

# Review of urban climate research in (sub)tropical regions

Matthias Roth\*

*Department of Geography, Faculty of Arts and Social Sciences, National University of Singapore, Singapore*

## Abstract:

Over the last 50 years the developing world, much of which is located in (sub)tropical regions, has seen a dramatic growth of its urban population associated with serious degradation of environmental quality. The total number of (sub)tropical urban climate studies, however, is still small (<20% of all urban climate studies). The available work is further biased towards descriptive studies rather than process work that seeks to indicate the physical climatology of (sub)tropical cities. The available results allow for a preliminary comparison with data from temperate latitudes. Urban heat island (UHI) intensities are generally lower compared to those of temperate cities with comparable population and show a seasonal variation with lower (higher) intensities during the wet (dry) season. (Sub)tropical population-based relations may exist but insufficient appropriate data is available to confirm a logarithmic relationship or systematic differences between different climate types. The (sub)tropical energy balance studies are biased towards dry, clear sky conditions. The amount of net radiation dissipated by sensible heat during daytime is about 40% which is similar to values observed in (sub)urban areas of cities located in temperate climates. Energy partitioning is modulated by water availability and higher percentage of vegetation promotes latent heat flux at the expense of surface heat storage. The apparent strong influence of vegetation and water availability on the energy partitioning irrespective of the climate type, suggests vegetation to be an effective means to reduce heat storage uptake during daytime and hence has the potential to effectively mitigate the nocturnal heat island. It is important to ensure that the rapidly expanding cities of the developing world incorporate climatological concerns in their design to provide a better living and working environment for a large segment of the world's inhabitants. Copyright © 2007 Royal Meteorological Society

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## INTRODUCTION

Urbanization and the conversion of the Earth's surface to urban uses are among the most visible and rapid anthropogenic changes. In recent years the most explosive population growth has occurred in developing countries, many of which are located in tropical (defined as the region between 23.5°S–23.5°N) and subtropical (between 23.5–35°S and 23.5–35°N) climates. Urbanization in these regions has brought about a number of environmental problems at various scales. As cities expand it is becoming increasingly clear that environmental impacts are not just limited to the actual footprint of a place, but may indeed occur at regional and global levels. Cities produce their own microclimate, but are connected to regional and global climates through the chemistry of the atmospheric effects on radiation balance and greenhouse gas emissions.

Past-urban climate research has primarily focussed on North American and European cities located in mid-latitude climates in the Northern hemisphere. In contrast, a similar body of work and therefore understanding in

the equatorial or subtropical context is not readily available. This is unfortunate because much of the future urban growth will take place in cities located in low latitudes. Many of these cities have sprung out from rural towns in very short time, often without much planning or restrictions on land use. They are already experiencing deteriorating environments and are often in a weak position to handle the influx of people and the associated social and environmental problems in a sustainable way. Climate-related environmental problems in (large) tropical urban agglomerations include (1) poor dispersion of air pollutants (generally low wind speeds and a lack of ventilation), (2) high levels of heat stress which decreases productivity, reduces human comfort and increases mortality due heat related illnesses and (3) space cooling needs which increases energy usage, which in turn may exacerbate climate change. Many of the cities in developing (sub)tropical countries lack adequate financial, technological and scientific means to effectively research and mitigate these problems, because other more pressing issues of daily survival are more important. On the other hand urban development in this region is often still at an early stage and opportunities exist for climate-sensitive urban design, for which it is necessary to better understand the nature of the climates of these cities.

\* Correspondence to: Matthias Roth, Department of Geography, Faculty of Arts and Social Sciences, National University of Singapore, 1, Arts Link, Singapore. E-mail: geomr@nus.edu.sg

The present paper will first give a review of the problem followed by results from a selection of past observational studies conducted in (sub)tropical cities. One focus will be on heat island work which has received the most attention in the past. The differences in magnitude of peak urban heat island (UHI) intensities compared to the large body of data available from mid-latitude cities, will be discussed in relation to the particular nature of (sub)tropical climates (wet and dry) and moisture availability of the surrounding undeveloped areas. A discussion of the few available energy balance studies follows. The present review does not seek to list and discuss all (sub)tropical urban climate observations ever conducted, rather examples of key studies are given, which enable a summary and generalized picture of urban climate processes in these regions. The ultimate goal of this work is to improve the scientific understanding of urban climates in (sub)tropical areas and provide data and guidance so that the rapidly expanding cities of the developing world can incorporate climatological concerns in their design. For an overview of such applied aspects, which are not covered here in any detail, the reader is referred to the summaries by Givoni (1989, 1991, 1992) and Emmanuel (2005a).

## CONTEXT AND FRAMEWORK

### *Climatological context*

(Sub)tropical regions are characterized by a rich variety of climates in terms of temperature and precipitation. Hence it is necessary to group the data or observations according to similar climate characteristics. For arid regions the potential for evaporation is often used as a qualifier. For tropical climates a useful starting point is the Köppen climate classification system, which also considers seasonality as an important characteristics of (sub)tropical regions. Within the tropics near the equator, the climate is dominated by uniformly high temperatures throughout the year and the seasonal movement of the Hadley cells. According to the Köppen classification (e.g. Köppen, 1900; Aguado and Burt, 2006), it is possible to define a *tropical wet climate* (Köppen classification: *Af*; characteristics: significant rainfall throughout the year; examples of cities include Singapore and Salvador), *tropical wet/dry (savanna) climate* (*Aw*; pronounced dry season; e.g. Mumbai, Miami), *tropical monsoonal climate* (*Am*; relative dryness for 1–3 months; e.g. Monrovia, Jakarta) and a *tropical highland climate* (*H* or *Cwb*; high altitude without which climate would be tropical wet/dry; e.g. Bogota, Mexico City). The subtropical climates have very warm to hot summers, but non-tropical winters with air temperatures which usually do not go below freezing and little rainfall. They include *subtropical desert climate* (*BWh*; low-latitude dry; e.g. Kuwait City, Phoenix), *subtropical steppe climate* (*BSh*; low latitude semi-dry; e.g. Delhi, Ouagadougou) and *humid subtropical climate* (*Cfa*, *Cfb* and *Cwa*; hot, humid summer and no or brief winter dry season; e.g. Shanghai, Porto Alegre).

Common to most urban climate research is the objective to gauge the urban effect as differences between urban and rural conditions. Because in some respects the physical characteristics of cities are quite similar, the likeness of rural characteristics needs to be considered when comparing urban effects from cities in widely different geographic areas. Given the large range of climatic conditions in the (sub)tropics, it is difficult to make generalizations. The surroundings of cities in the tropical wet climates (*A* climates) often include tall, lush vegetation, swamps, paddy fields or other forms of intensive agriculture. In these cases the rural areas would be characterized by higher (compared to the city) moisture availability and thermal admittance and lower albedo. Cities in subtropical hot and dry climates (primarily *B* climates) would be surrounded by bare or sparsely vegetated environs, sand or rock areas, scattered trees and shrubs. Here the moisture availability of urban areas depend on water supply. Rural thermal admittance would be lower and albedo higher compared to the urban area (Oke, 1986a). It is clear that moisture availability plays a key role in determining urban-rural thermal and humidity differences. The available studies discussed below are therefore grouped into *(sub)tropical wet* (*Af*, *Aw*, *Am*, *Cfa*, *Cfb*, *Cwa*) and *(sub)tropical dry* (*BSh*, *BWh*, *H*) climate types without further considering any other potential differences between tropical and subtropical settings. Not included are the Mediterranean climates (*Csa* and *Csb*) which are mostly found at latitudes larger than 35°. If additional studies providing a more detailed database become available, a fuller division into *equatorial wet* (*Af*), *tropical wet/dry* (*Aw*, *Am*), *subtropical dry* (*BSh*, *BWh*), *subtropical humid* (*Cfa*, *Cwa*) and *tropical highland* (*H*) may provide a more appropriate framework.

### *Demographic challenge*

The world's urban population continues to grow faster than the total population with about 50% now living in urban areas. Population growth is particularly rapid in the urban areas of less developed regions which are mostly located in the (sub)tropics. Here urban population is growing at an average of 3.5% per year as opposed to less than 1% in more developed regions. Cities in the less developed world are also expected to absorb almost all of the future population growth (Figure 1). Migration from rural to urban areas and the transformation of rural settlements into cities are important determinants of the anticipated high urban population growth (UN, 2006). While estimates regarding the growth of urban population are available, little is known as to how they will compare to the extent, rate of growth and the pattern of physical urban growth. The percentage of urban dwellers that will reside in cities with <500 000 (>1 million) inhabitants is projected to remain unchanged in the near future compared to the present values of 50% (40%) (UN, 2006). By 2030, Asia and Africa will each have more urban dwellers than any other major area, with Asia (incl. China, Japan and Korea) alone accounting for over half of

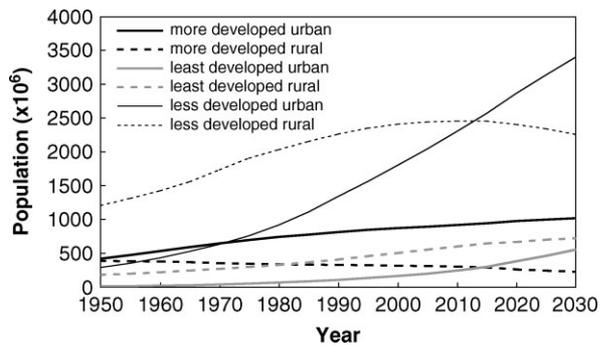


Figure 1. Population living in rural and urban areas in more developed, less developed and least developed regions. Data and projections are from UN (2006). Less and least developed regions include Africa, Asia (excl. Japan), Latin America, Caribbean and Oceania (excl. Australia and New Zealand).

the urban population of the world. Of the 20 megacities (>10 million) identified in 2003, 14 are located in the (sub)tropics of which six grew at rates above 3%: Dhaka (6.2% per year), Lagos (6.1), Delhi (4.1), Karachi (3.7), Jakarta (3.3) and Mumbai (3.1) (UN, 2006). Assuming similar expansion patterns as observed in some tropical Chinese cities, the amount of urban land could double or easily more than double (Seto and Fragkias, 2005).

#### Past reviews

Urban climate-related work has been the topic of a number of past reviews, all lamenting the relative lack of studies carried out in cities located in the (sub)tropics. Inquiry into tropical urban climate also lags behind that for mid-latitude cities. The possibly first tropical urban climate studies reported by Jauregui (1958) and Galindo (1962) about the local increase in turbidity and observations of global radiation in Mexico City were published at a time when comparable temperate work was already investigating the complex spatial and temporal variability and linkages to weather and urban structure. The first process-based work investigated the energy balance of Mexico City and was not carried out until 1985 (Oke *et al.*, 1992), which is roughly 20 years after similar work in temperate cities. Recognizing the enormous expansion in population and degradation in environmental quality in tropical cities a number of conferences and initiatives were conducted in the 1980s and early 1990s. The first such conference in 1984 ('Technical Conference on Urban Climatology and its Applications with Special Regards to Tropical Areas') sponsored by WMO and the Mexican Natl. Meteorol. Service was held in Mexico City and resulted in the still most comprehensive volume on this topic (Oke, 1986b). WMO subsequently launched a major research, training and education initiative, the 'Tropical Urban Climate Experiment' (TRUCE) (Oke *et al.*, 1990/91) which, together with the Mexican Natl. Meteorol. Service, sponsored the 'International Symposium on Urban Climate, Air Pollution and Planning in Guadalajara' which took place in Guadalajara (Mexico) in 1990.

A number of (sub)tropical urban (bio)climate review papers (Jauregui, 1986, 1988, 1993a) and bibliographies

(Jauregui, 1993b, 1996) demonstrate a slight increase in related work from about 2% in the period 1968–1980 to 7% tropical and 4% subtropical in the 1980s (Goldreich, 1992). This upward trend has continued during the last decade but the percentage of (sub)tropical work between 1996–1999 and 2000–2004 is still below 20% on the basis of two most recent urban climate bibliographies (Salmond, 1999, 2005). These low percentages are also reflected in the number of UHI studies carried out. Of the 223 cities used in a comprehensive analysis on the dependence of the UHI intensity on latitude, Wienert (2002) assigns about half to temperate climates, 17% to the tropics (defined between 0°S and 20°N) and an additional 35% to between 20 and 40°S or °N. The actual percentage of (sub)tropical work is probably bigger than implied above. Some of the studies are possibly not captured because they are not published in the English international review literature. In general, however, the percentage of (sub)tropical work is still very small given the size of the problem and potential concerns.

#### RESEARCH DURING THE LAST 10 YEARS (1996–2006)

Some of the research published during the last 10 years is listed below. The studies mentioned provide empirical data yielding important insight into urban thermal environment and atmospheric processes across (sub)tropical regions.

#### Air quality and pollution

The summary is not intended to be exhaustive but rather provides a representative cross-section of available work. It is probably not surprising that about 50% of all (sub)tropical research has concentrated on urban climate-related problems of immediate concern to the local population such as air quality and air pollution/chemistry. These are pressing issues given the intense industrialization occurring in many urban agglomerations in developing countries. A major research focus has been on the high levels of urban air pollutants (e.g. particulates, aerosols, ozone and volatile organic compounds) as a result of emissions from motor vehicles, industrial and domestic activities involving the combustion of fossil fuels. Much work has been conducted in Central and South American cities (Mexico City: Bravo and Torres, 2000; Baumgardner *et al.*, 2004; Sao Paulo: Souza *et al.*, 1999; Coury *et al.*, 2002; de Miranda *et al.*, 2002; Porto Alegre: Grosjean *et al.*, 1999; Buenos Aires: Ulke, 2000; Venegas and Mazzeo, 2000, 2003; Mazzeo and Venegas, 2004) and cities on the Indian subcontinent (Tripathi *et al.*, 1996; Delhi: Varshney and Padhy, 1998; Kanpur: Sharma and Maloo, 2005; Kolkata: Ghose *et al.*, 2005; Hyderabad: Latha and Badarinath, 2005a; various cities: Begum *et al.*, 2004; Gurjar *et al.*, 2004; Mouli *et al.*, 2004). South East Asian cities which have been the focus of extensive air pollution studies include Hong Kong (Chan and Kwok, 2000; Lee *et al.*, 2002; Tanner and

Law, 2003), the Taiwanese cities of Kaohsiung (Chen *et al.*, 2003a; Lin and Lee, 2004) and Taipei (Li and Lin, 2002), urban agglomerations in Thailand (Chueinta *et al.*, 2000) as well as Hong Kong, Bangkok and Jakarta which were the focus of a comparison of total suspended particulate loadings as a function of season (Panther *et al.*, 1999). Less work is available from Africa (e.g. Dar es Salaam: Jonsson *et al.*, 2004; Luanda: Ferreira–Baptista and De Miguel, 2005) and dry subtropical regions outside India (e.g. Phoenix: Doran *et al.*, 2003; Lee *et al.*, 2003).

More recently focus has shifted to air pollution dispersion modelling as demonstrated by air pollution models applied to Hong Kong (Li *et al.*, 2004; Xia and Leung, 2001a,b), Sao Paulo (Guardani, 2004; Ereitas *et al.*, 2005), Delhi (Gokhale and Khare, 2005), Coimbatore (Meenakshi and Saseetharan, 2004) and Kaohsiung (Tsai and Chen, 2004).

#### *Urban heat island*

UHI studies make up less than 20% of (sub)tropical urban climate research. Much of it pertains to the urban canopy layer and is based on standard weather stations which are not always ideal to monitor the urban temperature. The section on Urban Heat Island Studies below provides a more detailed review and synthesis of some of the work including older studies. Locations of recent UHI studies include in (1) *equatorial wet* climates Singapore (Tso, 1996; Nicol, 1996, 1998; Goh and Chang, 1999; Wong *et al.*, 2005; Chow and Roth, 2006); Kuala Lumpur (Tso, 1996), (2) *tropical wet/dry* climates Bangkok, Manila, Ho Chi Minh City (Hung *et al.*, 2006), Mumbai (Kumar *et al.*, 2001), Puerto Rico (Gonzalez *et al.*, 2005; Velazquez–Lozada *et al.*, 2006), (3) *tropical highland* climates Mexico City (Jauregui, 1997, 2005; Jauregui and Luyando, 1998), Guadalajara (Tereshchenko and Filonov, 2001), (4) *subtropical humid* climates Shanghai (Ding *et al.*, 2002; Chen *et al.*, 2003b), Hong Kong (Giridharan *et al.*, 2004, 2005; Nicol and Wong, 2005) and Buenos Aires (Figuerola and Mazzeo, 1998; Bejaran and Camilloni, 2003) and (5) *subtropical dry* climates Pune (Deosthali, 2000), Tuscon (Comrie, 2000), Phoenix (Brazel *et al.*, 2000; Hawkins *et al.*, 2004 and Fast *et al.*, 2005), Cairo (Rooba, 2003), Ouagadougou (Linden, 2004) and Eilat (Sofer and Potchter, 2006). UHI studies from various climate regions across the globe have been analysed by Wienert and Kuttler (2005). The results indicate a slight dependency of UHI intensity on latitude with lower values in the tropics (mean of  $\sim 4^{\circ}\text{C}$ ) which are increasing towards the temperate climate regions ( $\sim 6.1^{\circ}\text{C}$ ). They conclude that increased production of anthropogenic heat in the higher latitudes and differences in the surface energy balance are able to explain some of the observed increase with latitude. Their study does not, however, consider other relevant variables such as, for example heating/cooling degree days and differences in surface moisture of the undeveloped, rural environs which might be expected to

underlie any global patterns (see below). Of the studies reviewed only very few have employed remote sensing techniques to monitor the UHI (Nicol, 1996, 1998; Gonzalez *et al.*, 2005; Hung *et al.*, 2006).

#### *Urban design and human comfort*

Climate-sensitive design is crucial for human health and comfort especially in urban agglomerations located in the naturally extreme and often oppressive climates of the (sub)tropics. It is therefore surprising that only about 10–15% of the (sub)tropical urban climate literature deals with this topic. The available work is primarily concerned with the influence of the built form (geometry, height-to-width of street canyons) to promote ventilation, building materials and colour as means to reduce the absorption of solar radiation and storage of heat as well as the role of vegetation for shading and evaporative cooling to moderate the thermal and moisture climate. Studies were conducted in the following climate types and cities: (1) *equatorial wet* Colombo (Emmanuel, 2003, 2005a,b; Emmanuel and Johansson, 2006), Sao Paulo (Ribeiro, 2005) and Singapore (Wong *et al.*, 2003; Wong and Yu, 2005; Chen and Wong, 2006), (2) *tropical wet/dry* Belo Horizonte (Sad de Assis and Frota, 1999), (3) *tropical highland* Mexico City (Jauregui *et al.*, 1997) and (4) *subtropical dry* San Juan, Argentina (Papparelli *et al.*, 1996), Gaborone (Jonsson, 2004), Fez, Morocco (Johansson, 2006), various cities in Algeria (Ali–Toudert *et al.*, 2005; Ali–Toudert and Mayer, 2006), Dimona, Israel (Pearlmutter *et al.*, 2007a) and various settlements in the Negev desert of Israel which are reviewed by Pearlmutter *et al.* (2007b) with special attention given to the relationship between urban geometry and thermal stress.

#### *Urban boundary layer*

Reflecting a general trend in urban climate research, above-rooftop observations in the urban boundary layer are relatively rare: Ulke and Mazzeo (1998), Salcido *et al.* (2003) and Mok and Rudowicz (2004) investigated the height of the mixing layer over Buenos Aires, Mexico City and Hong Kong, respectively. Doran *et al.* (1998) conducted a comprehensive boundary layer study on the thermally and topographically driven flow patterns in the mixed layer of Mexico City using radar wind profilers, sodars and radiosondes. Doran *et al.* (2003) and Lee *et al.* (2003) studied the vertical mixing properties of ozone during a morning transition period in Phoenix and Nair *et al.* (2004) used a Dopplar sodar in Sao Paulo to observe the wind and temperature field. Using laser radar, spectroradiometer and pibal balloons Raj *et al.* (1997), Devara *et al.* (1998) and Tiwari *et al.* (2003) investigated the long-term nocturnal planetary boundary layer (PBL) and aerosols characteristics in Pune (India). Finally, Hua *et al.* (2004) and Tong *et al.* (2005) performed a numerical simulation of air pollution dispersion in the atmosphere over Hong Kong and Liu *et al.* (2001) evaluated a 3-D numerical model using ground-based

climate stations and Lidar observations of an internal boundary layer developing during sea breeze conditions in the same city.

#### *Wind, radiation, moisture, rain and carbon dioxide*

Other climate variables besides temperature in relation to the UHI have received relatively little attention. Bourbia and Awbi (2004) have analysed the relationship between surface and air temperatures in a canyon with different orientations and height-to-width ratios in El Qued, Algeria. Surface and air temperatures as well as net radiation over various urban surface types have also been reported for Ouagadougou (Offerle *et al.*, 2005). Wind and ventilation conditions have been studied in Phoenix (Brazel *et al.*, 2005), Sao Paulo (Oliveira *et al.*, 2003) and Buenos Aires (Ulke, 2004). Latha and Badarinath (2005b) comment on solar radiation attenuation due to aerosols in Hyderabad. Rasul *et al.* (2004) in Islamabad and Jauregui and Romales (1996) in Mexico City have analysed heavy rain events and long-term precipitation increase and Shepherd (2006) in Phoenix and Riyadh urban induced rainfall in arid cities. Humidity and evaporation in relation to the UHI intensity and other climatic variables have been explored in Mexico City (Jauregui and Luyando, 1998) and in relation to vegetation in Gaborone (Jonsson, 2004). Deosthali (2000) and Jauregui and Tejada (1997) have observed higher absolute humidity associated with the UHI during the dry season in Pune (India) and in Mexico City, respectively.

Various climatological variables were measured as part of a comprehensive full-scale experiment investigating the thermal exchange of pedestrians with the street canyon environment by Pearlmutter *et al.* (1999) in Dimona (Israel). Using an outdoor scale model Pearlmutter *et al.* (2005, 2006) investigated the microclimate and energy balance of an urban canopy in an arid environment. Turbulent transfer has been studied by Yadav *et al.* (1996) at a semi-urban site in Delhi and by Tsai and Tsuang (2005) in urbanized Dunhe (Taiwan). More recently carbon dioxide concentrations have been measured in Phoenix (Balling *et al.*, 2001; Day *et al.*, 2002 and Idso *et al.*, 2001) and Kuwait City (Nasrallah *et al.*, 2003) and carbon dioxide fluxes have been measured in Mexico City (Velasco *et al.*, 2005).

### URBAN HEAT ISLAND STUDIES

Similar to temperate climates, the UHI has been an intensely studied urban climate phenomenon. The probably first UHI study in a tropical location documented in the English literature was carried out in Singapore in 1964/65 (Nieuwolt, 1966). Sham Sani subsequently pioneered a number of studies in Malaysia which is also located in the humid tropics. Results from a short-term (2 days) study carried out in 1972 in Kuala Lumpur demonstrated that the urban core was generally warmer and drier than the countryside and large

open areas (Sham, 1972). These findings were confirmed by additional mobile measurements (Sham, 1973). Research carried out in Malaysia during the subsequent two decades is summarized in Sham (1984) who notes an increase in maximum UHI intensity between 1972 and 1980 and reduced (compared to mid-latitude regions) significance of wind speed in controlling the nighttime UHI and in Sham (1990/91) which includes a discussion of the implications of the major findings on planning and building design. The 1970s and subsequent decades also saw a proliferation of UHI and urban humidity studies in India. Locations include the tropical wet/dry cities Mumbai (Mukherjee and Daniel, 1976; Kumar *et al.*, 2001), Calcutta (Padmanabhamurty, 1986), Madras (Sundersingh, 1990/91) and Visakhapatnam (Padmanabhamurty, 1986) and the subtropical dry cities Delhi (e.g. Bahl and Padmanabhamurty, 1979; Padmanabhamurty and Bahl, 1982) and Pune which saw the first Indian UHI study in 1973 (Padmanabhamurty, 1979; Deosthali, 2000). Much of the early Indian research has been summarized by Padmanabhamurty (1986). The 1970s and 80s represent the most active period for UHI research in the (sub)tropics. Additional work for cities in South America and Africa has been summarized by de Figueiredo Monteiro (1986) and by Oguntoyinbo (1986) and Goldreich (1992), respectively.

The observations described above and in other studies not mentioned here show general similarities to results from temperate cities. They confirm that morphology of the UHI for example is sensitive to building density (higher UHI intensity is associated with densely-packed CBD areas of large cities) or landuse (cooler temperatures associated with the existence of parks). Differences in UHI morphology or intensity between cities can be traced to special features such as water availability or building material which would lead to similar variability in temperate cities (Oke, 1986a). Therefore geometry and thermal properties are also important factors in determining urban-rural thermal contrasts in the (sub)tropical context together with moisture availability of the rural surroundings as will be demonstrated below. In the following observations of the seasonal variability of the UHI intensity and its relationship with population are examined in more detail.

#### *Seasonal variability of UHI intensities*

Long-term observations from rural-urban station pairs can be used to assess the seasonality of the UHI intensity and hence the influence of rural moisture variations throughout the year. Nocturnal data from a range of (sub)tropical cities are plotted in Figure 2 and experimental conditions are summarized in Table I. Observations in these studies were taken at the time of the minimum temperature which usually occurred towards the end of the night. The exception is the data for Singapore which refers to observations at the time of the maximum UHI intensity which, however, was usually also observed after midnight (Chow and Roth, 2006). A marked seasonal variation is evident in

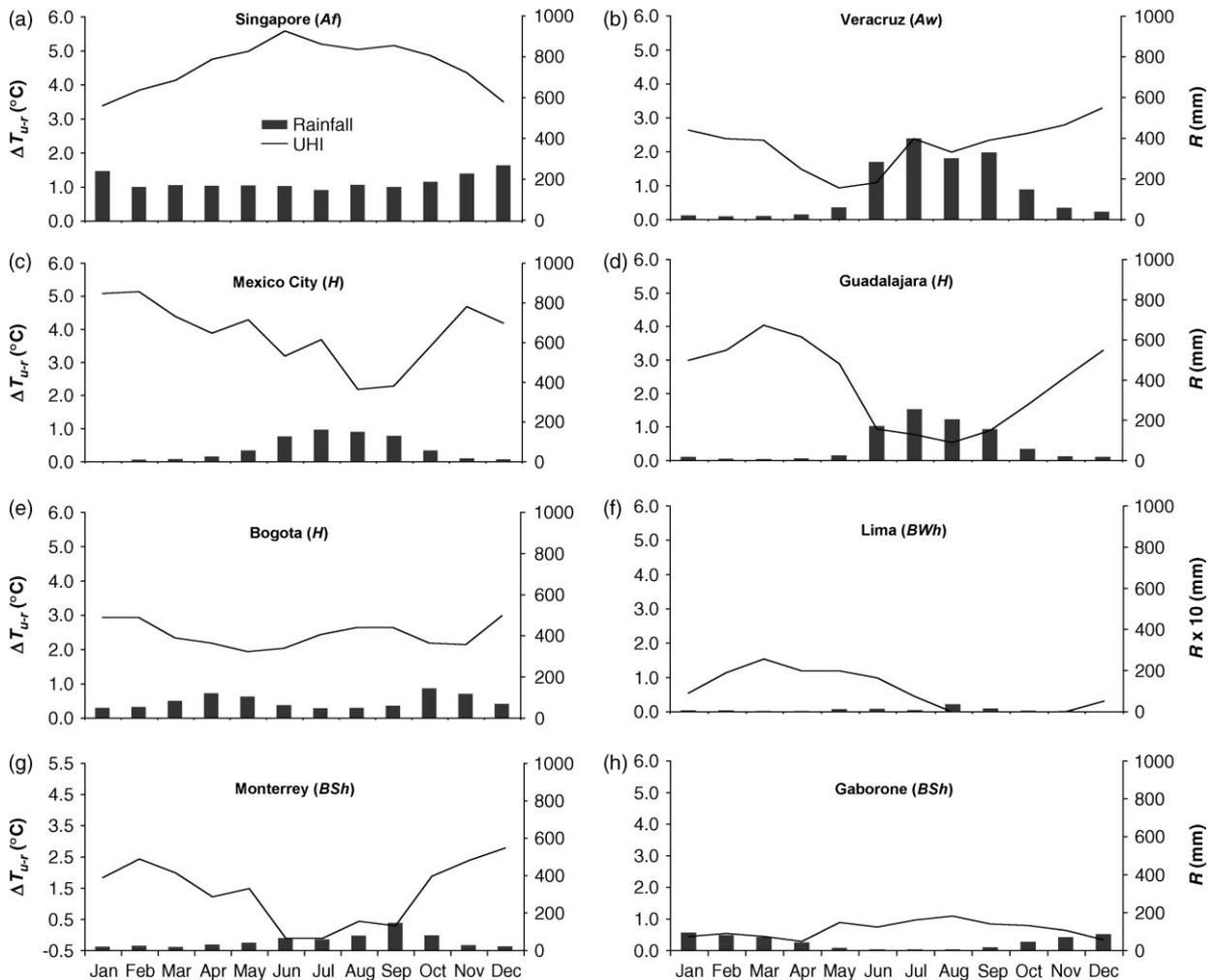


Figure 2. Seasonal variation of mean monthly nocturnal urban heat island intensity ( $\Delta T_{u-r}$  in  $^{\circ}\text{C}$ ) and climatological mean monthly rainfall ( $R$  in mm) for various cities in the (sub)tropics. Values are measured at the time of daily minimum temperature with the exception of Singapore where value is at time of maximum heat island intensity. Letters in brackets after city name denote Köppen classification (see text). Details of individual observations are provided in Table I.

all cities and the largest UHI intensities are usually measured during the dry season. This seasonal variation can even be observed in the case of Singapore (Figure 2(a)). Despite being characterized by uniformly high rainfall throughout the year the maximum (minimum) UHI values are clearly associated with the relatively drier (wetter) SW (NE) monsoon season. The same observation has been reported by Sham (1987) in Kuala Lumpur (Malaysia) ( $3^{\circ}\text{N}$ , *Af*). The UHI of Veracruz, a tropical city with a pronounced dry season, shows similar seasonal variation which is possibly modulate by particular wind patterns induced by the coastal location of this city (Figure 2(b)). The three cities with tropical highland climates show either a very pronounced seasonality (Mexico City and Guadalajara; Figure 2(c) and (d)) or little variation (Bogota; Figure 2(e)). Jauregui (1986) suggested that the small amplitude in the case of cities located near the equator such as Bogota could be due to the dry/wet seasonal rhythm which is less differentiated. This explanation, however, does not apply to Singapore which has a pronounced seasonal UHI variation and the highest mean monthly UHI intensity ( $5.7^{\circ}\text{C}$ ) of all cities included

(Figure 2(a)). Urban–rural seasonal thermal changes are also evident in dry climates. Here the UHI intensity is relatively less compared to the previous examples but both cities included, Monterrey in the Northern Hemisphere (Figure 2(g)) and Gaborone in the Southern Hemisphere (Figure 2(h)), exhibit clear seasonal variations. The same is true for the desert city of Lima where the little rainfall during the late summer is capable of diminishing the UHI intensity (Figure 2(f)). Dry season maximum mean monthly nocturnal UHI intensities of  $\sim 3^{\circ}\text{C}$  have further been observed in Ouagadougou ( $^{\circ}\text{N}$ , *BSh*) for 1992–2000 (Jonsson *et al.*, 2002) and  $\sim 3.5^{\circ}\text{C}$  in Dar es Salaam (Tanzania) ( $7^{\circ}\text{S}$ , *Aw*) in 2001 (Jonsson *et al.*, 2004). In both cities the wet season values were either very small or sometimes even negative (Ouagadougou). Oguntoyinbo (1986) and Goldreich (1995) also reported similar UHI variation with seasons for Ibadan (Nigeria) ( $7^{\circ}\text{N}$ , *Aw*) and small settlements located in the arid parts of Israel, respectively.

The marked seasonal variation observed in Figure 2 and other studies is probably tied to rural/urban surface moisture characteristics. Oke (1982) and Oke *et al.*

Table I. Summary of observational characteristics of studies used in Figure 2. See text for definition of Köppen classification.

City	Reference	Köppen	Latitude/ elevation (m)	Pop ( $\times 10^6$ )	Year; urban station
Singapore	Chow and Roth (2006)	<i>Af</i>	1°N/10	4	2003–04; canopy layer UHI
Veracruz	Jauregui (1986)	<i>Aw</i>	19°N/35	0.13	1982; location of urban station unknown; coastal city
Mexico City	Jauregui (1997)	<i>H</i>	19°N/2250	~10	1994; urban station above rooftops
Guadalajara	Jauregui (1986); Jauregui <i>et al.</i> (1992)	<i>H</i>	21°N/1600	2.7	1980; urban station above rooftops, semi-rural reference station
Bogota	Jauregui (1986)	<i>H</i>	5°N/2640	2	Unknown; unknown
Monterrey	Jauregui (1986)	<i>BSh</i>	26°N/530	1.4	1961–76; unknown
Gaborone	Jonsson (2004)	<i>BSh</i>	24°S/1000	~0.2	1994–96; data from official climatological stations near small rural airport and on fringe of city
Lima	Jauregui (1986)	<i>BWh</i>	12°S/160	2	Unknown; unknown

(1991) show that geometry and thermal admittance are primarily responsible for generating the nocturnal UHI. Assuming little vegetation cover, the urban cooling potential as a function of canyon geometry does not change much throughout the year. Unlike their urban counterparts, some of the physical properties of the rural surface (e.g. albedo and thermal admittance), however, are subject to considerable seasonal change affecting rural nocturnal cooling. During the rain season for example, when rural surfaces are either wet or saturated, thermal admittance will be increased. As a result the daily surface temperature range will be relatively small and rural cooling decreases with a corresponding reduction in the UHI intensity. Seasonal UHI differences are therefore likely to be strongest in situations where the seasonal contrast in rural moisture properties is large, i.e. in climates with a pronounced dry season.

#### UHI intensity versus population

For mid-latitude climates a relationship exists between the nocturnal canopy-layer maximum UHI intensity measured under clear and calm conditions ( $\Delta T_{u-r(\max)}$ ) and the size of a city measured by its population (Oke, 1973). It should be noted, that population is used as a convenient and widely available surrogate for urban geometry (sky view factor) which has been shown to be the important control on heat island intensity under these restricted conditions (e.g. Oke, 1981). The relationship also ignores the additional role of energy consumption per capita (Böhm, 1998). The regression lines for mid-latitude cities from Oke (1973) together with selected (sub)tropical UHI data are plotted in Figure 3. Only UHI values of cities which are not affected by unusual topographic settings and effects (e.g. valley or ridge location, katabatics winds) and where sufficient information about measurements and weather conditions at the time of the observations was available are included. All data represent the canyon-layer UHI and in most cases the values plotted have been gathered from traverses which sample across the UHI to find the spatial peak. All observations have been completed during clear and calm nights

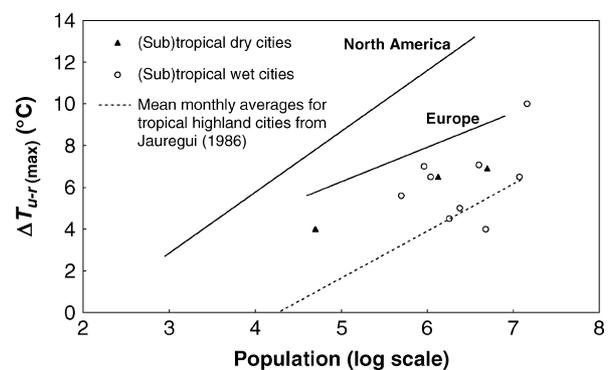


Figure 3. Maximum nocturnal urban heat island intensity measured during clear and calm conditions ( $\Delta T_{u-r(\max)}$ ) versus population for cities in various climatic regions. Solid lines are regressions through temperate cities (North America and Europe) taken from Oke (1973), symbols are for (sub)tropical wet (*Af*, *Aw*, *Am*, *Cfa*, *Cwa*) and (sub)tropical dry (*BSh*, *BWh*, *H*) cities taken from sources discussed in the text and the dashed line is a fit through maximum mean monthly urban heat island data from (sub)tropical cities located primarily in tropical highland climates (*H*) published by Jauregui (1986).

(often towards the end of the night) during the dry season, i.e. the time of maximum UHI development. Both inland and coastal cities are included. The (sub)tropical data are divided into two groups representing wet and dry climate regimes, respectively (see above). The data indicate some degree of relationship with population, and  $\Delta T_{u-r(\max)}$  values are smaller compared to those from temperate cities of comparable size. Given the lack of data points, it is not possible to conclude if this reduction is indeed more pronounced for (sub)tropical wet cities. Given reduced nocturnal radiative cooling associated with humid air and the reduced cooling potential of reference stations because of the relatively wetter rural surfaces, cities in (sub)tropical wet climates could potentially experience more limited UHI development.

Jauregui (1986) made the first attempt to add (sub)tropical data to the Oke (1973) relationship. For completeness they are also shown in Figure 3 (dashed line). It should be noted, however, that Jauregui's values are mean monthly UHI intensity measured at the time of the minimum temperature and were obtained from

fixed urban-rural climatological station pairs including all weather conditions. Given the very different experimental conditions under which these data have been collected, direct comparison with  $\Delta T_{u-r(\max)}$  data is not possible. Jauregui's data probably underestimate the maximum UHI intensity possible but they nevertheless show an increasing trend with increasing population (Figure 3).

## ENERGY BALANCE STUDIES

### *Ensemble energy balance*

The nature of physical climatology of (sub)tropical cities has received little attention in the past. Process-based studies, however, are necessary to be able to understand the observed urban-rural differences and other aspects of the urban climate such as for example, the heavy pollution often associated with cities in the developing world. The differential warmth of the urban atmosphere is a function of urban/rural energy-source and energy-partitioning differences (Oke, 1973). It is therefore not surprising that the presently available work has primarily focussed on the surface energy balance. The probably first indication of the nature of physical climatology in a (sub)tropical city has been provided by Oke *et al.* (1992) based on a pioneering study conducted at an urban site in Mexico City in 1985. Since then about eight studies with

results published in the English peer-reviewed literature have been conducted in (sub)tropical cities (Table II).

A selection of available results is plotted in Figure 4. In most cases the field sites are predominately residential with detached one- and two-story houses and some vegetation surrounding the buildings. The exception is the downtown site in Mexico City (SM93). All studies neglect any potential anthropogenic heat contribution and all observations have been conducted during the respective dry period under mostly clear sky conditions with the exception of Miami (Mi95) which represent conditions at the beginning of the wet period. The two Mexico City sites demonstrate how much the energy partitioning depends on the actual site characteristics. Considerable latent heat flux ( $Q_E$ ) is measured at Ta85 which is located in an area consisting of mixed residential, commercial and industrial land-use with some vegetation (Figure 4(a)). On the other hand, at the densely-built urban SM93 site with very little vegetation conduction or heat storage ( $Q_S$ ) dominates over sensible heat flux ( $Q_H$ ) as a result of the high thermal inertia of the immediate site surroundings (Figure 4(b)). As expected the two cities in arid climates show large magnitudes of mean daytime  $Q_H$  (Figure 4(c) and (d)). In both cases the measurement location was within a residential neighbourhood. The higher proportion of greenspace and additional irrigation cause the relatively large latent  $Q_E$  values until

Table II. Summary of (sub)tropical urban energy balance studies.  $Q_E$ —latent heat flux density,  $Q_S$ —storage heat flux density; EC – eddy covariance technique.

Year (dates)	City (code)	Reference	Köppen	Latitude/elevation (m)	Comments
1985 (3 Feb–31 March)	Mexico City (Ta85)	Oke <i>et al.</i> (1992)	<i>H</i>	19°N/2250	Tacubaya site; dry period; $Q_S$ parameterized, $Q_E$ as residual
1990 (10–23 June)	Tuscon (Tu90)	Grimmond and Oke (1995, 1999)	<i>BWh</i>	32°N/720	13% rain days during intensive observation period (IOP); all turbulent fluxes from EC
1993 (1–7 Dec)	Mexico City (SM93)	Oke <i>et al.</i> (1999)	<i>H</i>	19°N/2250	School of Mines site; dry period; all turbulent fluxes from EC
1995 (16–19 May, 28 June–3 July)	Mexico City	Barradas <i>et al.</i> (1999)	<i>H</i>	19°N/2250	Suburban vegetated (University reserve); turbulent fluxes measured with Bowen ratio approach; end dry beginning wet season
1998 (1–14 Dec)	Mexico City (PS98)	Tejeda–Martinez and Jauregui (2005)	<i>H</i>	19°N/2250	Preparatory School No 7; all turbulent fluxes from EC
1999 (21 May–21 June)	Miami (Mi95)	Grimmond and Oke (1999); Newton <i>et al.</i> (2000, 2007)	<i>Aw</i>	26°N/0	Beginning of wet period; all turbulent fluxes from EC
2001 (18–22 March)	Mexicali (Me01)	Garcia–Cueto <i>et al.</i> (2003)	<i>BWh</i>	32°N/25	Dry period, cloudless; all turbulent fluxes from EC
2003 (8–20 Feb)	Ouagadougou (Ou03)	Offerle <i>et al.</i> (2003, 2005)	<i>BSh</i>	12°N/300	Dry period, dusty, mostly clear; all turbulent fluxes from EC

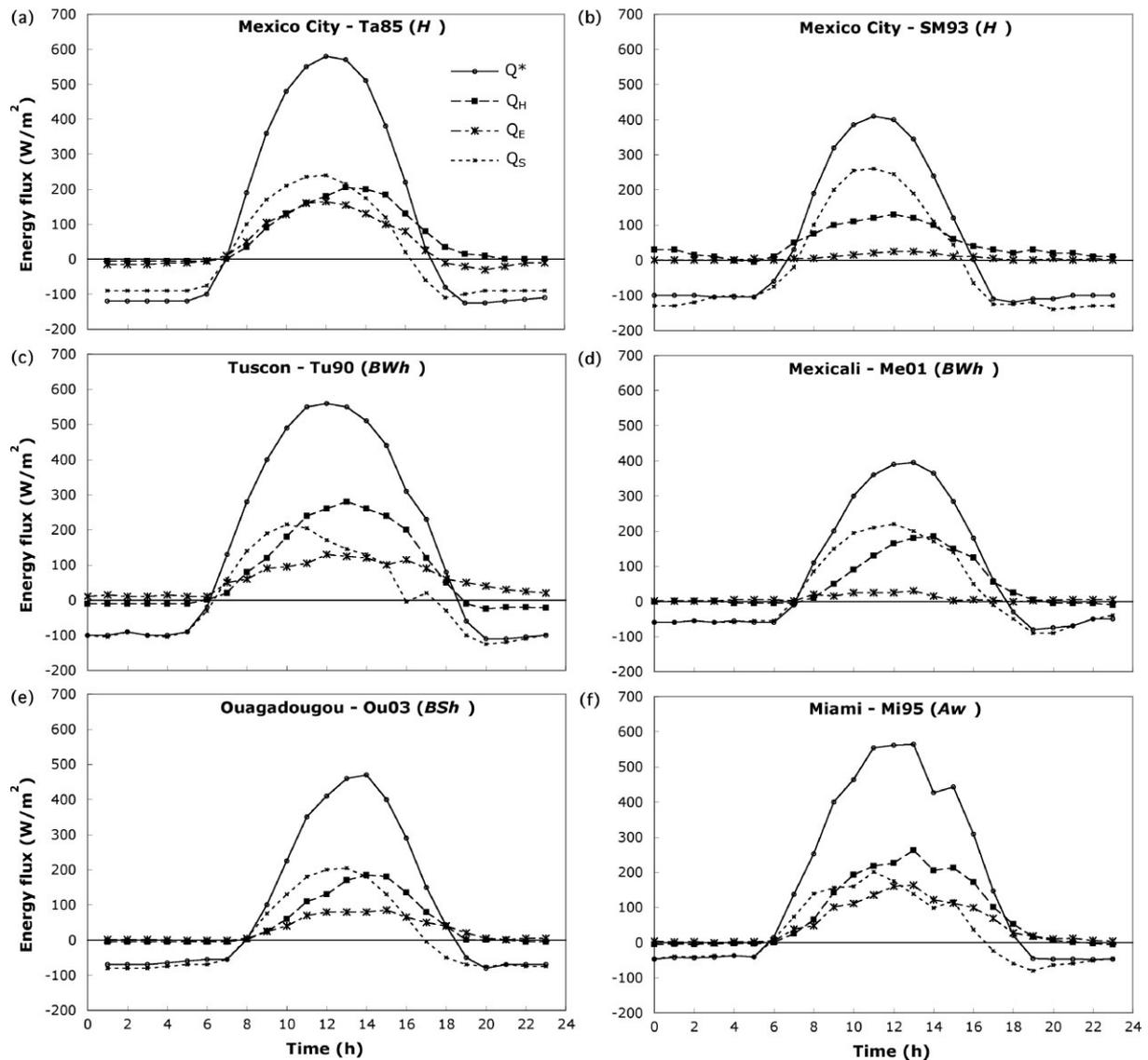


Figure 4. Ensemble average of surface energy balance for (sub)urban sites in a range of (sub)tropical climates under primarily dry and clear conditions. Codes, dates, experimental conditions and data sources are given in Tables II and III.  $Q^*$  – net radiation flux density,  $Q_H$  – sensible heat flux density,  $Q_E$  – latent heat flux density,  $Q_S$  – storage heat flux density.

late into the evening at Ta85 which reduces the amount of available energy available for storage compared to Me01. Similar to the examples from *BWh* climates, the energy exchange at Ou03 is also dominated by  $Q_H$  and  $Q_S$  (Figure 4(e)). In response to 10% tree cover, the  $Q_E$  flux is significant and cannot be neglected. The energy balance at Mi95 is similar to that measured in residential areas in temperate climates (Figure 4(f)).  $Q_E$  is smaller than anticipated for a tropical wet place, possibly because of reduced evaporation due to low vapour pressure deficits in this humid climate. Similar to mid-latitude cities, the mean peak of  $Q_H$  occurs in all cases in the early afternoon (between 12 and 14 h). All cities also show a hysteresis pattern between  $Q_H$  and  $Q^*$ , with enhanced  $Q_H$  in the afternoon relative to the morning. The magnitude of  $Q_E$  varies widely as a function of moisture availability at the surface depending on the amount of vegetation and irrigation patterns. When  $Q_E$  is very low  $Q_S$  becomes more important.

#### Ensemble energy flux ratio

To allow direct comparison of trends between cities which are not biased by the absolute magnitude of fluxes or different climate zones the ratios of the diurnal energy balance fluxes of above studies are presented in Figure 5. The data included represent mostly dry season and clear sky conditions. Only ratios based on directly measured fluxes (i.e. using eddy-covariance technique) are included. The daytime  $Q_H/Q^*$  ratios are closely matched in all cities surveyed despite the fact that they include sites with no vegetation (SM93), are located in arid zones (Me01) or represent a tropical wet climate (Mi95) (Figure 5(a)). As already noted by Oke *et al.* (1999) a simple relationship between built/green fraction, water availability and  $Q_H/Q^*$  does not seem to exist. The strong hysteresis pattern noted in Figure 4 is also evident in Figure 5(a). The values at around sunrise and sunset in Figure 5 are unusually large because they

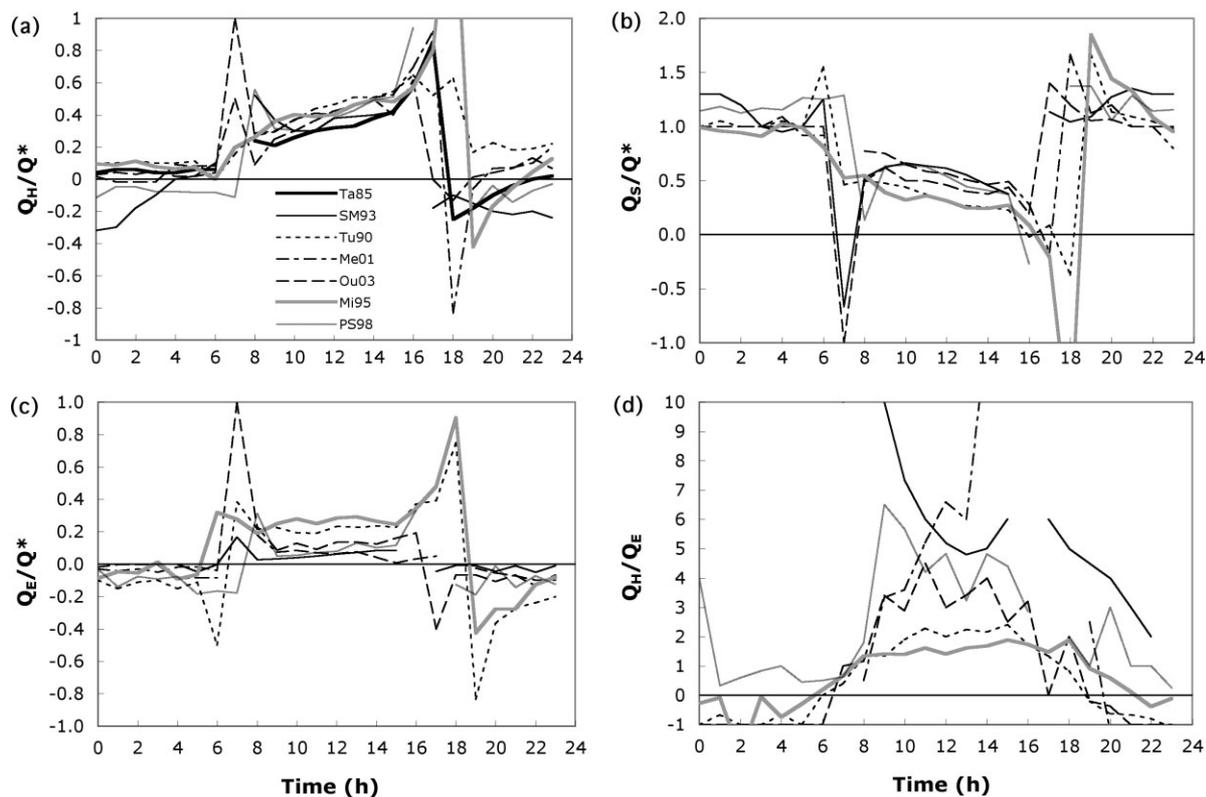


Figure 5. Diurnal patterns of (a)  $Q_H/Q^*$ , (b)  $Q_S/Q^*$ , (c)  $Q_E/Q^*$  and (d)  $Q_H/Q_E$  under primarily dry and clear conditions for the (sub)tropical cities plotted in Figure 4 and summarized in Table III. Codes, dates, experimental conditions and data sources are given in Tables II and III. Only data with directly measured turbulent fluxes are included.  $Q^*$  – net radiation flux density,  $Q_H$  – sensible heat flux density,  $Q_E$  – latent heat flux density,  $Q_S$  – storage heat flux density.

involve ratios with very small fluxes and can therefore be ignored. After sunset most ratios turn negative for some time indicating continuing positive sensible heat fluxes into the early evening. Only the two urban sites in Mexico City (SM93 and PS98) maintain positive sensible heat fluxes throughout the night. Variation in the energy partitioning amongst the sites is larger for  $Q_E/Q^*$  and  $Q_S/Q^*$  (Figure 5(b) and (c)). During daytime the amount of greenspace and water availability determines how much of the available energy is dissipated as  $Q_E$  with the remaining energy conducted into the ground. This inverse relationship can be clearly seen in the data for Mi95 or Tu90 which are locations characterized by relatively large amounts of vegetation and SM93 with no vegetation (Table III). Mi95 and Tu90 have the lowest (largest)  $Q_S/Q^*$  ( $Q_E/Q^*$ ) ratios, whereas the opposite is true for SM93. The critical influence of water availability or surface wetness (either as a result of human activity or due to rainfall) on the relative partitioning of the two turbulent heat fluxes is further demonstrated by the daily course of the Bowen ratio ( $\beta$ ) (Figure 5(d)). It is perhaps surprising that even for a tropical wet/dry location such as Mi95 at the beginning of the wet season, daytime  $\beta$  is larger than unity.

The mean daytime flux ratios of the studies included in Figure 5 are summarized in Table III. The data confirm the control of vegetation and water availability over the latent heat flux (i.e.  $Q_E/Q^*$  increases with increasing

fraction of vegetated land-use). Because  $Q_H/Q^*$  is relatively constant amongst all sites, dry locations experience increased heat storage uptake. Compared to typical values reported from temperate cities, the present (sub)tropical data from primarily dry season conditions are similar for  $Q_H/Q^*$  and  $\beta$  and experience less partitioning of  $Q^*$  into  $Q_E$  and more into  $Q_S$  (Table III).

#### SUMMARY AND CONCLUDING REMARKS

The total number of (sub)tropical urban climate studies is still small (<20% of all urban climate studies). This is unfortunate given the explosive growth of the urban population and cities in the less developed world which are almost exclusively located in (sub)tropical climates. The available work is further biased towards descriptive studies (e.g. of the UHI) rather than process work (e.g. energy balance studies) that seeks to indicate the physical climatology of (sub)tropical cities. (Sub)tropical climates encompass a wide range of cities located in the extreme dry (*BWh*; e.g. Lima) to the continuously wet (*Af*; e.g. Kuala Lumpur). The available data covers a large portion of the (sub)tropical climate types. There is, however, a lack of studies from tropical hot/wet climates which in 2003 were home to 9 of the 20 cities with more than 10 million inhabitants (UN, 2006) and which will experience a disproportionate amount of the projected urban growth. Much of the available observations are

Table III. Flux ratios for daytime (dry and clear) conditions at the (sub)tropical cities plotted in Figure 5. All quantities are non-dimensional. Only data with directly measured turbulent fluxes are included. See Table II for additional information on individual studies.  $Q^*$  – net radiation flux density,  $Q_H$  – sensible heat flux density,  $Q_E$  – latent heat flux density,  $Q_S$  – storage heat flux density,  $\beta$  – Bowen ratio.

City (code)	Köppen	Land-use (stories; % vegetated)	$Q_H/Q^*$	$Q_S/Q^*$	$Q_E/Q^*$	$Q_H/Q_E$ ( $\beta$ )
		Rural <sup>a</sup>	0.28	0.15	0.57	0.1–1.5
		Suburban <sup>a</sup>	0.39	0.22	0.39	0.25–2.5
		Urban <sup>a</sup>	0.44	0.27	0.29	0.4–>4
Mexico City (Ta85)	<i>H</i>	Dense urban mixed (1–2; <10%)	0.34	–	–	–
Mexico City (SM93)	<i>H</i>	Dense urban (1–2; 1% <sup>b</sup> )	0.39	0.56	0.06	7.4
Mexico City (PS98)	<i>H</i>	Urban-residential mix (1–3; <2%)	0.41	0.48	0.11	4.4
Tuscon (Tu90)	<i>BWh</i>	Residential (1, 28% <sup>b</sup> )	0.45	0.25	0.3	1.7
Mexicali (Me01)	<i>BWh</i>	Residential (2–4; <10%)	0.4	0.56	0.07	7.3
Ouagadougou (Ou03)	<i>BSh</i>	Residential (1; 10%)	0.41	0.44	0.14	3.1
Miami (Mi95)	<i>Aw</i>	Residential (1–2; 26% <sup>b</sup> )	0.40	0.33	0.27	1.5

<sup>a</sup> Values from Oke (1982).

<sup>b</sup> Plan-area vegetated from Grimmond and Oke (1999).

from the dry season probably because of the relative ease to carry out observations under such conditions. There is also an obvious shortage of data from cities in Africa reflecting a lack in economic development and focus on issues of immediate daily survival in this part of the world.

On the positive side the available results allow for a comparison with data from temperate latitudes and some preliminary conclusions. The UHI studies show:

1. Seasonal variation of mean monthly nocturnal UHI with lower (higher) intensities during the wet (dry) season.
2. Generally lower nocturnal maximum UHI intensities compared to those of temperate cities with comparable population.
3. (Sub)tropical population-based relations for nocturnal maximum UHI intensities may exist but insufficient appropriate data are available to confirm a logarithmic relationship or systematic differences between different climate types. Increased scatter compared to mid-latitude data for cities with a pronounced wet/dry cycle, may be due to rural wetness differences during the time of observation. Besides differences in urban morphology, variations in the nature of the rural reference environment selected, observation procedure and time of measurement prevent firm conclusions.

Tropical energy balance studies are biased towards dry, clear sky conditions and show the following general features:

1. The amount of net radiation dissipated by sensible heat during daytime is about 40 (33–45)% which is similar to values observed in (sub)urban areas of cities located in temperate climates; all cities show an often pronounced hysteresis pattern between  $Q_H$  and  $Q^*$ .

2. Energy partitioning is modulated by water availability; higher percentage of vegetation promotes latent heat flux at the expense of surface heat storage.
3. The results show resemblance to similar data from temperate cities differing only in magnitude and/or relative importance in response to special features (e.g. water availability) which would lead to similar variability in temperate cities.

Only a rudimentary understanding of the physical processes operating in the atmosphere of (sub)tropical climates is available. Because of the limited range of urban morphologies of the cities studied, the role of building density and material for example, cannot be explored in detail. The apparent strong influence of vegetation and water availability on the energy partitioning irrespective of the climate type, however, is an important result. Vegetation seems to be an useful way to reduce heat storage uptake during daytime and hence has the potential to effectively mitigate the nocturnal heat island.

In conclusion, it is important to ensure that the rapidly expanding cities of the developing world incorporate climatological concerns in their design to provide a better living and working environment for a large segment of the world's inhabitants. Cities in (sub)tropical climates will further be at the centre of the climate change debate because they will lead future urban growth, are major producers of the greenhouse gases thought to be responsible for global warming and emit vast amounts of other pollutants. They are likely to be significantly impacted by global climate change in the future but on the other hand are poorly placed to cope with climate change impacts. (Sub)tropical urban climate studies are therefore in need of a heightened profile in the scientific research community. It is important to plan new large projects in these very significant and highly populated cities. There is a need to establish long-term measurement programs to monitor the exact nature of (sub)tropical urban climates.

It is also necessary to quantify the anthropogenic carbon dioxide contributions by these rapidly growing cities through direct measurements as recently started in Mexico City (Velasco *et al.*, 2005). In this respect simple and cheap equipment should be made available to researchers across cities in the developing world for routine monitoring and a few well-defined, short-term, international research programs should investigate the physical processes and the anthropogenic contribution to the global carbon budget of a few key cities.

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