares the local warming effects of the projected development of the city in relation to the existing conditions. It employs a land-use / local climate classification system defined as Local Climate Zones (LCZ).

Likely local warming effects of the current and the projected urban fabric, classified according to LCZs are simulated using the Surface Heat Island Model.

The data is presented as a detailed comparison of the two stages, highlighting the LCZ changes that will most affect the Urban Heat Island intensity of the city.

Results and analysis reveal that almost all LCZs that transform to a higher density typology elevate the UHI intensity significantly. The typologies most affected are LCZ7 – Lightweight low-rise and LCZ8 – Large low-rise areas of the current urban fabric.

Keywords: Urban Heat Island, Warm Humid Tropics, Climate Change, Local Climate Zone, Colombo, Sri Lanka

Introduction

The climate of Sri Lanka has already changed. According to observed and potential impact scenarios for Sri Lanka, developed by Basnayake et. al. of the Department of Meteorology, under an A_2 climate change scenario, Sri Lanka's Mean Temperature would rise as much as 2.4^0C by the year 2100 (Samarasinghe, 2009).

Scientists attribute this warming trend seen throughout the country to both the enhanced greenhouse (global) effect as well as the 'local heat island effect' caused by rapid urbanization (Eriyagama et al. 2010). The city of Colombo is no exception to this observed warming trend. The question that arises is that with the definite push towards the rapid development of Colombo, how the changed urban fabric will impact a city already affected by the UHI phenomenon.

Background

The main focus of the research is Colombo, located at 6°54'N, 79°52'E on Sri Lanka's West coast, is a typical warm, humid city affected by Urban Heat Island (Emmanuel and Johansson, 2006). Colombo is a lowland region with a typically hot humid climate that is affected by the seasonal wind reversal of the Asiatic monsoon. The monsoon blows from the SW from late May to late September and the NE from late November to mid February. Air temperature and humidity are high throughout the year. Wind speeds are low, especially during the Inter-monsoon periods of March to April and October to November. The annual rainfall is 2300 mm, with 2 seasonal peaks. Solar radiation is intense under clear sky conditions. However, there is a high probability of cloud development, especially during the afternoon. The mean daily sunshine duration varies between 5 h in June and 9 h in February. [Based on data from Colombo city station, 1970–2004 (Department of Meteorology, Sri Lanka) as cited in Emmanuel and Johansson, 2006]

Zoning Plan 2020 for the City of Colombo

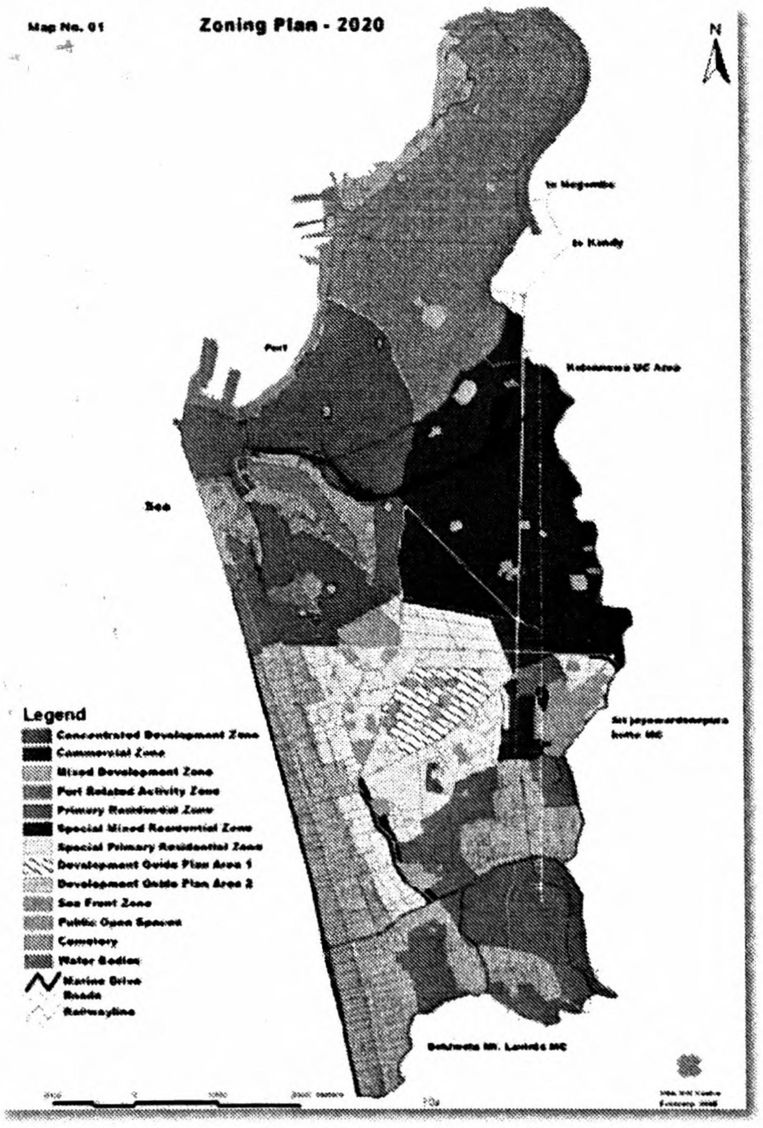

Fig. 1: Permitted development in the city of Colombo,2020. (Source: UDA, 2008)

The plan for 2020 superseded the plan for 2010 with the adoption of the City of Colombo Development Plan (Amendment) of 2008. (Fig. 1) The main difference is seen in terms of the definition of the urban fabric morphology for the city. It changes from that of a 'maximum permissible height' based strategy to a 'Floor Area Ratio (FAR)' based strategy. The plan also saw a redefinition of the land use zoning together with the permissible uses within the zones. It is deemed the newer zoning allows for greater flexibility, therefore brings a certain heterogeneity to the built fabric, although the main objective seems to be to free land for development, especially in the port related activity zone.

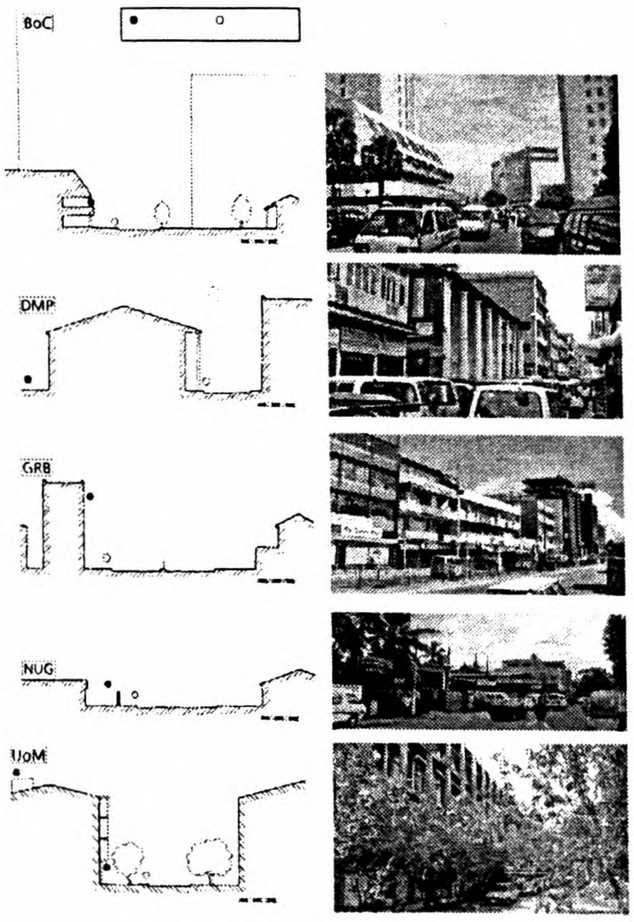

Fig 2: Positioning of measurement equipment within urban canyons. (Source: Emmanuel et al. 2006)

UHI and UHI studies in Colombo

A heat island is best visualised as a dome of stagnant warm air, over the heavily built-up areas of the city. These have been observed practically all over the world except in extreme cold climates. The effect is not so much felt during the day, as the increase in the maximum temperature is minimal. However, heat islands are intense at night, occurring a few hours after sunset. This has far-reaching implications for urban design in the equatorial tropics where night-time thermal stress is usually high. (Emmanuel, 1993)

Colombo's Urban Heat Island is well documented, especially by Rohinton Emmanuel, where his body of work includes a seminal paper in 2006, where the study examined the influence of urban morphology and sea breeze on the microclimate of Colombo. The microclimate was measured at 5 urban sites in Colombo, Sri Lanka and at a nearby rural site. (Fig. 2) The temperature differences between the urban sites reached 7 K on clear days in spite of the relatively wet period of measurement. Urban morphology had a significant impact on daytime air temperatures; the maximum daily temperature decreased with increasing H/W ratio. There was also evidence of a sea breeze effect; sites open to the sea were significantly cooler than other urban sites. In contrast to the daytime variations, only small intra-urban temperature differences were found at night. It is likely that both the intra-urban and urban–rural differences will be bigger during drier seasons. (Emmanuel and Johansson, 2006)

While the 2006 study examined existing sites of differing morphology, Emmanuel and Fernando, 2007, used a micro-scale urban simulation program, to examine the sensitivity of air temperature and mean radiant temperature (MRT) of built-up urban cores to urban-area geometry (the density of buildings), thermal properties of human-made surfaces (albedo) and green cover (street trees), in 2 warm-climate cities: Pettah, Colombo (Sri Lanka) and downtown Phoenix, Arizona (USA). Air temperature and MRT are indicative of human thermal comfort, and their rural/urban gradients signify the urban heat island (UHI) effect. It was found that, although high albedo values lead to low daytime temperatures in both cities, the best thermal comfort, quantified by both the air temperature and MRT, was found in high-density development. Thus, density enhancement is a viable UHI mitigation option in built-up areas of warm climate cities. (Emmanuel and Fernando, 2007)

The studies, highlighted above, demonstrate the importance of the morphology of the urban fabric in ameliorating the UHI effect as well as improving outdoor thermal comfort in warm, humid cities.

'Local Climate Zones' for Urban Temperature Studies

The new "local climate zone" (LCZ) classification system provides a research framework for urban heat island studies and standardizes the worldwide exchange of urban temperature observations (Stewart, 2012). It was developed to help fill a crucial void in UHI methodology; the lack of an accepted protocol to gather and report heat island observations in the canopy layer.
"Such a protocol should build on existing guidelines, conventions, and frameworks in urban climatology. The LCZ system does that, and provides a simple division of urban and rural landscapes into morphological classes, from which a standardized definition of heat island magnitude is derived. This approach moves the field closer to a cohesive and workable set of 'rules' to assess UHI magnitude in the canopy layer and to allow objective comparisons of UHI magnitudes in different cities" (Stewart, 2012).

Method

The primary approach to the study is to compare the existing UHI intensity of the city with that of the projected. The projected urban fabric of the city is based on the Sri Lanka Urban Development Authority, Zoning Plan 2020 for the City of Colombo.
The process of ascertaining the UHI intensity first adopts the LCZ system to simplify and categorise the existing and the projected urban fabric. The categorised LCZs are then simulated using the Surface Heat Island Model (SHIM) to determine the UHI intensity and subsequently compared to ascertain the impact of the changes.
Given the representative nature of the LCZ classification system, the results are likely to be applicable to all warm, humid cities on similar growth trajectories (Emmanuel et. al, 2011).

Classifying "Local Climate Zones"

The land-use/local climate classification system defined as the Local Climate Zone (LCZ) developed by Iain Stewart uses observational data to differentiate climate zones.

LCZs are defined as 'regions of uniform surface-air temperature distribution at horizontal scales of 10^2 to 10^4 metres' (Stewart and Oke, 2009). Their definition is based on characteristic geometry and land cover that generates a unique near-surface climate under calm, clear skies. The factors considered include vegetative fraction, building / tree height and spacing, soil moisture and anthropogenic heat flux.

The comprehensive nature of the classification system with its thorough coverage of all likely urban land use/land cover classes means that a given LCZ class is comparable across many different cities.

LCZ has 17 climate zones as shown in Fig. 3. The zones defined as building and land cover types are combined to create sub categories. These have been validated in Sweden, Japan and Canada (Stewart, 2011)

The sequential process adopted is based on the guidelines for classifying heat island field sites into local climate zones developed by Iain Stewart (2011)

Step 1 – Define the area of influence

In Ian Stewart's outline for field site selection is based on measurement conditions influencing the station set up in an urban context to be studied. These encompass; height above ground, building morphology, tree density, boundary layer stability, period of observation and wind direction.

The approach here is to understand the city in terms of morphology and its influence. Therefore, the 'area of influence' selection, adopts urban blocks as the primary defining element for the study. The selection of an urban block as a particular defined element allows effective simulation in envisioned future research. The urban block offers a definite boundary, be it street, a green area or water body. Factors encompassing plot coverage, built area fraction, green area ratio are better defined in a situation where the building plot boundaries and area are well established.

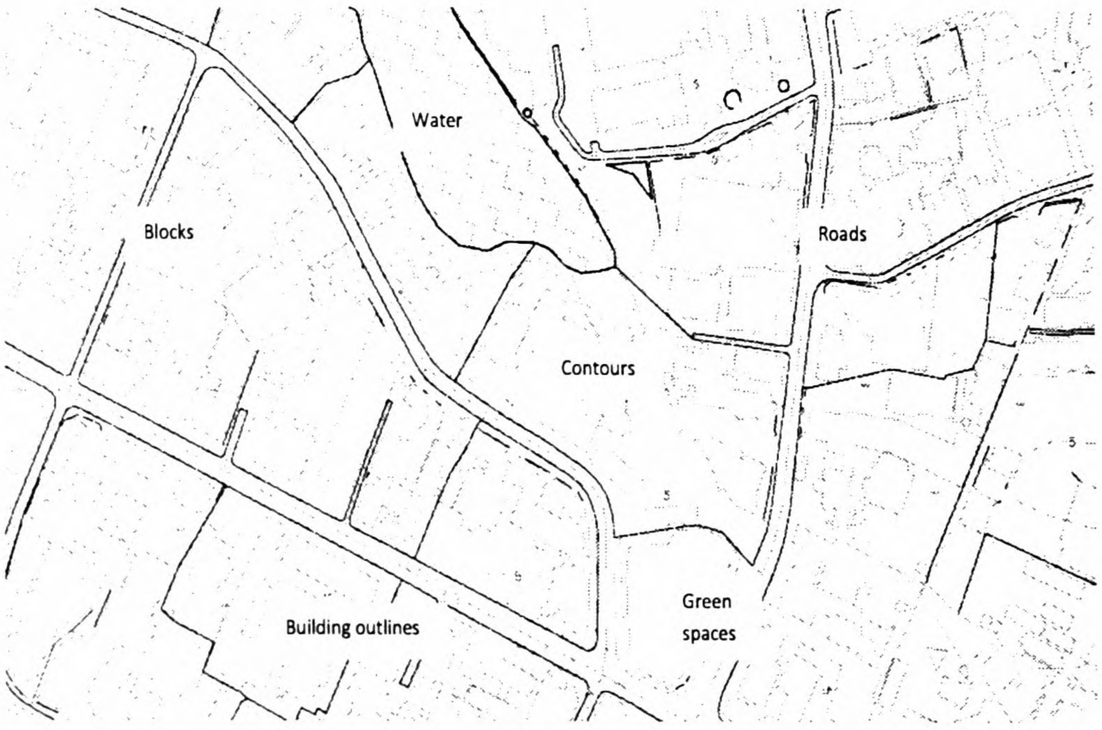

Fig 4: Detailed Map of a selected area. (Source; Author)

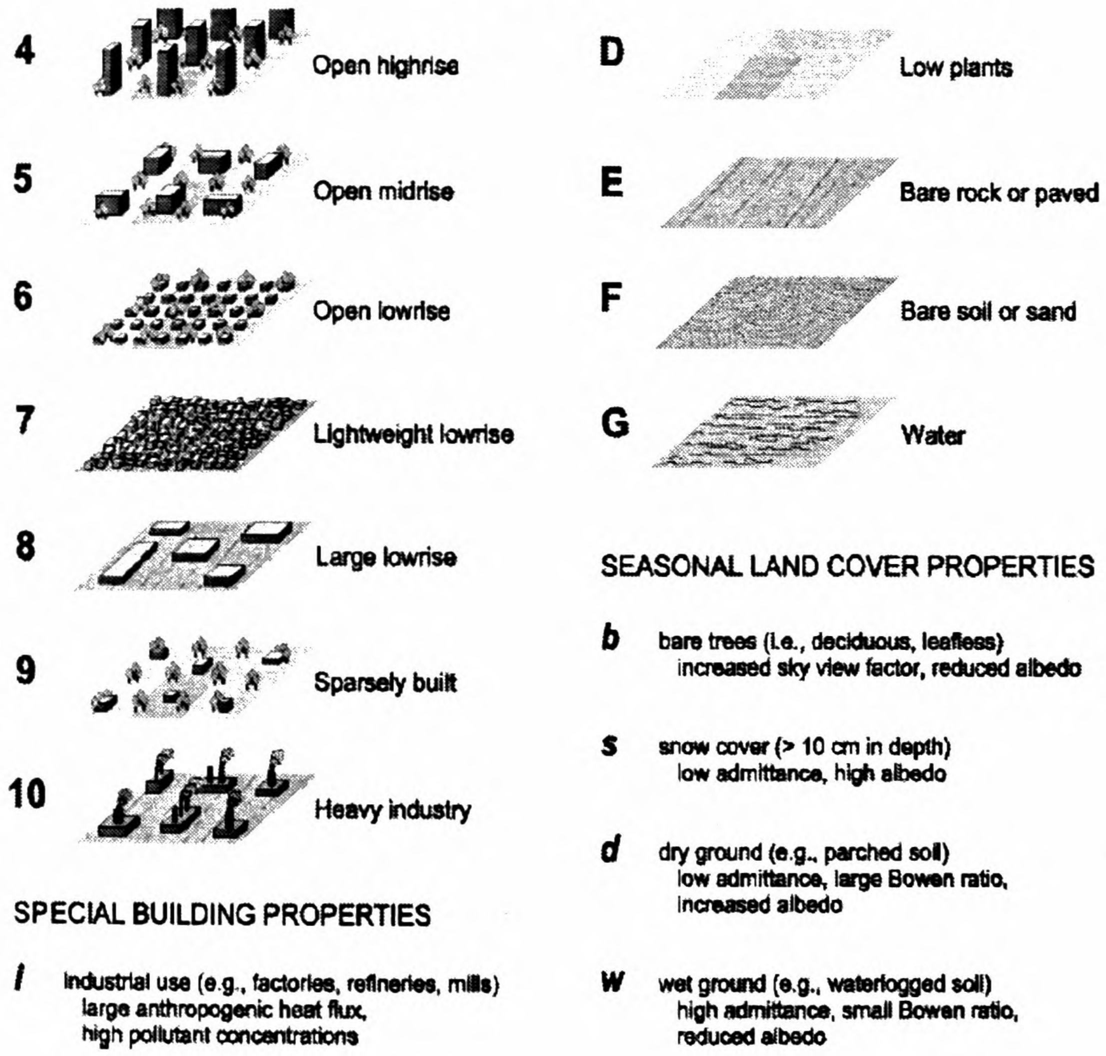

Fig 3: Local Climate Zone Types (Stewart, 2011)

The research primarily uses a detailed map of Colombo (in AutoCAD format generated from Geographic information system (GIS) data for Colombo, 2010) to establish the urban blocks for LCZ definition. The map includes urban blocks and building outlines, roads, water bodies and land Contours (Fig. 4).

The verification and modification of the block boundaries was done using on-field surveys, Google Earth Imagery and to a lesser extent Satellite data.

Step 2 – Collect site metadata

Metadata refers to the state of the urban context around a particular measurement site. The recording of the surrounding of a measurement site ensures the consideration of the effect of the existing built fabric in relation to future changes on a particular site, measured at a future date. The protocol to be adopted is defined by Oke (2004) and Aguilar *et. al.* (2003).
In this situation, the objective is to establish and simplify the nature of the urban fabric itself. The data collected adhered to the 'Zone Properties' defined in the 'Local Climate Zone' Data sheets developed by Iain Stewart (2011).

Outlined below are the methods adopted to observe each property.

Property		**Method adopted**
Sky View Factor	-	Fish-eye Lens Photographs
Aspect ratio	-	Detailed maps, Field surveys, Google earth, Satellite imagery
Mean Building / Tree Height	-	Detailed maps, Field surveys, Google earth, Satellite imagery
Terrain Roughness class	-	As per LCZ data sheets
Building Surface fraction	-	Detailed maps, Google earth, Satellite imagery
Impervious Surface fraction	-	Detailed maps, Google earth, Field surveys
Pervious surface fraction	-	Detailed maps, Google earth, Field surveys
Surface admittance	-	Estimated from published values / LCZ data sheet as guide
Albedo	-	LCZ data sheets based on field survey observations
Anthropogenic heat flux	-	As per LCZ data sheets

Step 3 – Select LCZ

The relevant Local Climate Zone for each block is selected by correlating the observed data with that of the selection guideline developed by Iain Stewart (2011).
The guidelines are broadly categorised according to;

1) Zone definition - Physical characteristics that all zones in this class possess
2) Zone illustration – Typical views of the built fabric portrayed using sketches and images
3) Zone properties – Parameters that are deemed to drive the Urban Heat Island phenomenon.

Classifying "Local warming effects" of the urban fabric

Likely local warming effects of the existing and the projected urban fabric classified according to LCZs are simulated using the Surface Heat Island Model (SHIM) developed by Johnson

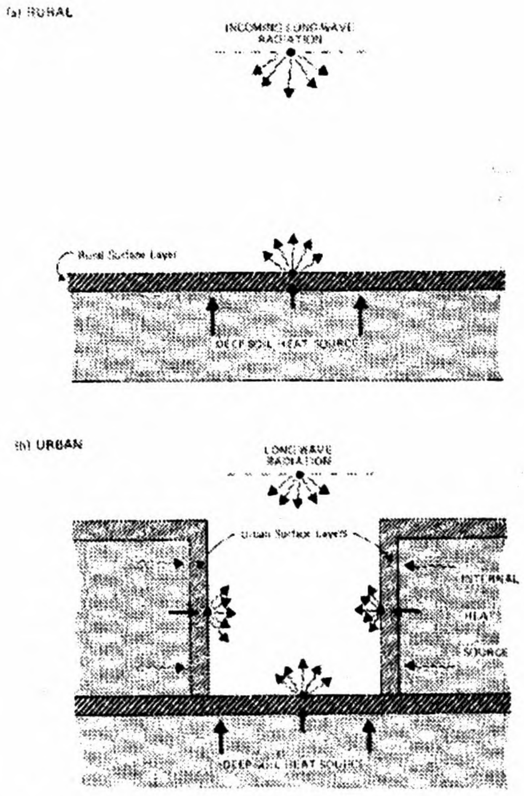

Fig. 5 – Rural / Urban surfaces
(Source – Johnson et al. 1991)

et. al. (1991). The SHIM is a simple force-restore model that simulates the nocturnal cooling of an urban canyon (walls and street) under 'ideal' conditions of calm winds and clear skies. SHIM is initiate at the time of sunset and requires several inputs to run the model. These include initial surface temperatures, emissivities, thermal admittance, and deep temperatures for each canyon facet, incident longwave radiation (L↓) at the top of the canyon and the canyon height to width ratio (H/W). The model is set up to calculate surface cooling for each of the canyon facets and also calculates the surface radiation budget (L*) for each of the facets (Szpirglas et al, 2003) (Fig. 5)

As seen in Fig 5, the model is based on a two-layer approximation of soil temperature changes (a small top surface soil layer that responds to near-periodic daily forcing and a deep soil layer underneath that does not respond to periodic forcing). The surface forcing is due to radiative changes during the day as well as the restoration by the deep soil layer from below. This forcing is 'idealised' thus, no possibility exists to account for variable cloud cover or frontal conditions.

Furthermore turbulence and advection are not incorporated so that all cooling is assumed to take place via radiative heat loss. No account of evaporative heat transfer is possible. However, the SHIM is an excellent tool to isolate the effects of urban geometries (density, height: width ratio and the sky view factor) as well as surface thermal properties. It thus enables us to explore the urban warming potential of rapid changes in urban growth epitomised by densely arranged buildings with excessive thermal capacities. (Emmanuel et. al, 2011)

The governing force-restore equation used by SHIM for the nocturnal cooling of a homogeneous substrate with layer thickness D is given as:

$$\frac{dT\,(D_i,t)}{dt} = \frac{\sqrt{2\Omega}}{\mu_i} L^{*}{}_i - \Omega(T_i(D_i,t) - T_D)$$

Where T(D*i*,t) is the temperature of a layer *i* at time t, TD represents a "deep temperature" that is constant, μ is the thermal admittance of the soil, Ω is the angular frequency of the heating wave and L* is the net long-wave radiation

Table 1: UHI Intensity of LCZs

LOCAL CLIMATE ZONE		Urban / Rural Temperature Difference
Zone #	**Zone Title**	
1	compact highrise	4.40
2	compact midrise	3.96
3	compact low-rise	3.19
4	open highrise	4.35
5	open midrise	3.71
6	open low-rise	1.87
7	lightweight low-rise	0.31
8	large low-rise	1.10
9	sparsely built	-
10	heavy industry	-
A	dense trees	-0.12
B	scattered trees	-0.09
C	bush, scrub	-
D	low plants	-0.64
E	bare rock or paved	1.04
F	bare soil or sand	-0.90
G	Water	0.62

SHIM requires initial values of the surface temperature (T), deep soil and/or building temperature (T_G or T_B), surface thermal admittance (μ), sky view-factor (ψ_S) and surface emissivity (ε) for all of the surfaces to be simulated in addition to the incoming long-wave radiation to the total system ($L_{\downarrow}$).

Values for each were determined by various means as outlined below together with the values defined by the individual LCZs. These measured values were also used as metadata for classification of LCZs.

T Measured directly or a measured near-surface air temperature was used as a surrogate, (using Technoterm 9400 Surface Temperature Probe)

T_g Estimated using the 3-day average air temperature as suggested by Deardorff (1978)

T_B Estimated from building interior set point temperature (assumed to be 27^{o}C)

μ Estimated from published values (e.g. Oke, 1987)

Ψ_s Calculated from fisheye lens photographs

ε Estimated from published values (especially Arnfield, 1982 and Oke, 1987)

$L_{\downarrow}$ Calculated using the empirical formulae of Idso and Jackson (1969) with measured humidity and air temperature.

Fig 6: Local Climate Zone Map, Colombo

The numerical model was run in a Microsoft Excel environment based on data measured on a stable day (January 04, 2011) in Colombo, Sri Lanka. The SHIM model simulation results are compared with the rate of cooling at a 'rural' station (using data from the synoptic weather station at the Colombo International Airport (Lat: 7° 10'N; Lon: 79° 52'E; Elevation: 8m asl; WMO Station ID: 434500) and an 'urban' weather station at the Colombo City Airport (Lat: 6° 49'N; Lon: 79° 52'E; Elevation: 5m asl; WMO Station ID: 434670).

RESULTS AND DISCUSSIONLCZ Map of Colombo

The survey of existing LCZ typologies relevant for Colombo showed that much like many cities in developing countries, Colombo is dominated by residential and mixed use zones. Although large areas of Colombo remain low rise, these urban blocks are seeing an infusion of mid rise and high rise blocks. (Fig. 6)Most of the zones classify as LCZ3 – Compact Lowrise (48.1%), LCZ2 – Compact Midrise (8.9%) and LCZ8-Large Lowrise (23.7%) categories. LCZ1 – Compact Highrise (0.3%) and LCZ4 – Open Highrise (1%) form a very small fraction of Colombo's built fabric. A significant percentage falls under the category LCZ7- Lightweight Lowrise (4.9%). LCZs of the Land cover types show minimum UHI characteristics compared to the rural site chosen.Significant urban warming can be seen at sites with highrise development. Areas with the largest intensity of urban growth, LCZ3 and LCZ2 show a range of 3.19-3.96°C difference in UHI intensity. (Table 1)Of the building type LCZs, the lowest intensity is seen from LCZ7 – Lightweight low-rise. It is deemed that these areas are greatly affected by the material properties modelled (Thermal admittance and Emissivity). The end result is such that both the heating and the cooling of the fabric happen in a rapid manner.

Projected LCZs and the UHI intensity difference above the existing LCZs

Table 2 shows the LCZ variation once the UDA plan for 2020 takes full effect. Here it was envisioned that all sites would be developed to maximum allowable levels. The table also shows the corresponding UHI intensity over that of the existing LCZ for a particular urban bloc

Table 2: Projected Temperature Difference above Existing LCZ (^{0}C)									
Existing LCZ		**Projected LCZ**							
Zone Number	**Zone Title**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	compact highrise								
2	compact midrise	0.44			0.39				
3	compact low-rise	1.21	0.77		1.16				
4	open highrise	0.05							
5	open midrise	0.69	0.25						
6	open low-rise	2.53	2.09	1.32	2.48	1.84			-0.77
7	lightweight low-rise	4.09	3.65	2.88	4.04	3.4	1.56		0.79
8	large low-rise	3.3	2.86	2.09	3.25	2.61	0.77		

Overall, the LCZ changes in almost all urban blocks have a negative impact on the UHI of Colombo.

The greatest intensity difference of 4.09°C is seen when LCZ7- lightweight low-rise is transformed in to LCZ1- compact highrise areas. This is happening at very high rate in Colombo, where underserved communities are now being housed in highrise developments. Although the strategy allows the release of land for development, the new developments themselves take the form of LCZ1.

A socially accepted strategy in the attempt to re-house the underserved settlements is to adopt high density walk-up housing. The table shows that a LCZ7 to LCZ3- Compact low-rise transformation will increase the UHI intensity by 2.88 °C; yet, this seems to be the least harmful change when compared to other applicable LCZs of 2, 4 and 5.

A similar strategy is seen to be applied in dealing with the significant quantum of warehouse areas within the city. The LCZ change is from LCZ8- Large low-rise to LCZ1 or LCZ4 – Open highrise, creating a UHI intensity change of 3.3 °C and 3.25 °C respectively.

In this context, transforming of more compact areas of the city, namely LCZs 2, 3 and also LCZ5 – Open midrise to either LCZ1 or LCZ2 seem to experience a lesser impact in terms of intensity. The LCZ change that would create a reduction in the UHI intensity is when LCZ6 – Open low-rise areas are transformed in to LCZ– Large low-rise. A reduction seen is 0.77 °C. This is currently seen in Colombo, where traditionally residential areas are being transformed into mainly educational institutions.

Many older parts of the city is now being re-purposed in terms of use only with little or no impact on the overall morphology and therefore the LCZ. This seems to be the best strategy as it is very evident from Table 2 that almost all transformations have a negative impact.

Conclusion

The main objective of the study was to ascertain the impact of the changed urban morphology with the adoption of the proposed UDA development Plan for 2020.

The use of the LCZ classification system allows for the effective simplification of the urban fabric at both stages of the development, therefore the comparison of intensities ascertained by SHIM are deemed more relevant. The main limitation to the method is that the simulation assumes ideal conditions of calm, clear skies and an urban fabric of relatively uniform materiality: It is shown that the City of Colombo, Sri Lanka, is a warm, humid city affected by Urban Heat Island, with intensities up to 4.40 °C over the 'rural' site selected.

Results and analysis reveal that almost all LCZ zone changes push the UHI intensity to a higher level than the existing. The typologies most affected are LCZ7 – lightweight low-rise and LCZ8 – Large low-rise.

In this context it can be concluded that the UDA development plan for 2020 has both positive and negative impacts. The positive impacts being that most of the already densely built areas have been earmarked for more intense development, therefore the intensity increase is minimal. Table 2 shows a range of 0.44-1.21°C for the transformed LCZ2 and LCZ3 areas. While the more open low-rise and midrise areas have been preserved as is. The negative impacts being the decision to develop the underserved areas (LCZ7) into highrise areas, creating the largest UHI intensity change of 4.09°C (LCZ1) and 4.04°C (LCZ4).

It is recommended that the development and therefore LCZs of these areas (LCZ7) be limited to open low-rise (LCZ6 – 1.56°C change) or large low-rise (LCZ8 – 0.79°C change) areas. Examples of these functions would be educational or similar institutional functions, and high-end housing areas; therefore mixed developments with plenty of green space in-between and reduced vehicular commuting.

It is deemed such an approach would replicate the model adopted currently, where freed underserved areas pay for the new development. Yet, in this situation the people are housed in the more dense parts of the city. This strategy, in a purely UHI mitigation perspective can be adopted, to at least, keep the current intensity levels static.

The challenge for future research is to see how to develop the City of Colombo to meet the demands of the future while adapting to, maintaining, mitigating the negative effects of such development.

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