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Linking the 'in' and 'out:' new comfort goals for the rapidly urbanising equatorial tropical megacities in a changing climate

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Abstract

Comfortable urban outdoors are increasingly becoming difficult in the rapidly urbanizing tropics. While global climate change partly explains this reality, haphazard urbanisation is the primary cause for street level discomfort in the equatorial tropics. The study of the problem, exemplified by the urban heat island effect, is relatively new in the region, leading to a paucity of urban design and planning exemplars to tackle the negative consequences. Based on fifteen years of research on the urban climate anomaly in the warm-humid areas of Sri Lanka, this paper presents key challenges to outdoor comfort in the equatorial tropics and posits a way forward to a new approach to equatorial urban thermal comfort. Data and equity dimensions are explored.

Keywords: Urban heat island, tropical cities, outdoor thermal comfort, equity

Introduction

Tropical climate, especially the equatorial tropics, offers conditions closer to the 'ideal' weather year-round. For example, the annual range in maximum temperature in the equatorial coastal city of Colombo, Sri Lanka (6.9^{o}N, 79.87^{o}E) is 30.0 – 32.0^{o}C while the range for minimum is 22.5 – 26.0^{o}C. This compares favourably with the standard prescribed for indoor thermal comfort (24±1^{o}C). Yet the achievement of thermal comfort by passive means is remarkably difficult in the tropics. The reasons have to do with high humidity, near absence of annual variations, weak macro-level winds and higher enthalpy. High humidities make evaporative heat loss – the principal means of thermoregulation at higher temperatures – exceedingly difficult. The twice-a-year passage of Sun directly overhead (and the associated presence of the Inter Tropical Convergent Zone – ITCZ) leads to weak macro-level conditions in the tropics even though the region is very dependent on wind movement for thermoregulation. The high year-round incidence of solar radiation nearly obliterates seasonal climatic variations, thus greatly amplifying the perceived discomfort due to minute changes in air temperature. High incident solar radiation and the associated high humidity also lead to high enthalpy – thus high energy need – to achieve thermal comfort.

Local and global climate changes make these difficulties increasingly problematic. Prominent among these is the inadvertent climatic consequences of haphazard urbanisation – characterised by the 'urban heat island' (UHI) effect (Oke, 1987). While the UHI effect is both a blessing and a burden in temperate climates, all aspects of urban changes to the equatorial tropical climate are negative.

Given these difficulties, the achievement of thermal comfort by passive means and at a level adequate to enhance local quality of life, is increasingly becoming difficult in the equatorial urban tropics. Combined with the fact that the wider tropical region is home to the largest urban transformation in contemporary human history and in the face of global and regional changes to climate, the creation of comfortable urban spaces become imperative, even if the mechanics of achieving it are exceedingly difficult.

This paper examines the emerging best practices in urban thermal comfort enhancement and hypothesises a way forward towards a new regime of equatorial tropical urban thermal comfort for a higher quality of life. The planning and design as well as data and equity implications are explored.

Background

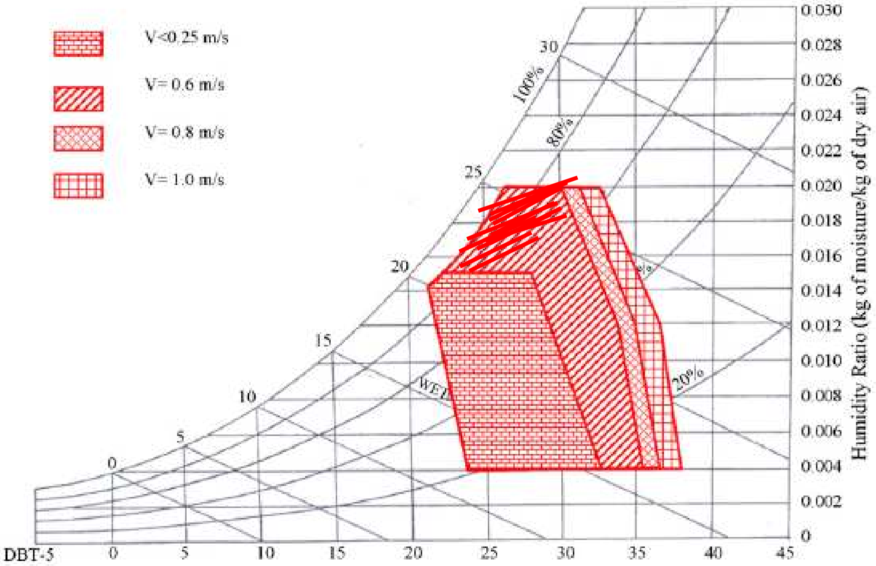

Figure 1: Bioclimatic recommendations for Anuradhapura, Sri Lanka (8^{o}20'N, 80^{o}25'E)

Source: Bioclimatic chart from Halwatura and Jayasinghe (2008) and each line indicates a month's climate, similar to a method used by Lam et al., (2006)

Tropical thermal comfort

A typical case of equatorial thermal comfort is illustrated by the situation in the Sri Lankan inland city of Anuradhapura (Figure 1 – each red line represents the weather for a month). The bioclimatic diagram indicates that even the seasonality of rainfall offers little thermal relief; barely tolerable conditions may be had only with excessive wind movement (> 0.6 m/s). The achievement of such wind movements by passive means (especially in the indoors) is nearly impossible. Since temperatures and relative humidities are high, dehumidification is also necessary. This will involve the use of energy: no passive dehumidification technology applicable at a 'whole-house' scale exists at present.

The 'urban heat island' effect in the topics

While the background climate thus presents a barely-tolerable condition, urbanisation and its attendant local climate changes are making the achievement of thermal comfort by passive means, increasingly difficult. The reasons have to do with the energetic basis of the inadvertent changes to urban climate, epitomized by the ‘urban heat island effect’ (cf. Oke, 1982; 1987; Arnfield, 1990) (see Figure 2 for illustration):

1. The geometry of cities – especially the three dimensional volume formed by buildings that abut streets (so called ‘canyon geometry’ effect) that efficiently traps solar radiation
2. Thermal properties of urban surfaces – higher storage and multiple reflections
3. Anthropogenic heat – Heat waste from combustion and metabolism;
4. Urban ‘greenhouse’ effect – Increased incoming long-wave radiation from polluted urban atmosphere;
5. Evapotranspiration loss – Reduction of green areas in cities lead to more sensible than latent heat transfer;
6. Wind shelter – Reduced ability of wind to carry heat (turbulent transfer) either as sensible or latent heat (cf. Todhunter, 1990: Oke, 1988*a* & 1988*b*; Oke, *et al.* 1991; Saitoh and Hoshi, 1993; Emmanuel, 2005)

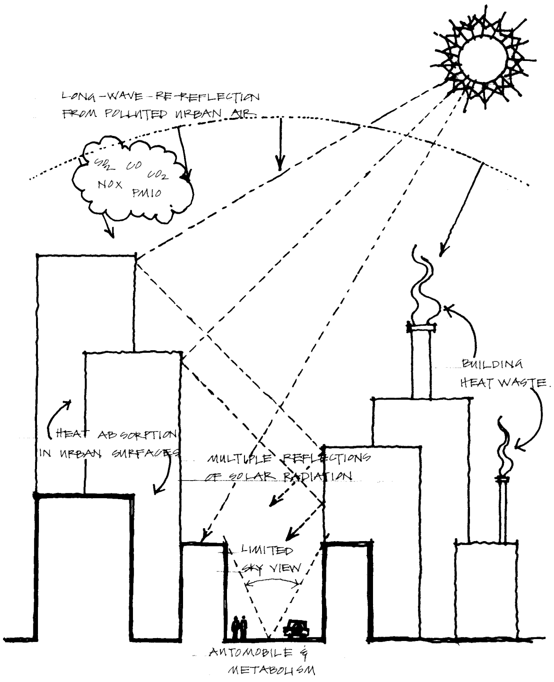

Figure 2: Energetic basis of urban microclimate changes

Source: (Emmanuel, 2005)

Although the urban climate of tropical cities is not extensively studied, the few that do exist suggest that the microclimatic changes due to urbanization in the region is substantial and the anatomy of tropical heat-islands bears a close resemblance to temperate ones (Oke, 1982).

A review of early (1966 – 2005) tropical UHI studies is provided by Emmanuel, 2005 (see especially Table 2.3, p. 30 in Emmanuel, 2005). The earliest tropical urban micro-climatic study we could find was by Nieuwolt (1966) in Singapore. Taking air temperature and relative humidity measurements at various points in the city and suburban areas, and comparing them with the readings from the Singapore Airport (representing a “rural” setting), Nieuwolt found that the city was appreciably warmer (3 - 3.5 deg.C) and drier (relative humidity up to 20% lower) than the airport. This study is representative of the findings by many UHI studies from the region (see, for example, Giridharan et al., 2004; Emmanuel and

Johansson, 2006; Johansson and Emmanuel, 2006; Emmanuel and Fernando, 2007; Giridharan et al., 2008).

Amelioration of urban climate changes in the equatorial tropics – current best practices in urban planning and design

The UHI mitigation strategies can be grouped into three major themes (cf. Emmanuel, 2005):

1. Increase vegetation cover
2. Increase thermal reflectivity (albedo) of urban surfaces, particularly roofs
3. Manipulate urban geometry.

Increase vegetation cover

Simulation studies suggest increase in urban vegetation will lead to 15 to 35% reductions in building cooling energy costs in the U.S. (Akbari et al., 1992). Other studies on climate enhancement/building energy reduction associated with urban vegetation cover have indicated widely varying benefits. These include: up to 27^{o}F (15^{o}C) reduction in surface temperature during hot, summer days in Miami, Florida (Parker, 1983); up to 25% reduction in building cooling energy needs in the eastern United States (Heisler, 1986); 30% reduction in daily cooling energy need and 27-42% reduction of peak power demand in Sacramento (Akbari, et al., 1997b); 10^{o}F (5.5^{o}C) air temperature reduction within 2 mile radii of Mexico City urban parks (Jauregui, 1973) and 3-5% reduction in regional summertime cooling load for U.S. cities located between 25-45^{o}N latitude with low-to-moderate humidities (Sailor, 1998). The climatic effect of urban vegetation occurs on top of other non-climatic benefits.

The direct effect of vegetative cover upon urban comfort is not so much due to the reduction in air temperature as radiation reduction (Robinette, 1973; Barradas et al, 1999). Trees affect urban microclimates on two levels: human comfort and building energy budget (Parker, 1983; Miller, 1988). Not only what vegetation does is important, but also what it prevents – i.e. heating up of urban canyons (Oke, 1989). While the direct temperature reduction due to the presence of a large urban park is only about 1-2 deg.C, the prevention of heat build-up (Oke, 1989) and partitioning of more heat into latent rather than sensible means (cf. Barradas, et al., 1999) will be of greater value to urban dwellers.

However, the ability of urban trees to improve the thermal comfort conditions in the surroundings is a function of the seasons, background climate, size of green area, type of surface over which trees are planted and the amount of leaf cover. In the sub-tropical Mexico City, Barradas, et al., (1999) found that during the dry season trees dissipate nearly 70% of the net radiation via sensible heating and only 25% through latent means. In the wet season however, the numbers are reversed. Thus, water availability is a crucial factor in the increase of latent heat transfer by vegetation. Similarly, cooling effects of urban trees are more pronounced in an area with warmer background climate (Shashua-Bar and Hoffman, 2000). Furthermore, the bigger the urban green pocket, more pronounced will be the thermal comfort improvement (Gomez, et al., 2001). Additionally, trees planted over vegetated areas are able to transpire better than those over asphalt areas (Kjelgren and Montague, 1998). When urban trees completely cover the sky dome, air temperature reductions up to 3.3^{o}C can be expected (Shashua-Bar and Hoffman, 2002).

Another variant of urban green enhancement approach is the greening of rooftops (the so-called “green roof” approach). The city of Tokyo is a leading champion of this approach to mitigate the negative effect of the UHI. In the context of a rapid increase in the Tokyo UHI and increasing mortality associated with heat stroke (cf. Nakai, et al., 1999), the Tokyo city authorities have imposed building regulations that mandate at least 20% green cover on all newly built structures (cf. Tanikawa, 2002).

In an experimental study using analogous models, Takakura et al., (2000) found that a concrete roof with ivy cover resulted in a room temperature of 24-25^{o}C while a bare concrete roof resulted in a room temperature of nearly 40^{o}C. However, the nighttime cooling experienced by the bare concrete roof was slightly better than the ivy-covered roof.

Niachou et al., (2001) measured the indoor air temperatures and thermal performance of a roof with and without green cover in a real building in Athens, Greece, during the summer, and then estimated the cooling energy saving due to green roof. It is reported that green roofs reduced cooling load by up to 48% in non-insulated buildings with night ventilation. However, the cooling load reduction due to green roof in a well-insulated building was negligible (less than 2% reduction).

In addition to reducing indoor temperatures and building-level cooling energy use, green roofs also improve the surrounding air temperature on account of a large amount of heat partitioning into latent means (Ishihara and Chou, 1992; Papadakis, et al., 2001). However, the life-cycle cost of a green roof system needs to be taken into account when measuring the total benefits (cf. Wong, et al., 2002). This is particularly so with respect to the lifecycle costs of well-insulated buildings.

Increase thermal reflectivity

Proponents of increased urban thermal reflectivity (albedo) encourage light-coloured building surfaces, particularly the roofs. Garbesi et al., (1989), Akbari et al., (1992) and Fishman et al., (1994) suggest that increasing urban albedo by up to 15% will reduce air temperatures at the neighbourhood level by as much as 5^{o}F (2.8^{o}C).

Parker & Barkaszi (1997) white-painted roofs of several actual residential buildings in Southern Florida during mid-summer and compared the cooling energy consumption using a before and after protocol. White roofs reduced the average cooling energy consumption by 22% (and peak power consumption by 19%). Using a similar methodology, Akbari et al., (1997a) reported cooling load reduction up to 80% for a small house and 35% reduction for a large bungalow in Sacramento, California.

Using scale models, Simpson and McPherson (1997) reported slightly better energy consumption performance under a white roof than silver-coloured roof, indicating the importance of emissivity in addition to albedo.

Manipulate urban geometry

The primary design strategy to manipulate urban geometry is to enhance the shading potential of the urban mass. It may be noted that sun control of individual buildings in the tropics where the sun is closer to the azimuth, is relatively easy. It is therefore necessary to enhance the comfort potentials of the urban outdoors in the tropics where considerable living occurs. Such an action needs to be taken at the neighbourhood scale that utilizes its urban geometry (massing) to reduce the heat island effect, by shading itself.

An urban approach to shade enhancement was first proposed by Emmanuel (1993). The concept, called “shadow umbrella” utilizes the urban massing to shade the areas between buildings. Emmanuel (2005) details the procedure and presents design strategies derived from this concept.

A variant of the geometry manipulation approach was suggested by Swaid (1992). In this proposal, an adjustable vertical shading device is attached to the top of a canyon wall. This in turn increases the street canyon depth at daytime (i.e. leads to more shading). The device can be retracted at night, thus the night-time SVF remains unchanged.

Exemplar efforts in the equatorial urban tropics

This section presents a case study of an effort to enhance thermal comfort at a neighbourhood scale, in a large housing estate in the central lowlands of Sri Lanka (Anuradhapura, 8^{o}20’N, 80^{o}25’E). The project involved the development of a 1500-unit housing estate and associated infrastructure. The author was involved as the sustainability consultant to the architects for this scheme. The discussion below quantifies the thermal comfort consequences of design choices at both the settlement- and building-levels. Bioclimatic conditions of the background climate is shown in Figure 1.

Figure 3 shows the proposed street layout option proposed by the Architects for the housing scheme. Street canyon is oriented northeast-southwest while houses are coupled but staggered (i.e. front and backyard width vary alternatively). Property lines too, are staggered.

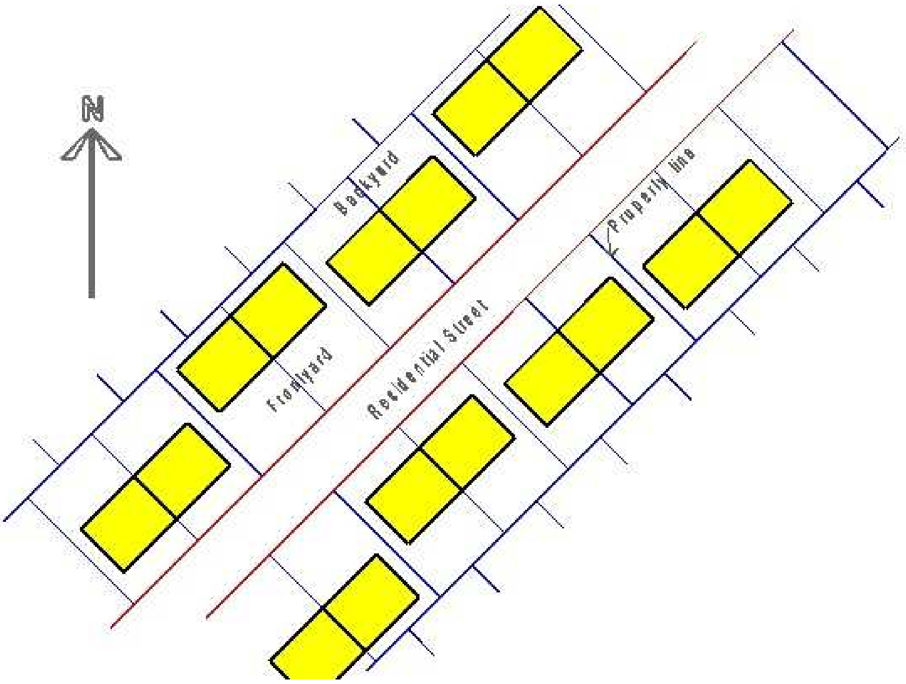

Figure 3: Typical schematic layout of dwelling units

Additionally, streets are tree-lined and the backyards are kept as green as possible. Exterior surfaces of buildings are painted in light colours and the street itself is paved in light-coloured concrete.

The quantification of thermal comfort in the above neighbourhood was simulated using a freeware called ENVI-met (Bruse, 2004). ENVI-met is a 3-dimensional non-hydrostatic model for the simulation of surface–plant–air interactions, especially within the urban canopy layer. It is designed for the micro-scale with a typical horizontal resolution from 0.5 to 10 m and a typical timeframe of 24 to 48h with a time step of 10 s. This resolution allows the investigation of small-scale interactions between individual buildings, surfaces and plants (Bruse 2004).

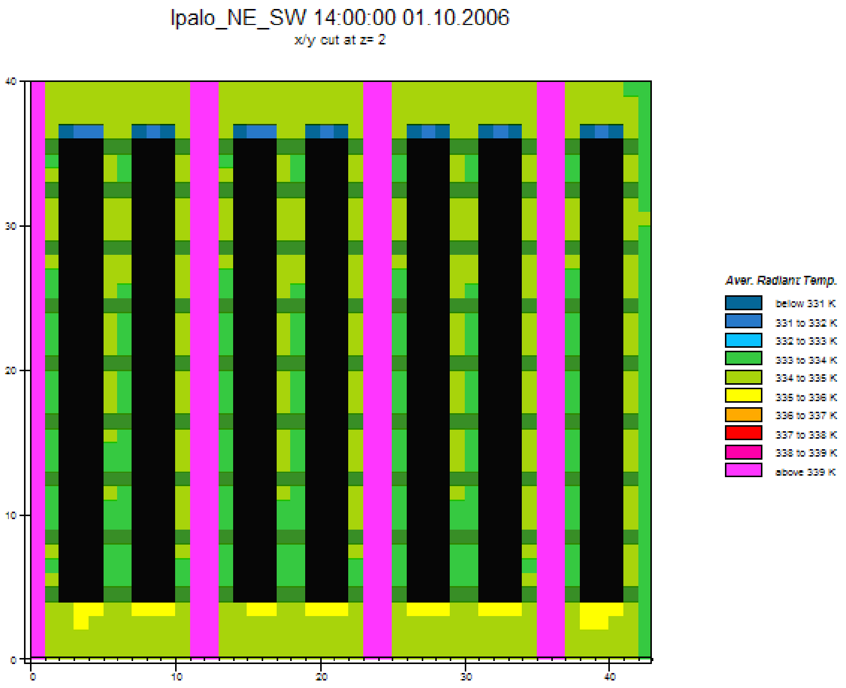

Figure 4: Simulated distribution of Mean Radiant Temperature (MRT)

Figure 4 shows the distribution of Mean Radiant Temperature (MRT) within a three adjoining street canyons laid out as shown in Figure 3. (see Emmanuel and Fernando, 2007 for a justification for using MRT as a proxy for outdoor thermal comfort in the tropics). It appears that substantial MRT differences are possible in areas surrounding the individual buildings by this high-density, staggered arrangement of buildings with high greenery and high albedo.

The ENVI-met simulation of three street orientations (Northeast-Southwest, North-South and Northwest-Southeast), two options for building arrangements (staggered), a landscaped street ("Green case") and one option for street paving ("green" paving instead of standard asphalt-paved road) showed that street orientation contributes the most to the outdoor temperature (and, by inference, to the thermal comfort). A strategy to plant trees in the front-yards of lots would also be beneficial. The effect of non-asphalted street was minimal (See Figure 5).

Indoor conditions

The indoor thermal environment of a typical house in this housing scheme was simulated using a building-level simulation program called DEROB-LTH, using the following parameters:

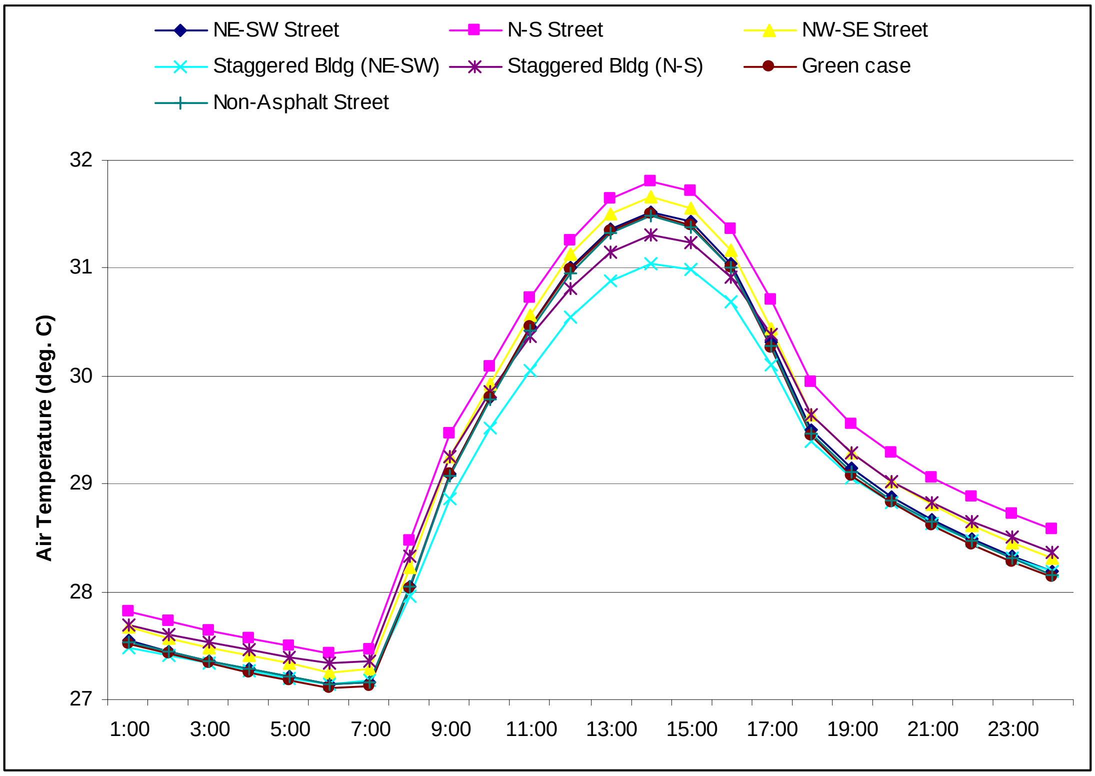

Figure 5: Air temperature variations around individual housing units

1. 9m wide street, lined with 150m2 plots on both sides, each plot surrounded by 1m high live hedge
3. Each plot has a 75m2 single-story house with two bedrooms, a toilet, a kitchen and a living/ dining area. Houses are laid on a staggered form, with alternating houses having the legal minimum rear space (2.5m). Every other house has a larger rear space (and thus smaller front yard). For reasons of simplicity of the computer model, the internal partitions of the house are ignored
4. The house is constructed of 225mm thick brick walls, plastered both sides (outside rough plastered and dark coloured inside lime plastered and white coloured); calicut tile roof on timber frame with flat asbestos sheet ceiling; 6mm thick, single glazed windows on wood frames; tiled floor on 100mm mass concrete
5. All windows are shaded by 1m wide horizontal shading devices
6. The house is considered air-conditioned for the purpose of calculating the cooling load. The rate of infiltration is assumed to be 1 Air Change per Hour (ACH). In reality however, houses will not be air-conditioned. This exercise was used solely for the calculation of potential energy savings

Internal temperature of the house is set lower at night and slightly higher during the day. The house is assumed to have four occupants.

In addition to the above case, the following options were studied:

1. Main entrance facing East;
2. corrugated cement-fibre sheet roof;
3. Tile roof with “Styrofoam” insulation;
4. White painted roof cover

The first option was studied to estimate the effect of layout (orientation), while the other three options estimate the effect of various roofing options. In a tropical context, roof is the most important controller of indoor comfort; the high solar angles make walls less important from the solar point of view. Results are shown in Figure 6.

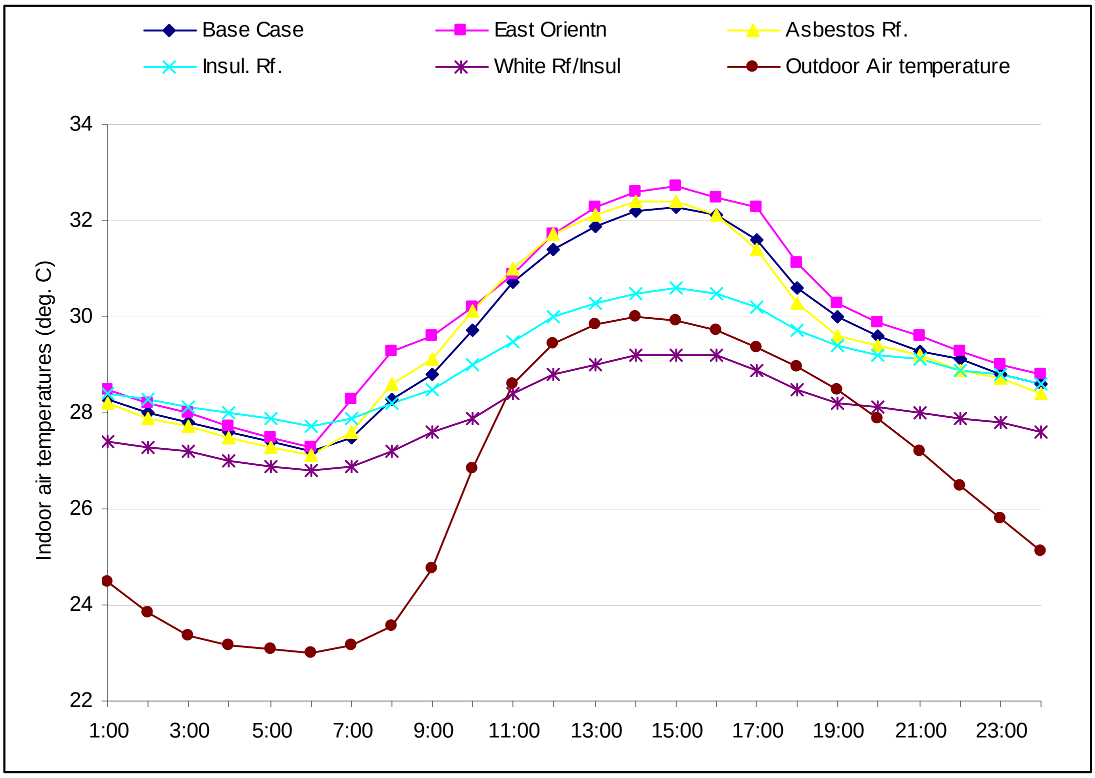

Figure 6: Indoor air temperature in a typical house studies

The best indoor comfort option is to paint the roof white and use roof insulation. The second best option would be to use roof insulation. Up to 3 deg. C reduction in indoor air temperature is possible with white roof/roof insulation combination. Nearly 2 deg. C reduction could be achieved by insulating the roof. Such reductions are remarkable in the context of constant and warm outdoor conditions in the equatorial tropics. In terms of layout, East-West orientation (i.e. main entrance facing east) is seen as the worst option.

Table 1 shows the potential cooling load reductions that could be achieved by manipulating the roof design. These are worked out on the hypothetical basis of air conditioning the house (i.e. keeping the windows closed). This was done as a thought experiment to quantify the potential cooling effect of different roof design strategies. However, windows are most likely to remain open in practice, resulting in cooler temperatures.

Table 1: Potential cooling load reductions due to different roofing strategies

	Cooling Load (kWh)	**Saving over Base case**
Option 'A'		
Base Case	26.32	0.0%
Insulated Roof	23.83	9.5%
White Roof w/ Insulation	21.74	17.4%
Option 'B'		
Base Case	29.26	0.0%
Insulated Roof	26.88	8.1%
White Roof w/ Insulation	24.57	16.0%

It appears that white roof with insulation will afford the most savings in terms of cooling load, while roof insulation by itself contribute to up to 9.5% reduction in cooling load. Roof insulation by itself has the potential to reduce the cooling load by approx. 2.5 kWh per day. This will be equivalent to an annual energy saving of 1,500x 365 x 2.5 kWh (1.3 GWh) for the entire housing scheme. In the context of rising electricity tariffs, such savings will be economically significant at the national scale.

From the above, we could surmise the following at two scales, urban design (settlement-level) scale and building design (individual units) scale:

Best approaches – Settlement-level

i. Northeast – Southwest street orientation is better, especially when the houses are staggered
ii. North-South street orientation is the worst orientation
iii. Encourage at least one medium-size tree (crown dia. = 10m) in each front-yard
iv. Wind speeds around buildings were similar even when buildings were not aligned equidistance from street line
v. Encourage backyards to be as green as practical

Best approaches – building level

i. Preferred orientation: Main entrance facing South
ii. Differences in energy saving between different housing options is minimal
iii. Preferred roof cover: Tile
iv. Roof insulation will reduce 8.0-9.5% of the cooling load
v. Roof strategy: at least 20mm roof insulation
vi. White roof will reduce an additional 8% of the cooling load.

Equatorial thermal comfort – a synthesis

The present study shows that substantial improvement in indoor thermal comfort is possible only if efforts to do so begin at the neighbourhood scale (i.e. outside the building). Indeed, the manipulation of settlement geometry, street orientation and external factors such as street trees are key to achieving thermal comfort in the equatorial tropics. Having done this, attention at the individual dwelling-level should focus on roof design. At the minimum, good roof insulation is needed. If it could be “aesthetically managed,” a white (or at least light coloured) roof design could further augment the indoor comfort.

In light of the above, the following are posited as the most profitable ‘macro-level’ strategies for the equatorial tropics:

1. Shade public spaces
2. Promote ventilation at settlement level
3. Increase greenery at the planning stage (Emmanuel, 2009)

Enlightened approach to equatorial tropical thermal comfort – a proposal

In the face of growing evidence for rapid increase in atmospheric carbon, dwindling resources and concerns over energy security, the need to achieve thermal comfort by passive means assumes great significance. This need is all the more urgent in the equatorial urban tropics, which currently experience an explosive urban growth. Design evidence from the equatorial tropics as shown in the previous section indicates the broad contours of indoor thermal comfort by passive means.

There is clear evidence to the link between indoor thermal comfort and outdoor weather (which now acknowledged in the so called ‘adaptive approach’ to thermal comfort – de Dear and Braeger, 1998). At the same time, there is great frustration at the inapplicability of ‘universal thermal comfort models’ to the specific problem faced by tropical urban dwellers, especially in those regions devoid of great annual variation in climate (including the equatorial tropics) (cf. Andreasi et al., 2010). While the problem of ignoring the contextual factors in contemporary thermal comfort quantification is well recognised (for example, the focus on adaptive approach to thermal comfort) there are other issues that need to be addressed for the effective tackling of the thermal comfort problem in the equatorial urban tropics.

Our work in Sri Lanka as presented above show that the achievement of thermal comfort indoors, must begin well outside the confines of the buildings. This is especially true in the so-called ‘free-running’ buildings that are open to the vagaries of daily weather. These facts dictate a fresh approach to urban thermal comfort in the tropics, and we posit a few pointers for the specific case of the equatorial urban thermal comfort.

1. Link the ‘in’ to ‘out’: It is necessary to specify not the indoor conditions to be achieved but the magnitude of change that ought to prevail between the ‘in’ and ‘out’ sides of buildings
2. Focus on specifying standards for climatically ‘cool’ urban public spaces
3. Work towards dynamic thermal comfort standards that respond to changes in urban microclimate as well as regional and/or global changes to climate

A critical lacunae in approaches to ‘universal thermal comfort’ is the lack of specification of the outdoors. This is especially important in the equatorial tropics where the design norm is naturally ventilated buildings. An exclusive focus on indoor standards need to give way for a new approach that links the ‘in’ and ‘out’ (i.e. express standards in terms of percentage reduction over the contextual surroundings). It is suggested that such an approach aim to increase the difference between the ‘in’ and the ‘out’ to a level that thermal delight is enhanced by the magnitude of the difference. This will help perceive the indoor as a ‘cool oasis’ in a harsh and increasingly warm urban outdoors.

Such a link between the indoor and outdoor thermal conditions ought to reflect the purpose for which thermal comfort standards are being promulgated. Lenzuni et al (2009) suggest differentiation of thermal standards along the following: the subject’s thermal sensitivity, accuracy required for carrying out the task and the practicality of thermal control. We suggest a fourth, the difference between indoor and outdoor conditions to be achieved.

Secondly, thermal comfort standards for the equatorial tropics need to engage the outdoors more explicitly. Given the year-round possibility to use the outdoors for daily living, urban thermal comfort gains greater importance in the overcrowded tropics where room occupancy rates are unhealthy (cf. Correa, 1989). A critical need is to specify outdoor thermal standards in terms of urban activities (Emmanuel, 1993) that facilitate comfortable movement in the outdoor, leading to greater quality-of-life.

Finally, there is a need to acknowledge the urban changes to climate in any future thermal comfort standards for the equatorial tropics. The urban growth in the region is in its early infancy. While population growths have tapered off, urban growth is about to take off with great vigour. Given the lack of resources and the sheer scale of the problem, it is likely the outdoor climatic conditions will be subject to intense heat island pressures in the coming decades, before stability is established. Outdoor thermal comfort standards need to reflect the urban changes to climate in a dynamic manner. Precedence for such an approach was recently suggested by Kwok and Rajkovich, (2010) which attempt to link thermal comfort standards to reflect global climate changes.

Limitations

The development of standards for urban thermal comfort is predicated on detailed weather data for cities. Multiple weather stations are rare in many equatorial cities. Even where they exist, urban weather stations are deliberately chosen to be 'unrepresentative' of the urban conditions (standard weather stations studiously avoid the urban 'contamination'). Thermal standards on the other hand, cannot be based on conditions based away from cities (usually at airports) that are unrepresentative of the climatic realities of most urban dwellers. This is an urgent need, in the face of the so-called 'climate change amplification co-efficient' (Coley and Kershaw, 2010). There is however, a coordinated effort to codify the standards for measuring urban weather by the World Meteorological Organisation (see, Oke, 2006) and these need to be followed to increase the urban climatic evidence that could underpin the new urban thermal comfort standards.

A focus on urban thermal comfort (as opposed to indoor comfort standards) is critical to enhance the quality of life of greater number of people as the tropics continue their raid urban growth. This bodes well from an equity standpoint. However, care is needed to ensure the standards reflect the activity patterns of as many urban users as possible (not just to promote better indoor comfort). This will necessitate that the standards for urban thermal comfort be coupled with non-thermal attributes of the urban commons. Correa (1989) suggested that a primary concern ought to be access to the commons. Urban equity demands that our work towards better outdoor thermal comfort be linked to the wider improvement of the urban public realm for the benefit of all.

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