A historical review and assessment of urban heat island research in Singapore

Matthias ROTH

Winston T. L. CHOW
Singapore Management University, winstonchow@smu.edu.sg

Singapore Journal of Tropical Geography

doi:10.1111/sjtg.12003

A historical review and assessment of urban heat island research in Singapore

Matthias Roth[1] and Winston T.L. Chow[1,2]

[1]Department of Geography, National University of Singapore, Singapore
[2]Department of Engineering, Arizona State University, Mesa, Arizona, USA

Correspondence: Matthias Roth (email: geomr@nus.edu.sg)

This historical review of 20 studies since the 1960s examines the influence of urban development on the thermal environment in Singapore, a fast growing tropical island city-state. Past observations are critically assessed with regard to experimental controls and station metadata. Given the availability of historical climate and developmental data spanning almost 50 years, changes in urban heat island (UHI) intensity and spatial coverage can be traced temporally. Rapid urban expansion in Singapore is clearly reflected in spatially and temporally changing air and surface temperature patterns. The nocturnal canopy-layer UHI intensity – measured as the difference between the commercial urban core and undeveloped areas close to primary or secondary rainforests for example – doubled in magnitude between 1965 and 2004. At the same time, the spatial extent of the nocturnal UHI has also expanded with the development of new housing and industrial districts. The influence of the growing city is also reflected in surface temperature. Two satellite images dated 13 years apart demonstrate the encroachment of areas with high surface temperatures into previously cooler areas during daytime corresponding with new public housing estates and low-rise residential areas or facilities being built. The results from our study contribute to the growing body of tropical heat island research. They provide baseline data for future research and urban development in the Singapore context and, more generally, offer important cues for urban planners to make tropical cities more sustainable.

Keywords: urban heat island, climate change, tropical, urbanization, Singapore

Introduction

One of the most thoroughly investigated features of inadvertent anthropogenic climate modification is the urban heat island (UHI). Writing in 1818, British scientist Luke Howard was probably the first to note that air temperatures in cities such as, in this case, London, are higher than in undeveloped rural surroundings (Howard, 2007). Many studies have since described the spatiotemporal distribution of urban temperatures through different techniques of stationary or mobile observation (e.g. Yow, 2007). A more process-based approach attributes UHI formation to energy balance changes brought about by urbanization (e.g. Oke, 1982), which are in turn controlled by variations in urban structure, form, cover and metabolism.

Increased urban warmth is not just measured in the near surface air, but throughout all layers of the city. As each UHI subtype can be caused and modified by different factors, it is important to clearly distinguish between UHIs (i) in the ground (subsurface), (ii) of the surface (e.g. measured by remote sensing instrumentation), (iii) in the air volume between buildings (the so-called urban canopy-layer, which most studies focus on), and (iv) in the air above the buildings (within the urban boundary layer that can be probed by tall towers or balloons). Another important methodological consideration is the proper classification of reference measurement sites such as through the recently proposed 'local climate zones' scheme (Stewart & Oke, 2009) that offers an improvement over the traditional 'urban–rural' classification. When so defined, the UHI becomes a more robust indicator of local climate modification.

The UHI influences several major urban environmental issues in different ways. For instance, generally positive effects occur within cities in cool climates, as additional urban warmth reduces demand for residential heating. But cities in perennial hot climates would expect increased demand for air conditioning (AC), which transfers the indoor heat burden to the external local environment. At larger scales, additional electrical demand for AC systems increases greenhouse gas concentrations from power stations consuming fossil fuels. The UHI in warmer climates likely increases thermal discomfort and associated heat-related maladies. Further, in all cities, additional warmth is likely to stimulate urban ecological activity through changes in local flora and fauna distribution, and potentially catalyzing chemical reactions arising from air pollution (e.g. increasing near surface ozone concentrations). The corollary resulting from these largely detrimental UHI impacts is that cities can also be important analogues in analyzing global climate change issues (Changnon, 1992). Through sustainable city design, global carbon dioxide emissions can be reduced via examining the footprint of human activities in urban agglomerations. This can be achieved in several ways, for example by (i) intelligent urban planning via promoting efficient resource use (e.g. Mills, 2007), (ii) increasing building energy efficiency, or (iii) mitigating the UHI to reduce air conditioning use where appropriate.

The above considerations are relevant for cities located in (sub)tropical climates, which are amongst the fastest growing globally in terms of population. Such cities rapidly contribute to greenhouse gas emissions and are also likely to be significantly influenced by global climate change impacts. It is therefore important that they incorporate climatological considerations in their design to provide sustainable living and working environments. Given the relative imbalance in the volumes of temperate versus tropical UHI research, Roth (2007) concluded that (sub)tropical urban climate studies are in need of a heightened profile in the scientific research community. In this spirit, the primary objective of this paper is to review the available UHI literature on Singapore, a fast growing tropical metropolis. The review critically assesses past observations, and provides reference data for ongoing and future research planned either at the local (individual housing estates) or mesoscale (entire city). We first document Singapore's physical environment which is necessary to be able to interpret subsequent results that span close to 50 years of research. Each relevant study is then reviewed, followed by considerations on how applied urban climate research can contribute to Singapore's future urban development.

Climate and urban development in Singapore

Singapore is an island state located at the southern tip of Peninsular Malaysia with an area of 712 km^2 in 2010 (DOS, 2011). This geographical location (1 °N, 104 °E) translates into an equatorial wet climate with consistently high monthly mean temperatures and little month-to-month variation (annual mean of ~27.5 °C; monthly range < 2 °C), a relatively small diurnal temperature range (~7 °C) and high annual total precipitation (mean rainfall ~2190 mm) (MSD, 2009). Singapore is subject to regional climate variations caused by the Asian monsoon, with weak mean surface winds (monthly mean <3 m s^{-1}) predominantly from the northeast during the Northern Hemisphere winter months (December–March), with a regular seasonal reversal to the southwest during the summer months (May–September). During the intermonsoon months, wind direction is highly variable with generally lower mean wind speeds compared with monsoonal periods. The monsoon's influence is not limited to wind direction. A prominent peak in monthly precipitation occurs between November and January caused by northeast monsoonal storms. Conversely, slightly lower than average precipitation is usually measured during the southwest monsoon.

The equatorial climate of Singapore presents a challenging living environment, likely exacerbated by increasing UHI intensities. Singapore's outdoor thermal comfort, based on metrics using standard meteorological variables such as ambient air temperature, humidity and wind speed, was studied by Ellis (1953), Stephenson (1963) and de Dear (1989), although the validity of the earlier two studies has been questioned for incomplete calculations of respondent heat balances (de Dear *et al.*, 1990). Regardless, the compiled thermal comfort indices suggest that the optimal comfortable period occurs during the winter monsoon, while the most uncomfortable period occurs during the onset of the summer monsoon in April–May. The difference largely arises from the combination of high (low) wind speeds and low (high) temperatures/radiant loads during the optimal (uncomfortable) period(s).

Singapore can be divided into three topographical areas. The central hilly area, which contains Singapore's highest peak (Bukit Timah Hill at 164 m) and is designated the 'Central Catchment area', comprises of a large rainforest area and several large reservoirs. The western and southern areas include undulating terrain and numerous hills. The eastern area is relatively flat, and predominantly composed of alluvium and sediment.

Singapore's rapid urbanization has been notable, especially since independence in 1965 (Figure 1). Population increased from 1.8 million in 1965 to almost 5.1 million in 2011, translating to a very high mean population density of 7126 persons km^{-2} (DOS, 2011). Keeping pace, residential dwelling units have almost doubled between 1998

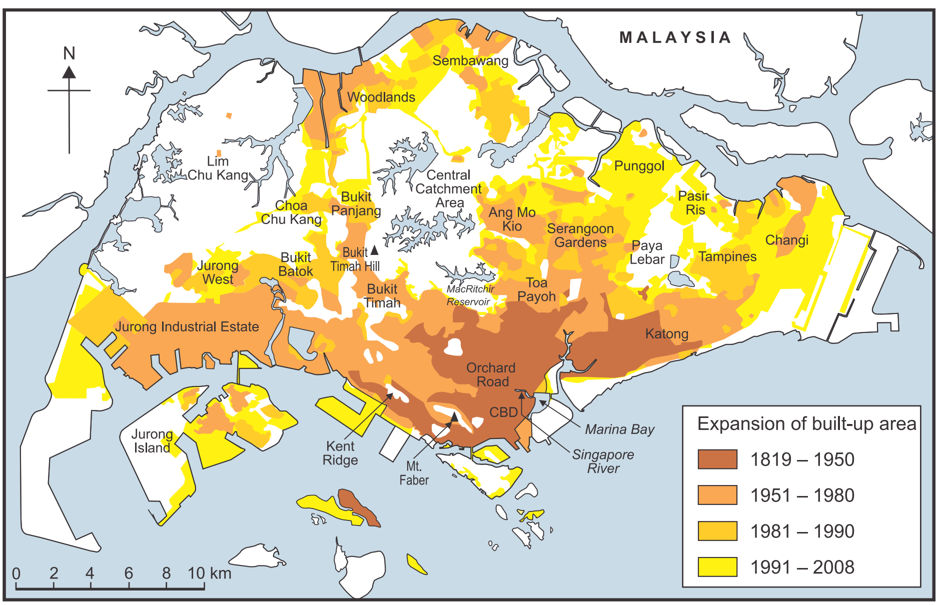

Figure 1. *Map of Singapore illustrating location of geographical features, towns and estates, as well as the extent of urbanization from 1819 to 2008.*

(655 000) and 2008 (1 156 000). Much of this development is typified by high-rise (15–55 m) residential apartments built by the Housing Development Board (HDB) – in 2008 constituting 77 per cent of all dwellings – and by high-rise private condominiums (15 per cent) (DOS, 2008). Consequently, the urban morphology has changed dramatically since 1965 when the HDB began removing traditional and informal lightweight and low-rise settlements (dubbed as 'kampongs'), and rehousing the majority of the local population in purposely built high-rise residential clusters known as new towns or housing estates (where, in 2008, 81 per cent of Singaporeans lived). Finally, some 5 per cent of residential dwellings are privately owned low-rise houses, mostly semidetached or terraced, which are distributed throughout the island in small enclaves (e.g. Serangoon Gardens in the centre and Katong in the east).

Overall, rapid land use change has seen a doubling of Singapore's built-up area between 1965 and 2000, primarily at the expense of forest and farm areas. Apart from residential land uses, large swamp and forest areas have been converted into industrial estates. From 1968 to 2008, Jurong Town Corporation (JTC), a governmental statutory board, managed the development of 66 km^2 of land designated for industrial use. Several general industrial areas (e.g. electronics, manufacturing) are located within residential estates, but most heavy industry (e.g. oil refining, steelworks) are concentrated in the expansive Jurong industrial estate, located in western Singapore, which includes several reclaimed offshore islands to its south (e.g. Jurong Island). Singapore's commercial and financial/business centres are located in the south. The large commercial area with shopping malls, hotels and entertainment complexes centred on Orchard Road generally has a high density of human and vehicular traffic that continues past midnight. The traditional central business district (CBD), housing the financial and banking activity, boasts a skyline of numerous tall skyscrapers (maximum height = 280 m) along the south banks of the Singapore River. Ten per cent of Singapore's land is committed as greenspace, of which about half are gazetted nature reserves. If these areas are added to the extensive roadside greenery and islandwide park connector network, more than 50 per cent of Singapore's total land area is covered by mainly managed vegetation and young secondary forest (Yee *et al.*, 2011).

Review of urban heat island studies of Singapore

Questions about the influence of rapid urbanization on Singapore's atmospheric environment first manifest in academic research in the early 1960s. Stephenson (1963) produced the first quantitative assessment of Singapore's outdoor thermal comfort, followed by Simon Nieuwolt's (1966) UHI study – probably the first to be published in English for any tropical city. These laid the foundation for subsequent local urban climate research, and also precede comprehensive UHI work in the 1970s in nearby Kuala Lumpur, the capital city of Malaysia (e.g. Sham, 1990/91).

The following section examines all published UHI studies of Singapore in chronological order and contains research not included in the review by Tso (1996). To facilitate intercity UHI comparisons, the following notions are adopted unless indicated otherwise. First, we assess reported UHI intensities to establish if these are individual maximum UHI intensity magnitudes ($\Delta T_{\text{u-r(MAX)}} = \text{UHI}_{\text{MAX}}$) – calculated as the largest temperature difference between an urban (T_{u}) and rural reference (T_{r}) observation measured under *ideal* (clear and calm) conditions as opposed to average values (e.g. across a range of sites and weather conditions). Second, we evaluate studies with respect to (i) experimental procedures employed and (ii) ambient conditions encountered during the study (such as definition of measurement sites, location metadata, or weather during observations). This is to partly address Stewart's (2011) recent criticism of the lack of methodological rigour underpinning the measuring and reporting of UHI intensities. Third, all times are standardized to *local apparent time* (LAT) corresponding to 12:00 hrs equalling solar noon. Most studies report *local time* (LT), which is about one hour ahead of LAT.

Canopy-layer urban heat island studies

For several days in June 1964, a team of university students measured dry (ambient or air, T_a) and wet bulb temperatures at nine urban locations in southern Singapore (Nieuwolt, 1966). Urban T_a observations were compared to simultaneous readings taken at Paya Lebar Airport, then located in a predominantly rural area 10 km northeast of the city centre. Maximum daytime $\Delta T_{u\text{-}r}$ was as high as 3.5 °C, with the highest magnitudes measured at the urban core (on China Street, in the vicinity of present-day CBD) on days when 'the weather was fine, with occasional cloudiness but no precipitation' (Nieuwolt, 1966: 31). Nighttime T_a were observed during several days, but results from only one clear night were available when a UHI_{MAX} of ~3 °C occurred close to sunrise. A larger, anomalous $\Delta T_{u\text{-}r}$ of 4.5 °C occurring earlier in the night is discounted because Neiuwolt (1966: 35) attributed it to 'localized air mass movement'. $\Delta T_{u\text{-}r}$ magnitudes were lower at two suburban stations sited within lower density housing. Cloudy conditions reduced the UHI by ~1.5–2 °C. Nieuwolt suggested that the temperature differences were due to increased radiation absorption and lower surface moisture in urban areas, and also reported lower relative humidity and higher physiological temperatures (neglecting the effects of wind) in the city.

About 15 years later, the Singapore Meteorological Service (SMS, 1986) (now the Meteorological Service Singapore) mapped 21:00 hr T_a distribution for the entire island using three datasets obtained from nine total days between 1979 and 1981. The datasets were (i) stationary T_a at four meteorological stations located at Changi (CH), Tengah (TE), Paya Lebar (PL) and Seletar (SL) airports, (ii) T_a observations obtained at between 9 and 26 ad hoc 'suitable' sites distributed islandwide and (iii) mobile T_a using psychrometers along 3 vehicle traverse routes. As these traverses lasted 3–4 hrs, mobile temperatures were adjusted to 21:00 hr to account for surface cooling over the duration and to enable comparison with the stationary T_a data.[1] No daily or antecedent precipitation for several days was reported.

The SMS (1986) maps revealed a broad east-west belt of elevated nocturnal T_a values in southern Singapore during both summer (Figure 2, top) and winter monsoon seasons, bound by lower values in northern nonurban areas. Highest T_a of ~30 °C was measured in the southern commercial (C1) and CBD (C2) areas, the latter recording the primary or largest UHI intensity. Secondary UHI peaks were associated with the western Jurong industrial estate (JI). The warm belt in eastern Singapore covered the residential areas of Katong (K), and the urban expansion in the new towns and estates of Toa Payoh (TP) and Ang Mo Kio (A) in the centre. The SMS study also confirmed higher T_a relating with development along the north-south running Upper Bukit Timah Road (B). The three distinct cool areas identified were within the Central Catchment area (CC), in the undeveloped western region, namely Lim Chu Kang (LC) and south of Kranji Reservoir (KR), and a slightly weaker cool island in the east, in the then undeveloped but present-day Tampines estate (T). Local perturbations to the general temperature pattern also arose from topographically-driven cold air drainage, which were

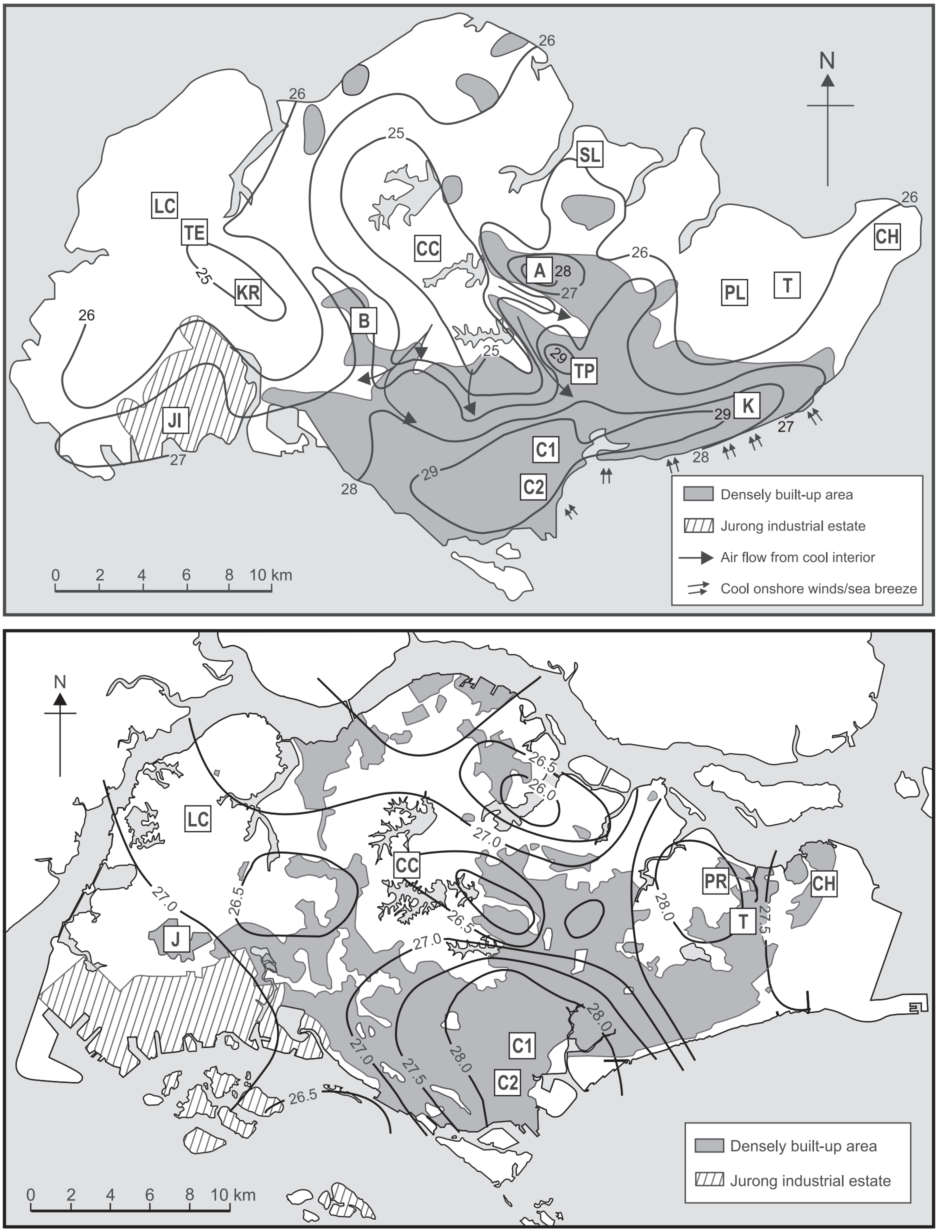

Figure 2. *Summer (warm period) canopy-layer temperature field (isotherm map) based on observations (top) between 20:00–21:00 hrs during May–August, 1979–1981 and (bottom) 21:00 hrs between 24–30 June, 1996. Letters identify locations noted in the text (A: Ang Mo Kio, B: Upper Bukit Timah Rd, C1/2: commercial and CBD areas, CC: Central Catchment, CH Changi, J: Jurong West, JI: Jurong industrial estate, K: Katong, KR: Kranji Reservoir, LC: Lim Chu Kang, PL: Paya Lebar, PR: Pasir Ris, S: Seletar, T: Tampines, TE: Tengah, TP: Toa Payoh).*

Sources: Redrawn after (top) SMS (1986) and (bottom) Chang and Goh (1998).

most pronounced in the upper basin of the Kallang River between the new estate developments of Ang Mo Kio and Toa Payoh.

UHI_{MAX} also differed significantly between seasons, with magnitudes of over 5 °C observed during the warmer and drier southeast monsoon period (May–June 1979) compared to 2–3 °C during the cooler and wetter northeast monsoon periods (January 1980 and 1981, and February 1981). SMS (1986) attributed the smaller UHI_{MAX} to the influence of steady daytime and nighttime northeast winds during the winter monsoon, which contrasted with otherwise calm nocturnal conditions favouring surface radiative cooling. The study did not specifically investigate diurnal variations of $\Delta T_{u\text{-}r}$, but data suggested that UHI_{MAX} likely occurred after midnight.

The spatial T_a distribution of Singapore was again investigated by Chang and Goh (1998). Primary T_a and humidity data were observed with calibrated sling psychrometers by volunteers at 15 sites uniformly distributed across Singapore, and supplemented by secondary data from 6 airport meteorological stations, including the same airfields used in SMS (1986). To directly compare with the SMS (1986) study results, T_a measurements (three observations within a 10-min period) were taken at ~21:00 hrs. Four 7-day periods were sampled between March 1996 and January 1997, corresponding to the two monsoonal and two intermonsoonal seasons. These data were kriged to produce islandwide isotherm maps similar to the SMS study. The results confirmed a major heat island over the commercial and CBD areas (C1 and C2), and cooler areas in the undeveloped and forested areas in the Central Catchment (CC), and in Lim Chu Kang (LC) in the northwest (Figure 2, bottom). A number of significant UHI changes were also noted. Areas that were undeveloped in the early 1980s, such as Tampines (T) and parts of Pasir Ris (PR) in the east, had been converted into high-density residential HDB estates by 1996 (Figure 1), which resulted in a new eastern secondary UHI. The overall spatial extent of the main cool area in the Central Catchment was also reduced by residential developments encroaching into the rainforest. Chang and Goh (1998) also noted that the construction of the Jurong West (J) estate did not result in a distinct heat island (unlike the eastern UHI over Pasir Ris and Tampines) and suggested that additional observations within its vicinity could have detected a micro- or local-scale influence affecting its UHI development. Subsequent unpublished studies have found that industrial areas have a lower UHI intensity compared to residential areas.

Reported $\Delta T_{u\text{-}r}$ were 4.8 and 2.5 °C during the summer (June) and winter (January) monsoons (similar in magnitude to the SMS study), and 3.3 and 3.5 °C during the March and October intermonsoon periods respectively. These results, however, potentially underestimate UHI_{MAX} as T_a was observed in 'open spaces to minimize the effects by surrounding buildings' (Chang & Goh, 1998: 6). Further, because the June T_a data were collected during wet as opposed to dry antecedent conditions in the SMS study, the different synoptic weather conditions likely complicates direct UHI_{MAX} comparisons.

The same authors subsequently investigated local temperature patterns in 17 selected HDB estates, relating canyon geometry and building orientation to temperature differences within the estates and in their immediate vicinity (Goh & Chang, 1999). Measurements were carried out on 2 nights at ~21:00 hrs during a dry March–May intermonsoon period in 1997. A sling psychrometer was used along an automobile traverse route to sample T_a at 8–18 sites, varying with the estate's size. For each estate, median height-to-width (H/W) ratios were regressed against ΔT_a measured between the estate's centre and vicinity, and a significant but weak relationship (R^2 = 0.28) was inferred. The validity and utility for comparison with other similar data (e.g. Oke, 1981;

Eliasson & Svensson, 2003), however, is doubtful for several reasons. While dry antecedent conditions were considered, other important atmospheric variables were not held constant, possibly affecting the significance of the H/W–T_a correlation. Synoptic wind speed, for example, varied between 1 and 5 m s^{-1} on individual nights, and nothing is known about cloud conditions during measurements. Further, the land cover and area description of sites where minimum (rural) temperatures were measured is unknown, and could be urbanized to some degree. Regardless, Goh and Chang (1999) provide useful estimates of local T_a impact from individual high-density housing estates and confirm the presence of local, intra-estate temperature variations of up to 3.0 °C.

The islandwide UHI intensity and the cooling influence of vegetation were studied by Wong and Yu (2005) using automobile traverses conducted on two nights in 2002. T_a was measured with a HOBO© temperature/RH logger located inside a plastic tube, mounted on a car rooftop perpendicular to the direction of the movement, during 01:00–03:00 hrs. One traverse along an east-west axis on 9 July 2002 recorded small T_a differences of 1.6 °C between the eastern industrial area of Bedok and the southern fringe of the Central Catchment (CC). The anomalous $\Delta T_{u\text{-}r}$ is likely due to (i) measurements affected by the particular nature of the immediate surroundings (road surfaces) as the traverse mostly followed a major highway, and (ii) the route not sampling enough land uses to reflect potential T_a extremes. Subsequently, 4 simultaneous traverses were carried out on 13 September 2002 through the eastern, western, and commercial and CBD areas (C1 and C2 respectively) (Wong & Yu, 2005; Priyadarsini *et al.*, 2008). $\Delta T_{u\text{-}r}$ measured between the CBD and secondary rainforest at Lim Chu Kang (LC) was 4.01 °C. Although some traverse routes still followed highways, the areas with distinct T_a maxima/minima were traversed on smaller roads. Unfortunately, neither Wong and Yu (2005) nor Priyadarsini *et al.* (2008) commented on two possible error sources: namely, methodological corrections accounting for surface cooling during the long traverse duration of 2 hours, and the possible lack of instrument ventilation affecting sensor response. At the indicated traveling speed of 50 km h^{-1} and with a sampling rate of 2 minutes, about one datum every 1.5 km is obtained, likely omitting small-scale temperature variations with larger maximum or minimum values. Nor was information given about weather conditions during measurements, limiting effective comparisons of their results with other studies.

One of the most comprehensive and systematic long-term UHI study to date in Singapore – or any other tropical city – was completed by Chow and Roth (2006).[2] Hourly averaged T_a observations were collected between March 2003 and March 2004 at 4 fixed urban stations representing different land use types: commercial (C1) and CBD (C2), HDB high-rise (Bedok South) and low-rise residential (Katong). A dedicated weather station sited in a small clearing within secondary rainforest at Lim Chu Kang (LC) served as the rural reference. The results were stratified according to wind speed and cloud condition measured at Changi (CH).

Largest $\Delta T_{u\text{-}r}$ magnitudes were consistently observed at C1, the commercial area. Average $\Delta T_{u\text{-}r}$ (maximum from all weather conditions) ranged between 2.6–4.7 °C depending on time of the year (Figure 3). Corresponding values were 0.5–1 °C lower at the other urban stations. Distinct seasonal variability was discerned with highest (lowest) $\Delta T_{u\text{-}r}$ measured in June (January), that is, during the dry summer monsoon (wet winter monsoon) seasons. Chow and Roth (2006) also investigated diurnal $\Delta T_{u\text{-}r}$ variations, with largest magnitudes observed 3–5 hrs after sunset at C1, and close to midnight elsewhere. Individual hourly averaged UHI_{MAX} values during clear and calm (<1 m s^{-1}) conditions at C1 were 7.1 °C (May) and 4.3 °C (December). The lower UHI

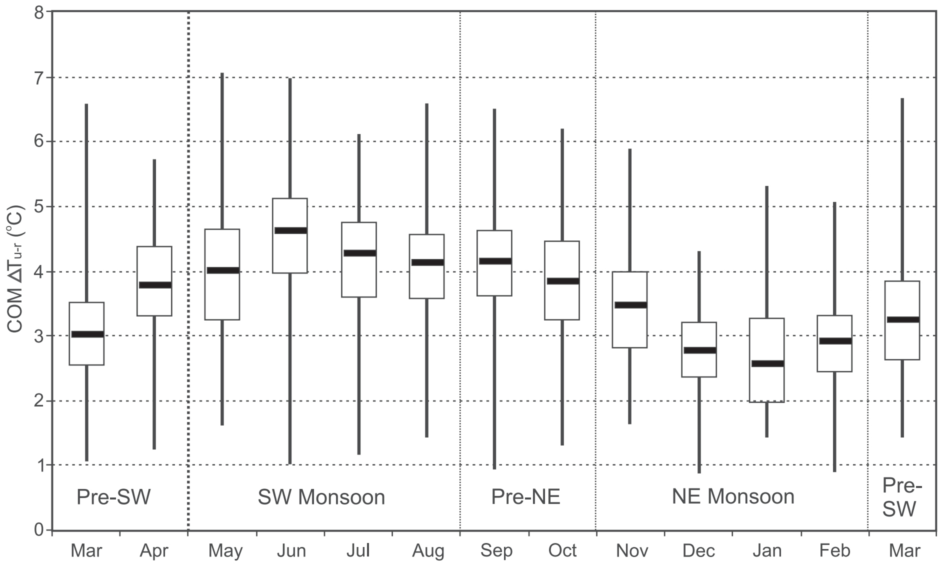

Figure 3. *Boxplot of daily nocturnal heat island intensities for all weather conditions between March 2003 and March 2004 for the commercial (COM) site located near Orchard Road. Shown are median (horizontal bar), middle 50 per cent of the data (box) and extreme values (end points of vertical lines) for each month.*
Source: **Modified after Chow and Roth (2006).**

intensities documented in December were likely due to two factors. First, higher soil moistures from heavier and prolonged winter monsoon precipitation result in higher rural thermal admittance that reduce rural cooling rates relative to urban cooling rates and therefore lower the UHI intensity. Second, the generally windy and cloudy weather during the winter monsoon period preferentially reduces nocturnal surface cooling magnitudes at the more open rural stations.

At all sites, maximum $\Delta T_{u\text{-}r}$ decreased with increasing wind speeds as urban–rural temperature gradients are reduced, similar to trends observed in other UHI studies (e.g. Yow, 2007). However, no clear relationship between morphological indices and UHI could be inferred as is sometimes observed (e.g. Yow, 2007). Despite the large H/W magnitudes, the relatively lower $\Delta T_{u\text{-}r}$ at the CBD (C2) compared to the commercial (C1) area (also observed by Nieuwolt, 1966) can be explained by three factors: (i) proximity to a river (200 m away) and the coast (500 m) possibly exposing the CBD to advective fluxes from nocturnal sea breezes, (ii) lower anthropogenic heat emissions (i.e. waste heat emitted from human activity, air conditioning systems and traffic) given the relative lack of activity after sunset – in contrast to the commercial area (C1) and (iii) daytime shading of the surface from the tall buildings within the CBD. The last factor is supported by the frequently observed presence of a daytime cool island in the CBD.

A summary of the studies reviewed, including UHI intensities, UHI_{MAX} and experimental details, is provided in Table 1. Generally, UHI_{MAX} magnitudes increased over time, with intermonsoon UHI_{MAX} doubling by ~3 °C between 1965 and 2004, and summer monsoon UHI_{MAX} increasing by ~2 °C between 1979 and 2004. It is possible that the larger database of 13 months in Chow and Roth (2006) captured periodic high UHI_{MAX} episodes which may have been missed by previous studies (lasting at most 1 month and often less). Increased UHI_{MAX} may, however, be the result of (i) urban

Table 1. Summary of nocturnal canopy-layer UHI studies in Singapore and reported UHI or UHI_{MAX} intensity values.

Study	Study period	Location of maximum T_a (U) and rural/reference (R) sites	Approx. time (LAT) of UHI_{MAX}*/ Weather	UHI/**UHI_{MAX}** (°C) (date)	Methodology; sensors used
Nieuwolt (1966)	2 Oct 1965	U: CBD (China Road) R: Airport (Paya Lebar)	Close to sunrise/ Clear skies	**3** (2 Oct 65)	5 fixed stations; psychrometers
Singapore Meteorological Service (1986)	May 1979–Feb 1981	U: CBD R: Primary, secondary rainforest (Bukit Timah, Lim Chu Kang)	21:00–22:00/Dry	**5** (16 May 1979) 3 (28 Jan 1980)	12 observer sites, 4 fixed stations and 3 car traverses; psychrometers combined with fixed met. station data
Chang & Goh (1998)	4 periods of 7 days: Jan, Mar, Jun, Oct 1996/1997	U: Western part of CBD R: Primary rainforest (Bukit Timah)	21:00/ Variable	2.5 (12 Jan 1997) 3.3 (4, 9 Mar 1996) 4.8 (24 Jun 1996) 3.5 (4, 5 Oct 1996)	21 fixed stations; psychrometers combined with fixed met. station data
Wong & Yu (2005); Priyadarsini *et al.* (2008)†	9 Jul 2002 13 Sep 2002	U: CBD R: Secondary rain forest (Lim Chu Kang)	02:00/NA	1.6 (9 Jul 2002) 4 (13 Sep 2002)	1 car traverse following highways (July), 4 simultaneous car traverses (Sep); HOBO©
Chow & Roth (2006)	Mar 2003–Mar 2004	U: Commercial (Orchard Road) R: Secondary rainforest (Lim Chu Kang)	21:00/Dry, clear and calm	**6.8** (Mar) **7.1** (May) **6.6** (Sep) **4.3** (Dec)	5 fixed stations; HMP45

T_a = air temperature; LAT = Local Apparent Time, which is about GMT +7.
*Apart from Chow & Roth (2006), observations have only been performed at one specific time in each study.
†Priyadarsini *et al.* (2008) state measurements were taken in August 2002, however measurement set-up and results are the same as in Wong & Yu (2005) and 13 September 2002 is assumed to be the correct date.

densification (through land cover conversion and construction of dense urban canyons) corresponding with the dramatic increase in Singapore's population from ~1.9 in 1965 to 2.7 in 1985 and ~4.3 million in 2004, and (ii) greater urban metabolism from large anthropogenic heat flux densities; for instance, a recent study concluded that the urban metabolism within the C1 area released anthropogenic heat fluxes of the same order of magnitude as calculated for city-centres in several mid-latitude cities during winter (Quah & Roth, 2012).

Surface heat island studies

Spatial variations in surface temperatures (T_s) can be obtained by measuring the black-body temperature through radiation sensors mounted on aircraft or, more often, on satellites. Due to its equatorial location, cloud-free images are generally rare for Singapore, limiting possibilities to measure and assess T_s. Thus, less is known about the surface UHI compared to the canopy-layer UHI.

Most of the current understanding of surface UHI in Singapore owes to Janet Nichol, who worked in the Division of Geography at Nanyang Technological University in the 1990s. Nichol's (1993; 1994) earliest papers on this topic investigated T_s patterns with a Landsat Thematic Mapper (TM) image recorded at 09:40 hrs on 24 May 1989. Because the relatively lower spatial resolution of thermal (compared to visible) imagery impedes analysis of small-scale temperature patterns, Nichol developed a procedure to increase the original thermal image resolution of 120 m by enhancing both spatial and spectral accuracy through correcting differential emissivities according with vegetation status within each pixel. An approximate atmospheric correction was carried out by calibration with known sea and inland water body temperatures.

Unsurprisingly, Nichol's (1993) analysis showed (i) that daytime T_s correlates strongly with vegetation densities, with the Central Catchment (CC) displaying coolest surface temperatures and (ii) the loss of cooler microclimates in the catchment area south of MacRitchie Reservoir, where previous rainforest vegetation was replaced by golf courses and defence installations. Nichol (1994) also pioneered Geographic Information System (GIS) techniques in registering image data to digital plans of street and building outlines, enabling spatial temperature patterns to be linked to urban morphology. Using high-resolution urban land use data for nine HDB estates located within central Singapore, the thermal data suggested a mosaic of potential microclimates at or below rooftop level, which were influenced by solar azimuth and thermal characteristics of the immediate active surface rather than local or mesoscale horizontal advection. The same study (Nichol, 1994) also found a close negative correlation between T_s and the biomass amount expressed through the leaf area index (LAI) (but < 1 °C variation over the available range of LAI), as well as similarity with T_a during the mid morning hours.

The relationship between T_s and T_a at (i) different heights and (ii) for different building orientations in HDB estates was the focus of another study by Nichol (1996a). During a four-week period in April–May 1994, T_s and T_a (at several heights within 1 m from the respective surface) were measured with handheld sensors every 30 minutes between 08:00 and 15:30 hrs within three HDB street canyons in Bishan East and Serangoon Central. T_a and T_s varied little between 1 m above ground and 43 m (near mean building roof height), with overall differences in both of < 1 °C. A close relationship in diurnal variability between T_a and T_s existed for both horizontal and vertical surfaces, with larger magnitudes and greater variability for T_s than T_a. Surface-air temperature differences were greatest for concrete surfaces (daytime average ~10 °C, with a maximum of 16 °C at noon), and least at the shaded canyon floor (2.7 °C; ~4 °C). Tree canopies were shown to have a significant cooling effect of 1.5–2 °C on daytime T_a. The coolest (warmest) T_a magnitudes were thus found below tree canopies (above concrete surfaces), rather than over exposed grassy surfaces. In terms of T_s, satellite images were also able to detect the cooling effect of vegetation, such as in relatively cooler tree canopy tops. This cooling effect was again less obvious over open grassy surfaces, where T_s also depends on surface moisture conditions which were not assessed in these studies (Nichol, 1993; 1994; 1996a).

During comparison with a supplementary TM image obtained from 2 years later (15 March 1991; 09:40 hrs), remarkably similar T_s patterns across the two estates were observed despite the difference in month of acquisition (Nichol, 1996b). Based on the close agreement between the spatial distribution of T_s in the satellite images and values measured in the field (though not measured concurrently), as well as between the simultaneously measured T_s and T_a in the field, Nichol concluded that for daytime conditions, when wind speed is low, satellite-derived surface temperature patterns are a good indicator of the UHI.

In two studies, Nichol (1996a; 1996b) examined how building morphology influenced T_a and T_s. Singapore's equatorial location and hence high sun angles throughout the year results in potentially rapid daytime surface heating. A common characteristic of Singapore's high-rise estates is the predominantly east-west orientation of the long axis of apartment blocks to minimize direct insolation on building faces. Further, HDB estates are closely spaced, which minimizes direct solar penetration to street-level and increases the effects of ground-level shading. Both T_a and T_s in the inner courtyards of these HDB estates were lower at most daytime hours due to the high-density building morphology, but this cooler daytime climate is likely offset by increasing nocturnal T_a from the slow release of daytime heat stored in the dense urban fabric. In these two studies, Nichol also noted that private estates with bungalow-style development appear considerably warmer than the average high-rise HDB estate. This is probably due to the larger proportion of warmer mean active surface area during daytime, which is larger in low-rise building configurations because of the lesser proportion of (shaded and cool) vertical walls. A similar result for canopy-layer UHI was also obtained by Chow and Roth (2006), where nighttime UHI_{MAX} were slightly higher in a low-rise residential area compared to an HDB high-rise estate characterized by buildings taller than 30 m.

Concluding Nichol's substantial contribution is the development of an automated model for visualizing T_s as a measure of T_a applicable to densely built tropical cities, which is based on thermal data from the 24 May 1989 TM image (Nichol, 1998). This model was derived from temperatures of the complete urban surface, that is, interpolating the 2D thermal satellite data over the 3D urban surface through GIS methods. The model compensates for systematic errors associated with the nadir viewing of satellite sensors based on the close agreement observed between morning T_s and T_a in her earlier work. Nichol (1998) concluded that the model is capable of predicting micro-scale climatic variations due to variations in building geometry and surface materials that are not readily apparent from the 2D perspective.

Two recent studies analyzed T_s derived from a cloud-free Landsat 7 ETM+ image from 11 October 2002, 10:09 hrs (Jusuf *et al.*, 2007; Priyadarsini *et al.*, 2008). 'Approximate' surface temperatures were calculated from Band 6, which provides 60 m resolution (Jusuf *et al.*, 2007). Unlike in Nichol's work, however, no corrections for spatial variations in either emissivity or atmospheric absorption were applied which, in the case of the latter, potentially results in an underestimation of up to 15 °C in the image data compared to actual T_s (e.g. Nichol, 1996b). Nevertheless, comparison of these images from the two periods gives an indication of T_s changes over 13 years resulting from urbanization. In 1989, highest T_s (35 °C and higher) corresponded to industrial areas including Jurong in the west (JI), port facilities along the south coast (P), Changi Airport (CH) in the east and Sungei Kadut (S) in the north (Figure 4, top). A number of private residential areas along the east coast such as Katong (K) and in Serangoon (SG) also displayed relatively high T_s (Nichol, 1996a). All these areas are characterized by (i) low-rise industrial and private residential buildings, resulting in a high proportion of horizontal surfaces seen by the satellite being part of the total active surface, (ii) street and parking pavement exposed to solar access, and (iii) surface thermal properties that readily accept heat (e.g. metal roofs in industrial areas). All aforementioned

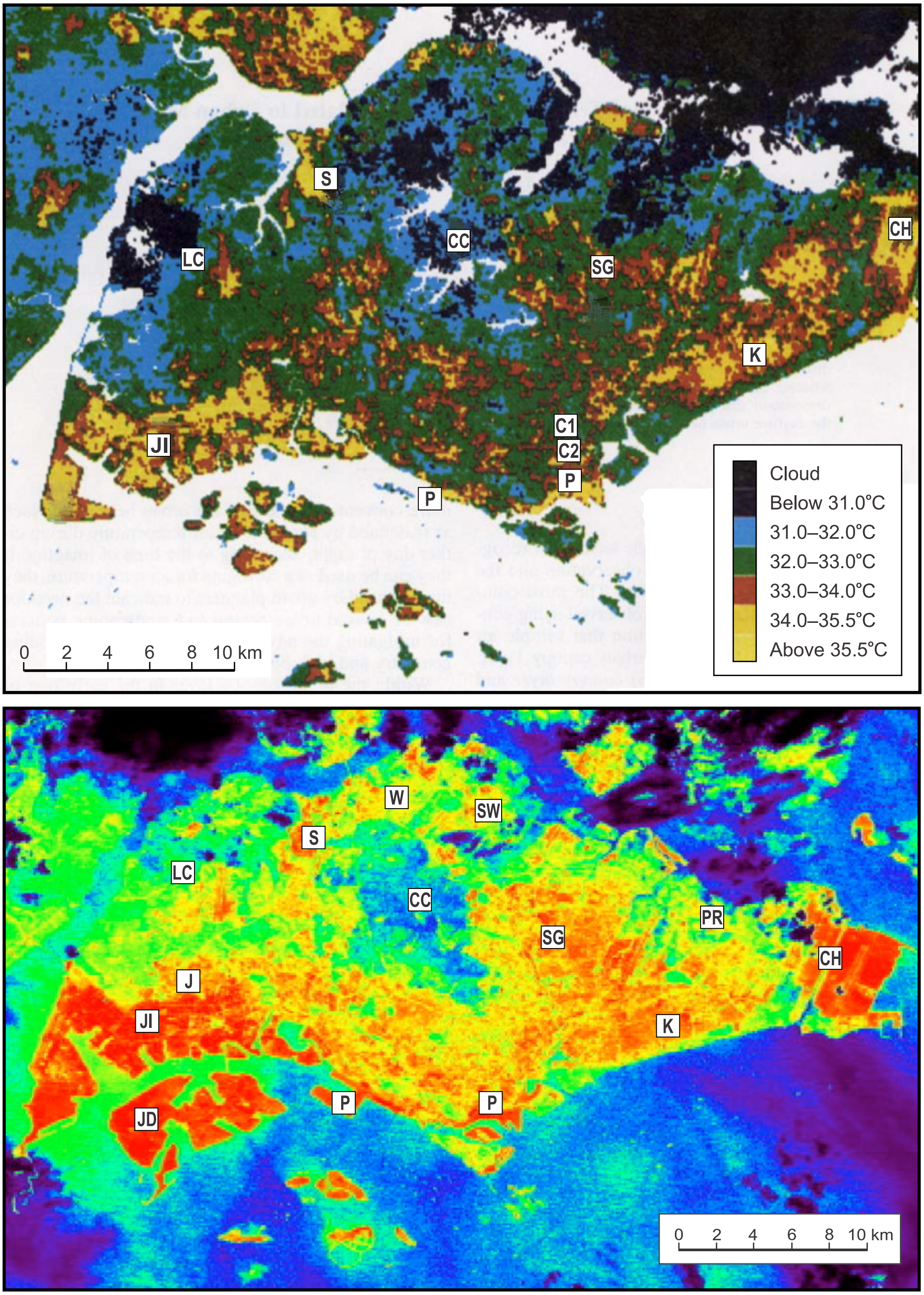

Figure 4. *Landsat thermal images of Singapore showing surface temperatures at (top) 09:40 hrs on 24 May 1989 and (bottom) 10:09 hrs on 11 October 2002. Note the differences in colour allocation to surface temperatures in the two images. Red and blue in the bottom image denote warm and cool temperatures respectively (colour version online). Letters identify locations noted in the text (C1/2: commercial and CBD areas, CC: Central Catchment, CH: Changi, JI: Jurong West, JD: Jurong island, JI: Jurong industrial estate, K: Katong, LC: Lim Chu Kang, P: port facilities, PR: Pasir Ris, S: Seletar, SG: Serangoon, SW: Sembawang, W: Woodlands).*
Sources: Modified after (top) Nichol (1996a) and (bottom) Priyadarsini *et al*. (2008).

characteristics are known to produce high daytime T_s (Roth *et al*., 1989). Note that both the commercial area (C1), where the maximum nighttime T_a is often measured, and CBD (C2) have lower T_s partly because much of the active surface area sampled is shaded by taller buildings.

The same areas (JI, P, CH, S, K and SG) again exhibit the highest surface temperatures 13 years later with the addition of new surfaces related to reclaimed (mostly barren) land at the western and eastern peripheries, Jurong Island (JD) and a number of expanded port facilities (P) along the southwest coast (Figure 4, bottom). Jusuf *et al*. (2007) estimated peak T_s of ~40–50 °C, though direct comparison with Nichol (1996a) is difficult given different image times and atmospheric correction procedures. The lowest surface temperatures in both image years are found over the undeveloped forested areas surrounding the Central Catchment (CC) and northwest Lim Chu Kang (LC) areas where treetop temperatures in 1989 measure ~30 °C (Nichol, 1996a). The most prominent differences are higher T_s magnitudes in the 2002 image associated with newly established HDB estates since 1989, namely in Jurong West (J), Woodlands (W), Sembawang (SW) and Pasir Ris (PR) (see also Figure 1). In 1989 these districts were characterized by T_s values similar to those of more vegetated or even forested areas.

Conclusion: future planning considerations and application of urban climate research

Continually expressed aspirations to further grow Singapore's population will likely increase environmental stresses such as through a warmer thermal environment from the UHI. Temperature increases associated with a growing UHI will result in several detrimental impacts, making minimizing heat loads an important planning objective for Singapore. Encouragingly, state authorities appear to pursue an intensive 'greening' campaign while simultaneously planning large-scale urban developments to support Singapore's continuing growth as a major business and financial hub. Recent urban design policies increasingly address questions of 'green' or low-energy buildings and climate sensitive planning at local scales. One example is the ambitious plan for the Punggol 'eco-town' and the eco-modernization developed by HDB (Ming *et al*., 2010). Punggol is planned as a 'living laboratory' to test new sustainability ideas and technologies, which integrate urban solutions to create a green living environment. Key initiatives include environmentally friendly buildings, introduction of common vegetated areas, a waterway traversing through the town, and planned freshwater lakes and reservoirs. When completed, it is expected to house 100 000 people in an area of ~10 km^2, of which half is residential in land use.

One measure of how successful such 'sustainable development models' applied in Punggol and future residential areas are is through evaluation of urban climate using a rigorous scientific process and results compared to baseline results summarized, for example, in this historical review. Detailed thermal information at varying spatial scales will be valuable to planners as human comfort is subject to effective landscaping wherever people live and work. Hence, further monitoring will be essential to produce appropriate urban climate data and objective results that are important in managing the projected significant growth in a more sustainable way and not at the expense of human comfort and liveability. Such data will also be important in evaluating a variety of possible urban climate modelling studies that examine the thermal environment of Singapore. Unfortunately, all but one study in Table 1 (Chow & Roth, 2006) do not meet the set of criteria outlined by Stewart (2011) to qualify as sound UHI research. We strongly suggest that future research should consider Stewart's critiques during study design so as to facilitate valid cross-study comparisons, not just in Singapore but also with other cities.

As yet, there is little information available on the environmental benefits of many of the proposed greening options, although some have investigated the application of urban vegetation and rooftop gardens as a general UHI mitigation approach (e.g. Wong *et al.*, 2002; 2003; Wong & Jusof, 2010). These concluded that (i) rooftop gardens reduce adjacent T_s and T_a, and lower heat transfer through rooftops, and (ii) mature, broad canopy trees could increase shading and thermal comfort for pedestrians in urban canyons. Some caveats have to be noted. While the principal benefits of rooftop gardens may be the lower building energy consumption (at least for the top floors) from both reduced AC demand and air quality improvements through vegetation filtering, there is still a need to prove that any effect on T_a is felt beyond the micro-scale. Further, both mitigation approaches would result in higher relative humidity, which may offset the thermal comfort from lower T_a and the potentially harmful impact on air pollution from biogenic volatile organic compounds emitted by such additional vegetation is yet unknown.

The effectiveness of possibly costly landscaping policies so far has been primarily judged empirically, for which spatial temperature data at various resolutions as reviewed herein will be of value. These temperature data are also needed to assess the increasing use of urban climate models that are employed to predict the effects of various climate-sensitive design options (e.g. Priyadarsini *et al.*, 2008). More investigation is also needed to assess the relative benefits of the various climate interventions currently employed such as green roofs, vertical greening (or gardens) or cool (highly reflective) roofing in reducing indoor temperatures and cooling needs, and their effect on local, street level T_a where mitigating the thermal environment is (arguably) more important.

Finally, the body of research reviewed here will provide important results for urban planning in rapidly growing low-latitude cities, where there is a pressing need to incorporate climatological concerns in designs to achieve better living and working environments (Roth, 2007). The magnitude of urban warming is comparable to that considered possible at the global scale and will be superimposed upon any temperature increases brought about by climate change. This highlights the urgency of mitigating UHI effects in cities located in already hot climates to the benefit of its inhabitants, including reducing energy consumption associated with cooling indoor living and work spaces.

Acknowledgements

We are grateful to Li Kheng Lee for help with Figures 1, 2 and 4, and acknowledge financial support from the National University of Singapore (R–109–000091–112). Winston T.L. Chow was also supported by the National Science Foundation (Grants EF-1049251, BCS-1026865 and DEB-0423704) through the Central Arizona-Phoenix Long-Term Ecological Research Project.

Endnotes

1 The timing of 21:00 hrs was selected based on Chandler's (1965) study that found UHI_{MAX} generally occurring within a few hours after sunset.

2 Stewart's (2011) critical assessment of scientific methodology in UHI research between 1950 and 2007 ranked this study at 10 out of 190 published studies.

References

Chandler TJ (1965) *The Climate of London*. Hutchinson, London.

Chang CH, Goh KC (1998) The nocturnal heat island phenomenon of Singapore revisited. Paper presented at the 5th Southeast Asian Association Geographers' Conference on Geography and Geographic Education in the 21st century, National Education Institute, Singapore, 30 November–4 December.

Changnon SA (1992) Inadvertent weather modification in urban areas: lessons for global climate change. *Bulletin of the American Meteorological Society* **73,** 619–27.

Chow WTL, Roth M (2006) Temporal dynamics of the urban heat island of Singapore. *International Journal of Climatology* **26,** 2243–60.

de Dear R (1989) Diurnal and seasonal variations in the human thermal climate of Singapore. *Singapore Journal of Tropical Geography* **10,** 13–26.

de Dear R, Knudsen HN, Fanger PO (1990) Impact of air humidity on thermal comfort during step-changes. *ASHRAE Transactions* **95** (2)**,** 236–350.

Department of Statistics (DOS) (2008) *Yearbook of Statistics Singapore 2008*. Ministry of Trade and Industry, Singapore.

Department of Statistics (DOS) (2011) *Yearbook of Statistics Singapore 2011*. Ministry of Trade and Industry, Singapore.

Eliasson I, Svensson MK (2003) Spatial air temperature variations and urban land use – a statistical approach. *Meteorological Applications* **10,** 135–49.

Ellis FP (1953) Thermal comfort in warm humid atmospheres – observations on groups and individuals in Singapore. *The Journal of Hygiene* **51,** 386–404.

Goh KC, Chang CH (1999) The relationship between height to width ratios and the heat island intensity at 22:00 h for Singapore. *International Journal of Climatology* **19,** 1011–23.

Howard L (2007[1833]) *The Climate of London (I)*, ed. Gerald Mills. International Association for Urban Climate reissue. Avalable at http://urban-climate.com/wp3/wp-content/uploads/2011/04/LukeHoward_Climate-of-London-V1.pdf (last accessed August 2012).

Jusuf SK, Wong NH, Hagen E, Anggoro R, Hong Y (2007) The influence of land use on the urban heat island in Singapore. *Habitat International* **31,** 232–42.

Meteorological Services Department (MSD) (2009) Weatherwise Singapore. National Environment Agency, Singapore. Available at app2.nea.gov.sg/data/cmsresource/20090324939502642695.pdf (last accessed August 2012).

Mills G (2007) Cities as agents of global change. *International Journal of Climatology* **27,** 1849–57.

Ming LJ, Suan TP, Toh W (2010) HDB's next generation of eco-districts at Punggol and eco-modernisation of existing towns. *The IES Journal Part A: Civil & Structural Engineering* **3,** 203–9.

Nichol JE (1993) Monitoring Singapore's microclimate. *Geo Info Systems* **4,** 51–55.

Nichol JE (1994) A GIS-based approach to microclimate monitoring in Singapore's high-rise housing estates. *Photogrammetric Engineering & Remote Sensing* **60,** 1225–32.

Nichol JE (1996a) High-resolution surface temperature patterns related to urban morphology in a tropical city: a satellite-based study. *Journal of Applied Meteorology* **35,** 135–46.

Nichol JE (1996b) Analysis of the urban thermal environment of Singapore using LANDSAT data. *Environment and Planning B: Planning and Design* **23,** 733–47.

Nichol JE (1998) Visualisation of urban surface temperatures derived from satellite images. *International Journal of Remote Sensing* **19,** 1639–49.

Nieuwolt S (1966) The urban microclimate of Singapore. *The Journal of Tropical Geography* **22,** 30–37.

Oke TR (1981) Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations. *Journal of Climatology* **1,** 237–54.

Oke TR (1982) The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society* **108,** 1–24.

Priyadarsini R, Wong NH, Cheong KWD (2008) Microclimatic modeling of the urban thermal environment of Singapore to mitigate urban heat island. *Solar Energy* **82,** 727–45.

Quah AKL, Roth M (2012) Diurnal and weekly variation of anthropogenic heat emissions in a tropical city, Singapore. *Atmospheric Environment* **46,** 92–103.

Roth M (2007) Review of urban climate research in (sub)tropical regions. *International Journal of Climatology* **27,** 1859–73.

Roth M, Oke TR, Emery WJ (1989) Satellite-derived urban heat islands from three coastal cities and the utilization of such data in urban climatology. *International Journal of Remote Sensing* **10,** 1699–720.

Singapore Meteorological Service (SMS) (1986) A study of the urban climate of Singapore. In Chia LS, Lee HC, Rahman AR, Tong PL, Woo WK (eds) *The Biophysical Environment of Singapore and its Neighbouring Countries*, 50–76. Geography Teacher's Association, Singapore.

Sham S (1990/91) Urban climatology in Malaysia: an overview. *Energy and Buildings* **15–16,** 105–17.

Stephenson PM (1963) An index of comfort for Singapore. *The Meteorological Magazine* **92,** 338–45.

Stewart ID (2011) A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology* **31,** 200–17.

Stewart ID, Oke TR (2009) A new classification system for urban climate sites, *Bulletin of the American Meteorological Society* **90,** 922–3.

Tso, CP (1996) A survey of urban heat island studies in two tropical cities. *Atmospheric Environment* **30,** 507–19.

Wong NH, Yu C (2005) Study of green areas and urban heat island in a tropical city. *Habitat International* **29,** 547–58.

Wong NH, Cheong KWD, Yan H, Soh J, Ong CL, Sia A (2002) The effects of rooftop garden on energy consumption of a commercial building in Singapore. *Energy and Buildings* **35,** 353–64.

Wong NH, Chen Y, Ong CL, Sia A (2003) Investigation of thermal benefits of rooftop garden in the tropical environment. *Building and Environment* **38,** 261–70.

Wong NH, Jusof SK (2010) Study on the microclimate condition alonga green pedestrian canyon in Singapore. *Architectural Science Review* **53,** 196–212.

Yee ATK, Corlett RT, Liew SC, Tan HTW (2011) The vegetation of Singapore – an updated map. *Gardens' Bulletin Singapore* **63,** 205–212.

Yow DM (2007) Urban heat islands: observations, impacts and adaptation. *Geography Compass* **1/6,** 1227–51.