Science of the Total Environment 512–513 (2015) 582–598

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions

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HIGHLIGHTS

- We report data of Urban Heat Island Intensity and Characteristics for 101 Asian and Australian Cities and Regions.
- The relationship between UHI intensity and population is examined.
- The influence of the weather parameters is investigated.
- The daily and seasonal variations of UHI intensity are analyzed.

ARTICLE INFO

Article history:
Received 22 December 2014
Accepted 20 January 2015
Available online 31 January 2015

Editor: P. Kassomenos

Keywords:
Urban heat island
Asian cities
Australian cities
Heat Island and Population

ABSTRACT

Urban heat island is the more documented phenomenon of climate change. Information on the magnitude and the characteristics of the canopy layer urban heat island measured in 101 cities and regions of Asia and Australia and collected through 88 scientific articles, are compiled, evaluated and presented. Data are classified in several clusters according to the experimental protocol used and the type of statistical information reported regarding the magnitude of the urban heat island. Results and detailed analysis are given for each defined cluster. Very significant differences on the UHI intensity are found between the clusters and analyzed in detail. The detailed impact of the main weather parameters and conditions on the magnitude of the UHI is also investigated. The specific influence of anthropogenic thermal fluxes as well as of the urban morphological and construction characteristics to UHI is thoroughly examined. The relation between the UHI intensity and the city size is assessed and global relationships of UHI as a function of the urban population are proposed. The seasonal and diurnal variability of the UHI is analyzed and discussed while specific features and conditions like the urban heat island characteristics in coastal cities and the existence of daytime cool islands are explored. Finally, the impact of the selected reference station and its characteristics is considered.

1. Introduction

Urban heat island phenomenon deals with the development of higher ambient temperatures in cities compared to the surrounding rural and suburban areas (Santamouris, 2001). The magnitude of the urban heat island is a function of the urban layout, materials' characteristics, synoptic weather and climate conditions, local meteorological factors, physical, structural and morphological characteristics of the cities and anthropogenic heat released while it also strongly depends on the selection of the reference rural measuring station (Oke et al., 1991).

Urban heat island has a serious impact on the energy consumption of buildings during the summer period and increases highly the cooling energy consumption and the corresponding peak electricity demand (Santamouris, 2014a; Santamouris et al., in press). In parallel, it is associated with an important increase of the concentration of urban pollutants and in particular of the tropospheric ozone (Stathopoulou et al., 2008), serious comfort, health and mortality problems (Pantavou et al., 2011; Santamouris and Kolokotsa, in press; Sakka et al., 2012) and finally an important increase of the city's carbon footprint (Santamouris et al., 2007).

Observations and monitoring data of the urban heat island characteristics are available since the beginning of the previous century and even before. Measured data on the characteristics of the near surface canopy layer urban heat island are available for hundreds of cities and in reality for most of the major cities of the world (Santamouris, 2007). In parallel, hundreds of studies are performed aiming to investigate the impact of urban heat island on human health, energy consumption, urban ecology, economy and well being of humans. At the same time, a highly important scientific activity has been initiated aiming to develop advanced mitigation and adaptation technologies and systems to counterbalance the impact of urban heat island. To this end, the issue

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http://dx.doi.org/10.1016/j.scitotenv.2015.01.060

of urban heat island has acquired an interdisciplinary character by involving climatologists, energy experts, material designers, medical scientists, urban designers, environmentalists, etc.

However, a thorough examination of the existing studies opens a serious discussion on the authenticity of the reported measurements, the accuracy and the representativeness of the results, and the overall validity of the scientific conclusions given (Stewart and Oke, 2012). In fact the knowledge on urban heat island is quite rich but is overshadowed by various inconsistencies as related to the performed experimental and theoretical analysis. Diverse monitoring techniques are proposed and employed involving mobile traverses, standard fixed measuring equipment and non-standard fixed observation stations. In parallel, the duration of the reported experiments, the number of measuring stations used, the season the monitoring has taken place, the format of the reported UHI intensity and the methodology to select the reference rural station, vary considerably between the reported studies making quite difficult any interstudy comparison. Recent analysis of many of the existing urban heat island studies (Stewart, 2011), found that almost 75% of the studies failed to report quantitative information on important factors such as site exposure and land cover.

The response to the above questions is not obvious, a fact which leads to a serious need for the systematic analysis of the existing fragmented literature in order to examine and classify existing knowledge in an uncontestable way and comprehensively explain recent scientific findings. The present study aims to analyze in depth the characteristics of UHI experimental studies performed for 101 Asian and Australian cities and regions. The magnitude of the heat island as well as the main parameters influencing the characteristics of the heat island are analyzed and discussed. The overall analysis offers coherent scientific explanations and pertinent results to be used by all relevant scientific disciplines working on the topic of urban heat island.

2. Density of the study

This study presents and analyzes published experimental data on the urban heat island magnitude and characteristics for 101 Asian and Australian cities and regions. It is based on information collected from 88 scientific articles published from 1966 to 2014 in peer review journals, conferences, books, research reports or other original articles published in accredited media. Only articles providing sufficient information on the spatial area considered, the type of experiments and the equipment used are taken into account. Studies not officially published were excluded. Articles published by the same authors in different sources reporting the same experiment were considered when different spatial or temporal data were reported. Many of the considered studies reported experiments and data for more than one city, thus in total the paper includes data from 133 observations performed in the 101 considered cities and regions. The study focuses on canopy layer ground basis observations of the near surface air temperature while articles addressing boundary layer heat island, surface heat islands using remote sensing equipment, subsurface and non-urban heat island are not considered. Only studies aiming to quantify urban heat island based on experimental methodologies are considered while articles investigating urban heat island characteristics using simulation techniques are rejected. The specific cities and regions considered as well the sources of information used for each case study are given in Table 1.

Table 1
Cities and regions and heat island studies in Asia and Australia considered in the present work.

Australia: Adelaide (Erell and Williamson, 2007), Melbourne (Morris et al., 2001; Morris and Simmonds, 2000; Torok et al., 2001), Camperdown (Torok et al., 2001), Colac (Torok et al., 2001), Hamilton (Torok et al., 2001), Hobart (Nunez, 1979), Sydney (Parliament NSW, 2014)
Bahrain: Bahrain (Radhi et al., 2013)
Bangladesh: Dhaka (Ershad and Nooruddin, 1994)
China: Beijing (Miao et al., 2009; Ren et al., 2007; W. Liu et al., 2007; J. Liu et al., 2007; Yu and Fei, 2006), Wuhan (Ren et al., 2007), North East China (Wang et al., 1990a, 1990b), Northern Plains (Wang et al., 1990a, 1990b), Middle Lower China (Wang et al., 1990a, 1990b), South East Coast (Wang et al., 1990a, 1990b), South West (Wang et al., 1990a, 1990b), North West (Wang et al., 1990a, 1990b), Shanghai (Cui et al., 2007; Zhao et al., 2006; Tan et al., 2010; Zhu et al., 2003), Large Cities (Hua et al, 2008), Medium Size Cities (Hua et al., 2008), Small Size Cities (Hua et al., 2008), Six cities in the Liaoning Province (Li et al., 2012), Guangzhou (Mo, 2014), Nanjing (Huang et al., 2008), Shenzhen (Zhang et al., 2008), Xi'an (W. Liu et al., 2007; J. Liu et al., 2007), Urban areas around Yangtze River Delta (Yin et al., 2007), Hong Kong (Giridharan et al., 2004; Giridharan et al., 2005; Giridharan et al., 2004), Suzhou (Zhang et al., 2011)
Japan: Tokyo (Kataoka et al., 2009; Saitoh and Shimada, 1996; Sakakibara and Owa, 2005), Osaka (Kataoka et al., 2009; Nabeshima et al., 2006; Masumoto et al., 2006), Kumamoto (Saito et al., 1990), Kyoto (TakahashI et al., 2004), Tachikawa (Kohji et al., 1986), Fuchu (Kohji et al., 1986), Fussa (Kohji et al., 1986), Higashimurayama (Kohji et al., 1986), Akigawa (Kohji et al., 1986), Sedai (Sakaida, 2014; Sakaida et al., 2011), Nagano Area (Sakakibara and Owa, 2005), Kumagaya (Kuwagata et al., 2014), Hakuba (Sakakibara and Morita, 2002), Matsumoto (Sakakibara and Mieda, 2002), Asashina (Sakakibara and Kitahara, 2003), Akaiwa and Tokida (Sakakibara and Kitahara, 2003), Tomono (Sakakibara and Kitahara, 2003), Koundai (Sakakibara and Kitahara, 2003), Obuse (Sakakibara, 1999), Kofu Basin (Akatsuka et al., 2011), Tsukumba (Kusaka et al., 2011).
India: Delhi (Mohan et al., 2013; Mohan et al., 2013), Guwahati (Borbora and Das, 2014), Pune (Deosthali, 2000), Visakhapatnam (Suryadevara, 2006), Chennai (Sundunndersingh, 1990), Thiruvananthapuram (Ansar et al., 2012), Bhopal (WMO, 1986), Calcutta (WMO, 1986), Mumbai (WMO, 1986), Vijayawada (WMO, 1986), Koshi, (Thomas AND Zachariah, 2011)
Indonesia: Jakarta (Kataoka et al., 2009)
Iran: Teheran (Mousavi-Baygi et al., 2010)
Iraq: Mosul (Turki and Shaheen, 2013)
Israel: Beer Sheva (Goldreich, 1995), Ashdod (Goldreich, 1995; Sharon and Koplowitz, 1972), Netanya (Goldreich, 1995), Tel Aviv (Goldreich, 1995; Saaroni et al., 2000), Eilat (Sofer and Potchter, 2006)
Korea: Seoul (Kataoka et al., 2009; Kim and Baik, 2002; Kim and Baik, 2005; Lee and Baik, 2010; Kim and Baik, 2004; Park, 1986), Incheon (Kim and Baik, 2004), Daejeon (Kim and Baik, 2004), Daegu (Kim and Baik, 2004), Gwanglu (Kim and Baik, 2004), Busan (Kim and Baik, 2004)
Kuwait: Kuwait (Nasrallah et al., 1990)
Malaysia: Kuala Lumpur (Elsayed, 2011; Sani, 1990), Various Cities in Klang Valley (Sani, 1990), Georgetown (Sani, 1990), Johor Bahru (Sani, 1990; Kubota and Ossen, 2014), Kota Kinabalu (Sani, 1990), Muer (Rajagopalan et al., 2014)
Mongolia: Ulaanbaatar (Ganbat et al., 2013)
New Zealand: Christchurch (Tapper et al., 1981; Kingham, 1969)
Oman: Muscat (Charabi and Bakhit, 2011)
Pakistan: Karachi (Sadiq and Ahmad, 2010), Hyderabad (Sadiq and Ahmad, 2010)
Philippines: Manila (Kataoka et al., 2009)
Saudi Arabia: Jeddah (Abdullah and Abar, 1991), Al-Hassa (Alghannam and Al-Qahtnai, 2012)
Singapore: Singapore (Tso, 1996; Nieuwolt, 1966; Chang and Goh, 1998; Wong and Yu, 2005; Rajagopalan et al., 2008; Chow and Roth, 2006)
Sri Lanka: Colombo (Emmanuel, 2005)
Taiwan: Taipei (Kataoka et al., 2009; Lin et al., 2008)
Thailand: Bangkok (Kataoka et al., 2009; Jongtanom et al., 2011), Chiang Mai (Jongtanom et al., 2011), Songkhla (Jongtanom et al., 2011)
Turkey: Izmir (Tayanc and Toros, 1997), Adana (Tayanc and Toros, 1997), Bursa (Tayanc and Toros, 1997), Gaziantep (Tayanc and Toros, 1997), Ankara (Karaca et al., 1995)

3. Classification of the studies and main characteristics

Studies are classified according to two specific criteria:

a) The experimental protocol used to collect the urban heat island data in each place. In particular articles are classified in three clusters according to the main experimental protocols mentioned in (Voogt, 2014): a) studies using standard experimental stations and equipment b) studies using non-standard experimental equipment and c) studies based on mobile traverses around the concerned area. Seventy five studies belong to the first cluster, ten studies in the second, and 48 cities in the third cluster.
b) The form and type of the UHI intensity reported. Given that studies based on mobile traverses and non-standard measuring equipment

are of a relatively short duration, usually the reported UHI intensity is the maximum measured temperature difference during the whole experimental period. However, studies based on multiyear measurements obtained using standard measuring equipment report either the annual average, or the annual average maximum or the absolute maximum UHI intensity or a combination of them. Hence, for comparison reasons, studies reporting multiyear measurements based on standard experimental equipment are divided into three groups according to the three possible reporting forms of the UHI intensity mentioned above. Studies reporting results in more than one form were classified in all the corresponding groups.

The quality and accuracy of the information provided by the relevant studies depend on many parameters like the duration of the experiments, the number of stations used, the experimental protocol selected, the accuracy of the measuring equipment and others. To assess information on the duration of the experiments, the cumulative frequency distributions of the total experimental length for the studies using standard and non-standard equipment as well mobile traverses are given in Figs. 1, 2, and 3.

As shown, observations based on mobile traverses are of much shorter duration than those of the other two types of experimental studies. This is logical given the manpower, scientific effort and cost required to collect data using mobile stations. In particular, almost 13% of the UHI experimental studies based on mobile traverses performed just one day of observations, while studies having less than ten days of observations represent about 51% of the cases. Only 14% of the studies extended measurements over a whole year or more. Experiments using non-standard measuring stations are extended for a quite longer duration. For almost 38% of the studies, available observations are performed for less than a month, while 63% of the cases measurements are carried out for less than 90 days. None of the studies has collected data for a complete year. Studies based on standard measuring equipment usually do not need any special preparation and are based on the analysis of routine meteorological stations installed in cities and rural areas. Hence, the reported results are usually extended over much longer periods. However, almost 36% of the studies report results covering less than a complete year, while almost 14% of the studies present data for less than 10 days. As mentioned, a high percentage of these studies, 45%, present results covering a period between 10 and 50 years.

The number of stations used to access the magnitude of the UHI in a city determines at large the degree the study covers the spatial distribution of the phenomenon. The cumulative frequency distribution of the number of stations used, including the rural ones, is given in Fig. 4 for the studies using standard and non-standard measuring stations. As shown, almost 43% of the studies using standard measuring stations are based on data collected from just one urban and one rural station. Almost 65% of the specific studies used less than 5 stations while about 30% of the studies used more than 10 measuring stations. As it concerns the studies employing non-standard measuring equipment, all of them used more than two stations while 14% of them used 3 stations and 37% employed less than 5 stations. Almost 37% of the specific studies used more than 10 stations per experiment.

4. Magnitude of the urban heat island phenomenon

The reported urban heat island intensity from all studies using mobile traverses is given in Fig. 5, while the corresponding cumulative frequency distribution is given in Fig. 6. The magnitude of the UHI varies between 0.4 K and 11 K. The average intensity for all studies is 4.1 K and the standard deviation is 2.3 K. For about 23% of the studies, the UHI was lower than 2 K, while for the 58% of them it was lower than 4 K. For almost 27% of the studies the UHI intensity exceeded 5 K. The measured intensity of the UHI for all studies employing non-standard measuring stations is given in Fig. 7, while the corresponding cumulative frequency distribution is given in Fig. 6. The magnitude of the UHI intensity varied between 1.5 K and 10.7 K. The average value was 5 K and the standard deviation 2.9 K. For about 18% of the experiments the measured UHI intensity was less than 2 K, while 45% of the articles reported UHI intensities lower than 4 K. A high percentage of studies reported intensities higher than 5 K (42%).

The reported values of the annual average, average maximum and absolute maximum UHI intensity for all studies using standard measuring equipment are given in Figs. 8, 9, and 10, respectively, while the

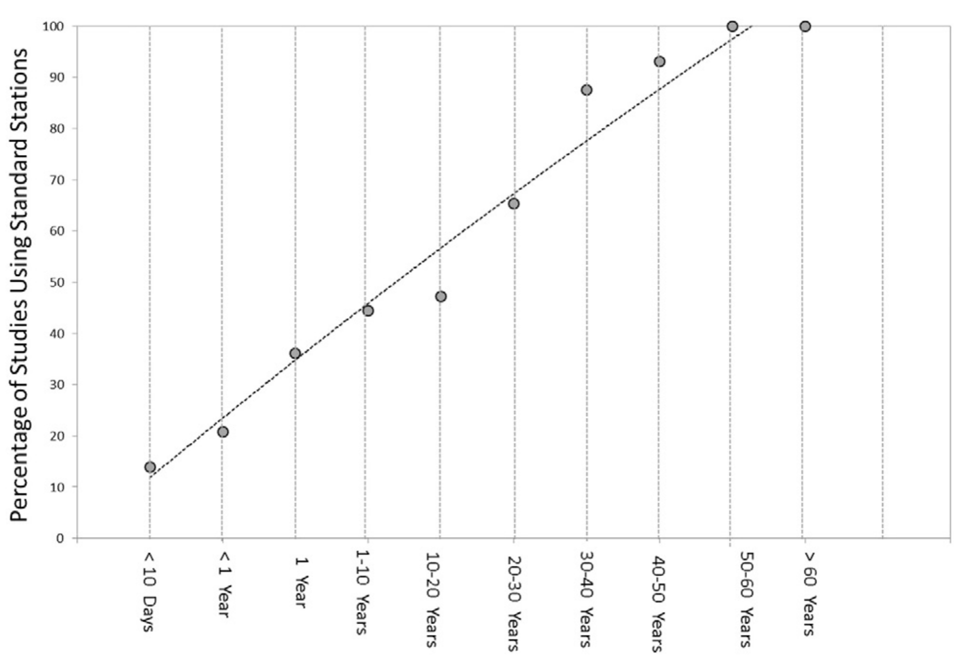

Fig. 1. Cumulative frequency distribution of the duration of reported measurements for all studies using standard measuring equipment.

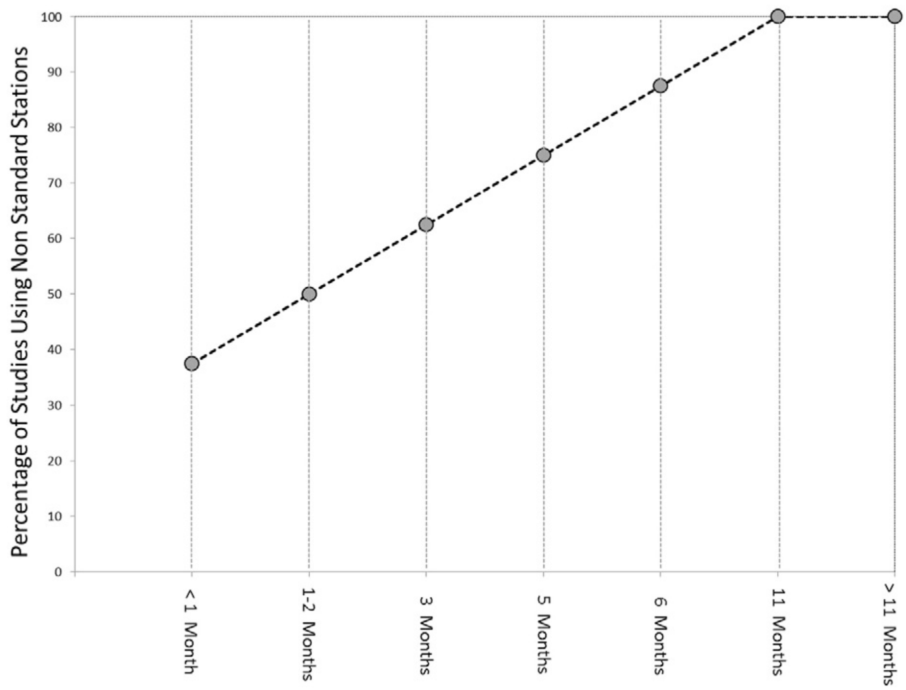

Fig. 2. Cumulative frequency distribution of the duration of reported measurements for all studies using non-standard measuring equipment.

corresponding cumulative frequency distributions are given in Fig. 6. The magnitudes of the average annual, average maximum and absolute maximum intensities were 1.0 K, 3.1 K and 6.2 K. The corresponding standard deviations were 0.7 K, 0.8 K and 1.96 K respectively. About 58% of the studies reported an average annual UHI intensity lower than 1 K, while 55% of the articles presented an average maximum UHI intensity lower than 5 K. Finally, 30% of the studies presented an absolute maximum UHI intensity below 5 K, while for 20% of the studies the maximum UHI magnitude exceeded 8 K.

It is clear that studies assessing the UHI intensity using mobile or non-standard measuring equipment present a significantly higher UHI intensity than that of the corresponding studies using standard measuring stations. Mobile equipment and non-standard stations are frequently employed to measure ambient temperatures in dense

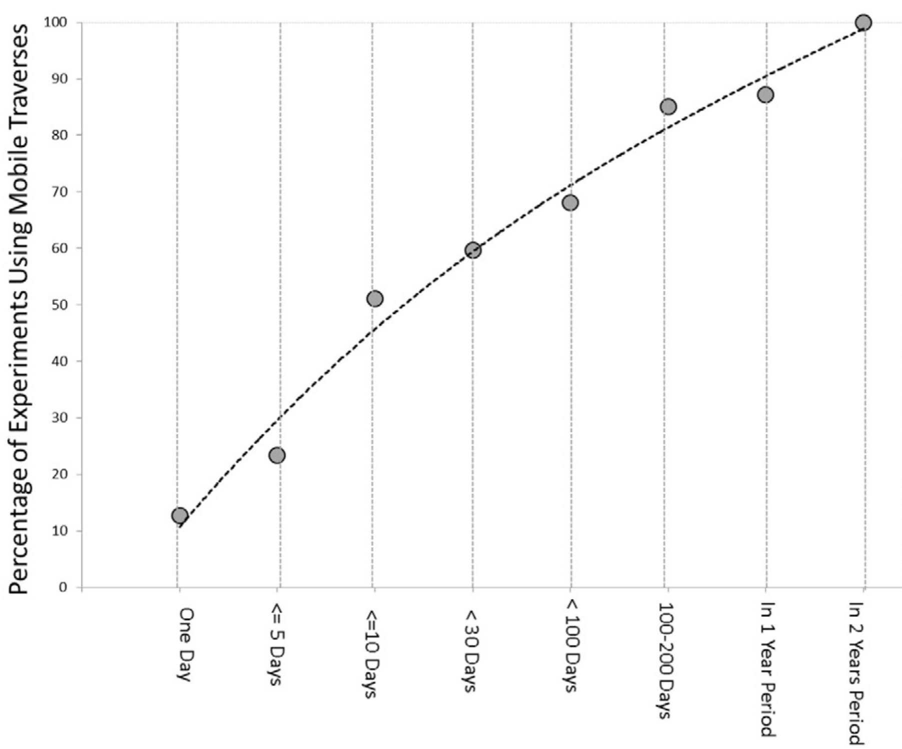

Fig. 3. Cumulative frequency distribution of the duration of reported measurements for all studies using mobile traverses.

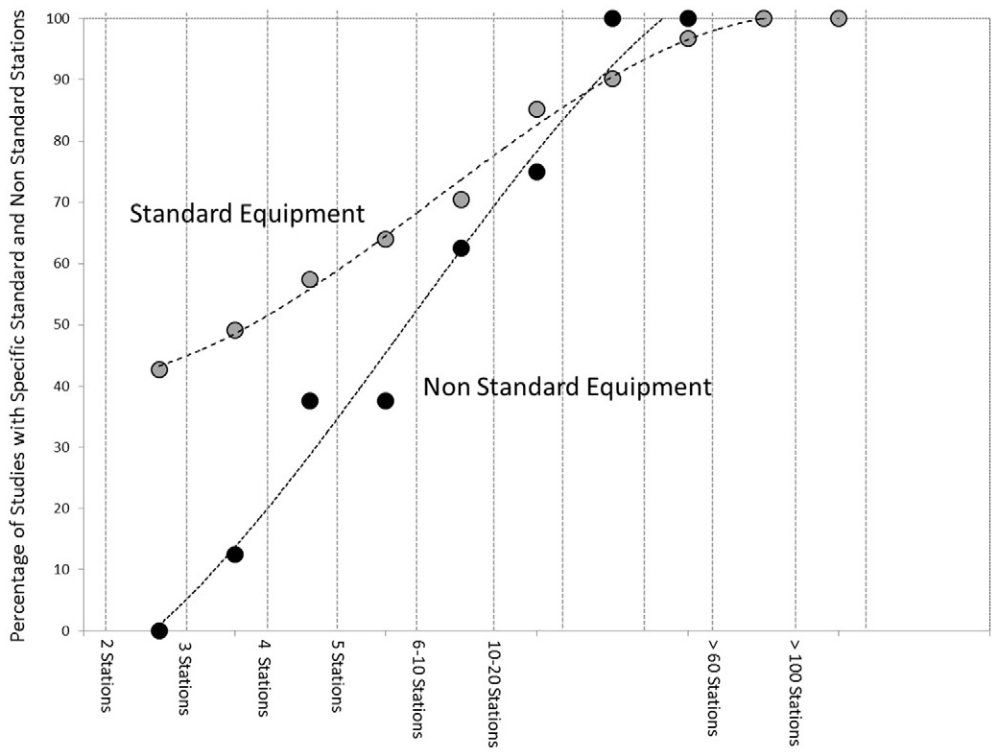

Fig. 4. Cumulative frequency distribution of the number of stations used in experiments using standard and non-standard measuring equipment.

urban areas highly influenced by the local urban characteristics, while standard meteorological stations are installed in quite undisturbed areas. As a consequence, mobile and non-standard stations are capturing the higher temperatures developed in urban zones where the thermal balance is much more positive than in undisturbed areas where standard meteorological equipment is installed.

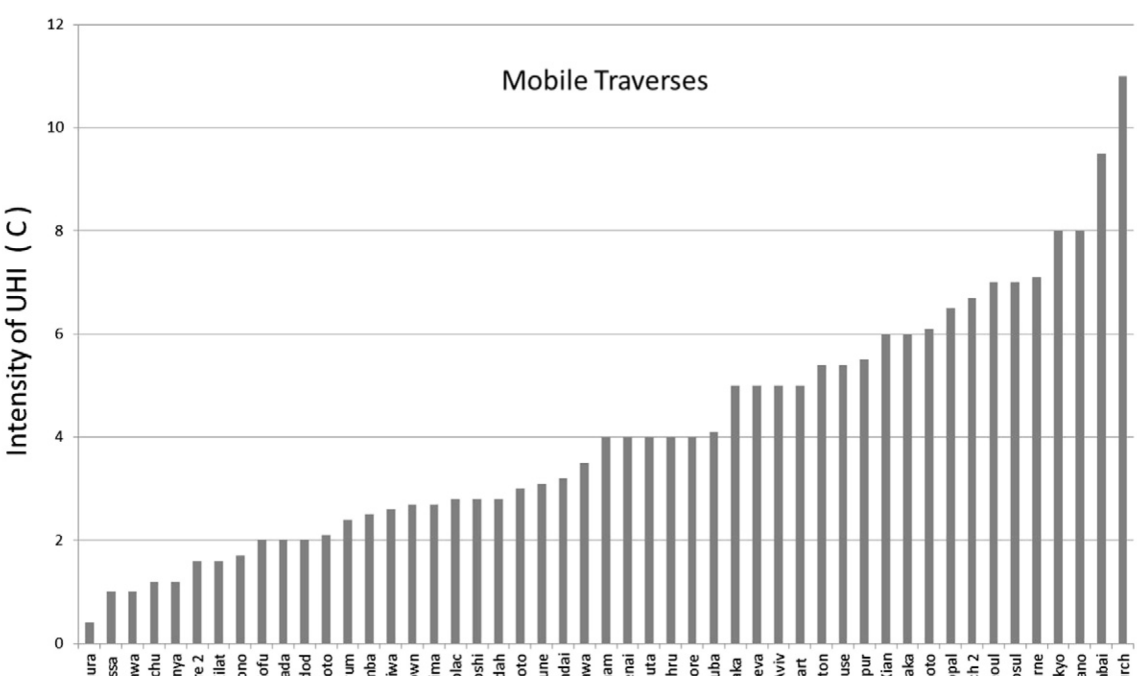

Fig. 5. Reported Intensity of the urban heat island for all studies based on mobile traverses.

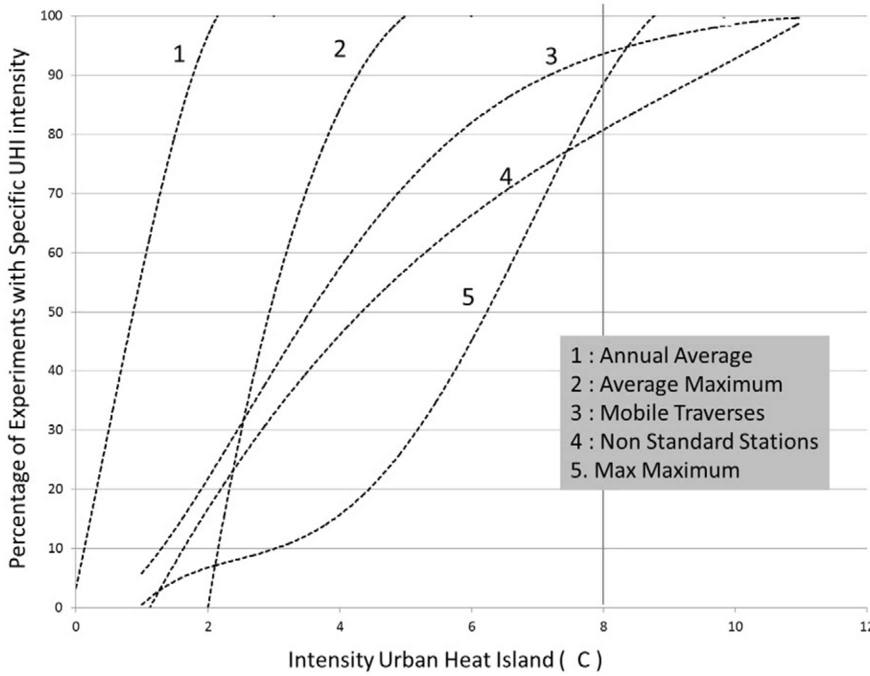

Fig. 6. Cumulative frequency distribution of the urban heat intensity for the annual average values, the average maximum, the maximum of the maximum as measured by standard measuring stations as well as the cumulative frequency distribution of the UHI as measured by experiments based on mobile traverses and non-standard measuring equipment.

5. The impact of weather conditions on urban heat island characteristics and magnitude

5.1. The impact of synoptic conditions

Many previous studies have investigated the impact of synoptic weather conditions on the development and characteristics of the urban heat island. Analysis for Birmingham, (Unwin, 1980), Madrid (Yague et al., 1991), Athens (Mihalakakou et al., 2002), Szeged, (Unger, 1996) and Buenos Ayres (Bejaran and Camilloni, 2003), have concluded that urban heat island is better developed under anticyclonic synoptic conditions while cyclonic conditions are associated with small intensities of the urban heat island. The impact of synoptic weather conditions on the formation of the UHI phenomenon in Melbourne Australia, is studied in (Morris and Simmonds, 2000). Anticyclonic conditions were found to be responsible for the largest 17% of the events presenting intensities higher than 2 K. In parallel, anticyclonic conditions were also responsible for the cooler 1% of the UHI events. Low pressure synoptic conditions were associated with very frequent events of relatively low amplitude not exceeding 1.0 K. In Seoul, analysis of the synoptic conditions has shown that the highest UHI magnitudes close to 5.2 K, occurred under anticyclonic conditions while synoptic conditions associated with relatively high cloudiness given the lowest intensities, close to 3.0 °C (Morris and Simmonds, 2000).

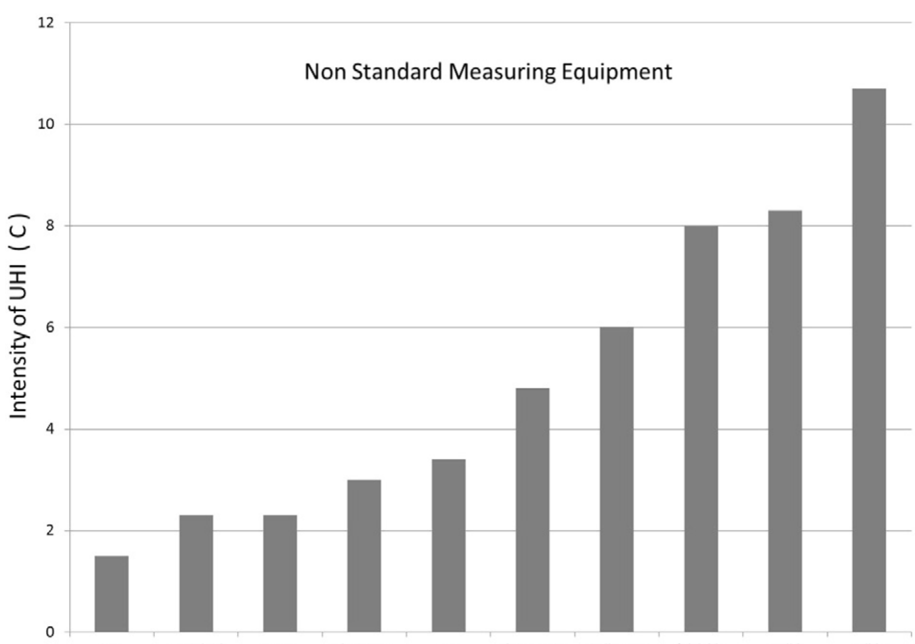

Fig. 7. Reported Intensity of the urban heat island for all studies based on standard measuring equipment.

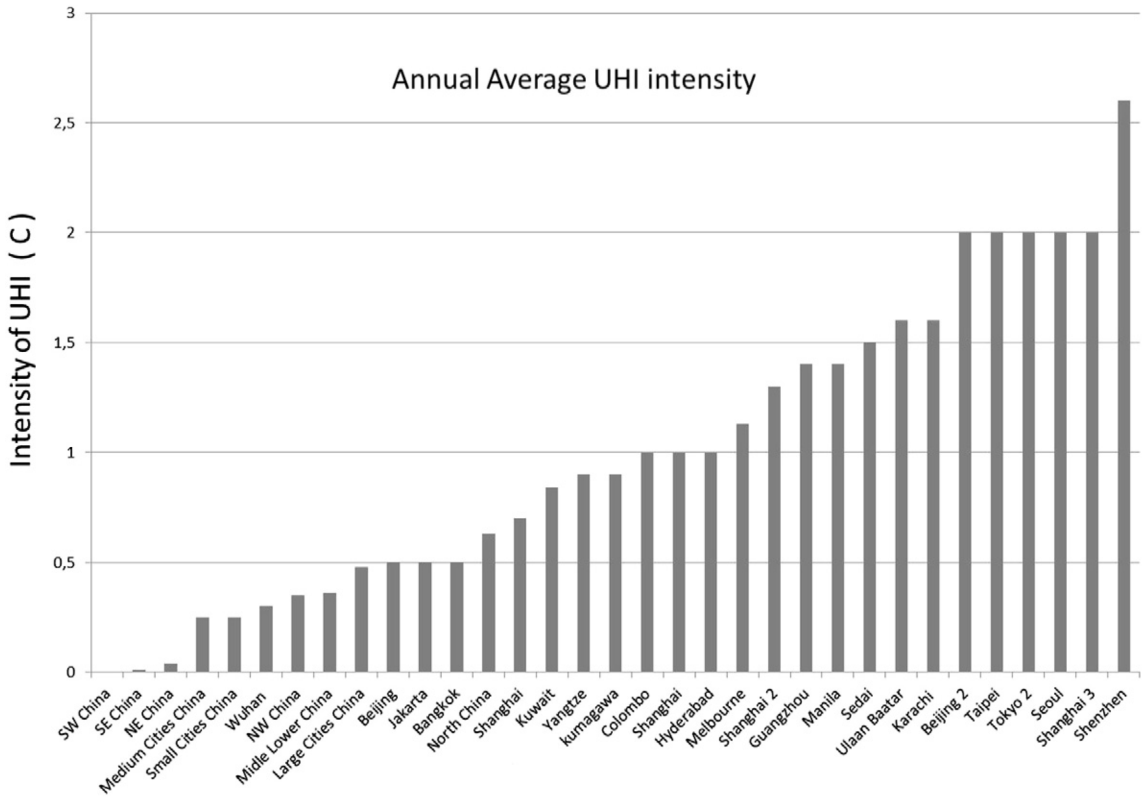

Fig. 8. Reported intensity of the annual average urban heat island for studies based on standard measuring equipment.

5.2. The impact of humidity and precipitation

The impact of precipitation and relative humidity on the urban heat island intensity is investigated in some previous studies (Sundborg, 1950). It is well known that ambient relative humidity is negatively correlated with the intensity of urban heat island and higher relative humidity corresponds to lower UHI intensities. Increased relative humidity is associated with higher evaporation rates from the urban

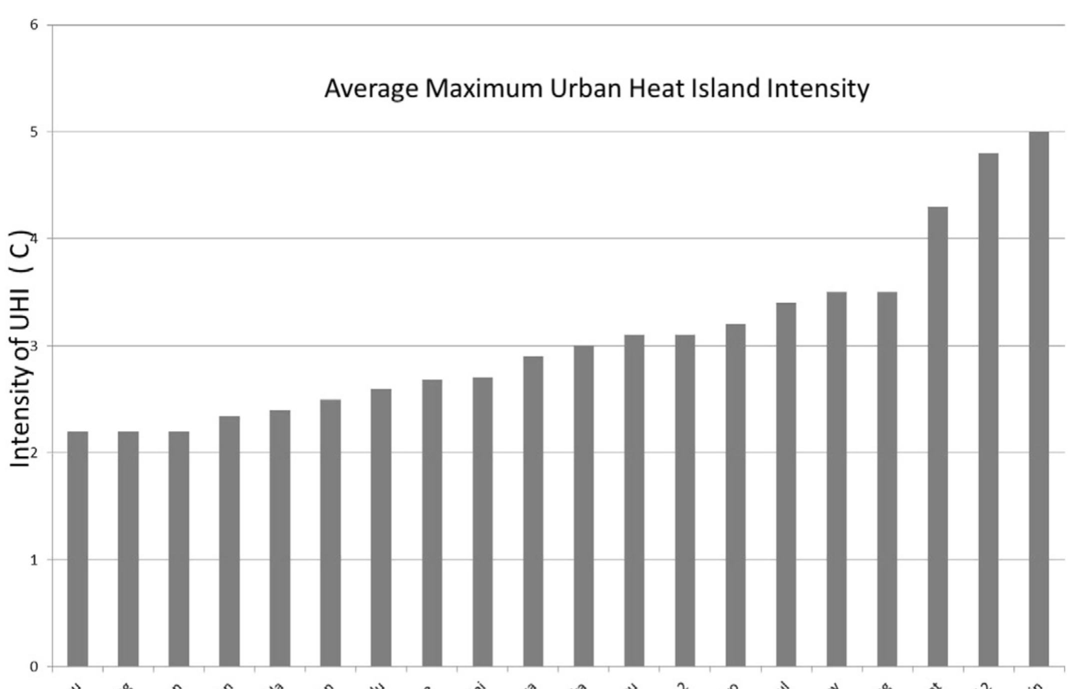

Fig. 9. Reported Intensity of the average maximum urban heat island for studies based on standard measuring equipment.

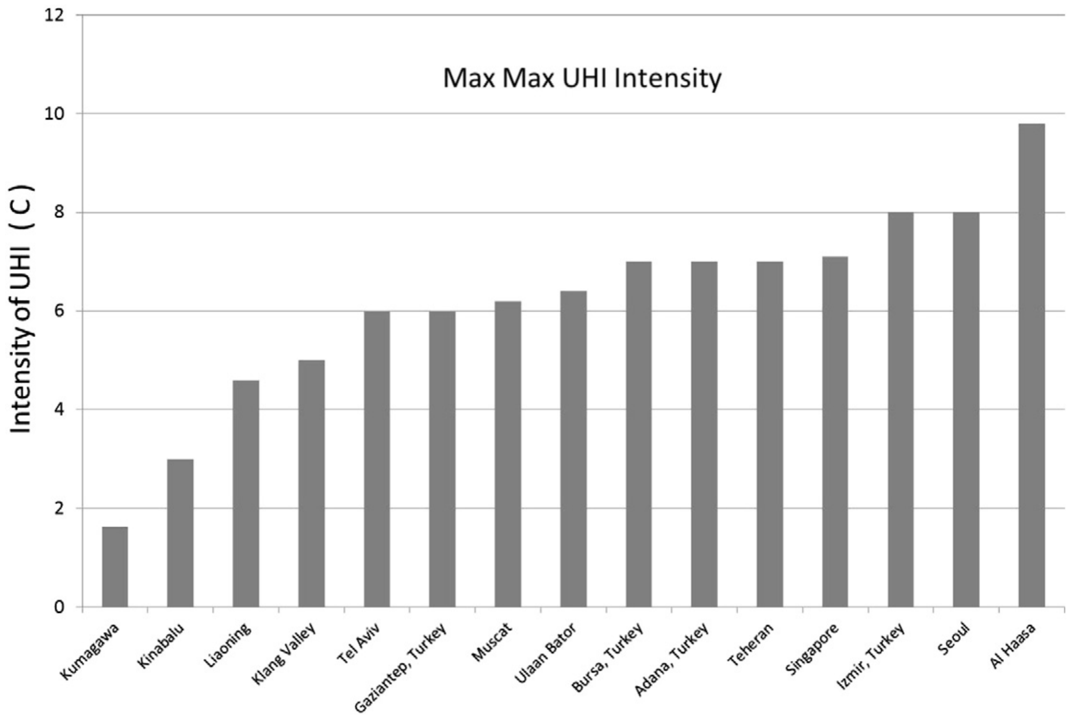

Fig. 10. Reported Intensity of the max–max urban heat island for studies based on standard measuring equipment.

surfaces that results in reduced surface and air surface temperatures because of the evaporative cooling (Kim and Baik, 2002). Thus, the maximum intensity of the urban heat island tends to decrease. Specific analysis on the impact of relative humidity on the magnitude of the UHI is performed for several Asian cities and in particular, Seoul Korea (Kim and Baik, 2002), Beijing China (W. Liu et al., 2007; J. Liu et al., 2007), Guwahati India (Borbora and Das, 2014), and parts of Saudi Arabia, (Alghannam and Al-Qahtnai, 2012). In all studies a negative correlation between the ambient relative humidity and the amplitude of the urban heat island is observed.

For almost similar reasons, the urban heat island intensity is reduced during the rainy days (Chow and Roth, 2006). Precipitation increases the thermal admittance in the rural areas and decreases the corresponding cooling rates compared to the cooling rates in the urban areas. Hence, during precipitation days, the magnitude of the urban heat island is reduced. Studies in Seoul, have shown that urban heat island intensity during the dry period was around 4.4 K and this was reduced to 2.6 K during the precipitation days (Lee and Baik, 2010). In Johor Bahru, Malaysia, the night intensity of the urban heat island was 4 K during the dry days while it was reduced to 2 K during the rainy period (Kubota and Ossen, 2014). In parallel, in Delhi, India the maximum UHI intensity was reduced to 2.2 K during the days of precipitation against 8.3 K during the rest of the period (Mohan et al., 2012). An important seasonal variability of the UHI intensity as a function of the precipitation is also reported for Singapore (Chow and Roth, 2006).

5.3. The impact of wind speed and cloud cover

It is widely accepted that the maximum intensity of the nocturnal heat island occurs under calm and clear sky conditions (Erell and Williamson, 2007; Eliasson, 1990, 1996; Papanikolaou et al., 2008). Stronger winds modify the cooling rates in the urban and rural zones and alter the magnitude of the nocturnal urban heat island. In parallel, clouds do not allow the terrestrial infrared radiation to escape, absorb and reemit it back altering the thermal balance of the area (Morris et al., 2001). Several studies are performed mainly in mid-latitude Asian and Australian cities aiming to quantify the impact of wind speed and cloud cover on the intensity of the nocturnal heat island. In Adelaide, Australia, the maximum UHI intensity, 5 K, is observed under calm conditions and particularly for wind speeds lower than 2 m/s. For higher wind speeds and irrespectively of the other climatic parameters, the intensity was reduced to 2 K (Erell and Williamson, 2007). In Melbourne, Australia (Morris et al., 2001), the maximum UHI intensity is observed at 06:00 under calm conditions. When wind speed exceeded 5 m/s, the observed magnitude of the UHI was the minimum one. A correlation between the UHI intensity and the wind speed was established for cloud covers lower than 2 octas, proportional to $U^{-0,366}$. It is pointed out that in (Eliasson, 1996), a similar correlation is established for European locations, proportional to $U^{-0,56}$. In Seoul, Korea, it is observed that the magnitude of the UHI decreases for wind speeds higher than 0.8 m/s, while for much stronger winds the UHI was not detectable (Kim and Baik, 2002, 2004). A strong decrease of the magnitude of the UHI for increasing wind speeds is also observed for five Korean cities and in particular, Daejeon, Busan, Daegu, Incheon and Kwangju (Kim and Baik, 2004). The critical wind speeds over which the UHI was insignificant and lower than 0.3 K, was 6.9 m/s in Seoul, 12.1 m/s in Incheon, 6.4 m/s in Daejeon, 9.4 m/s in Daegu, 7 m/s in Kwangju, and 0.9 m/s in Busan (Kim and Baik, 2004). In another similar study in Korea, aiming to identify the levels of wind speed over which the UHI is destroyed, it is found that the critical wind speed is a function of the city size (Park, 1986). A similar conclusion is drawn in (Oke and Hannel, 1970), where an empirical formula to calculate the critical wind speed as a function of the city size is given. The Korean study (Park, 1986) found that the critical wind speed in Seoul is 11.1 m/s, a much higher value than the one given in (Kim and Baik, 2004). The observed critical wind speed for four smaller Korean cities varied between 3.9 and 6.9 m/s, (Kim and Baik, 2004). A similar critical wind speed as in Seoul, is also calculated for Teheran, Iran, 11.8 m/s, (76), using the formula proposed in (Oke and Hannel, 1970). A significant decrease of the UHI intensity for higher wind speeds is also observed for the Japanese cities of Fuchu (Kohji et al., 1986) and Nagano (Sakakibara and Owa, 2005), Beijing China (W. Liu et al., 2007; J. Liu et al., 2007), Delhi, India (Mohan et al., 2012), Visakhapatnam, India (Suryadevara, 2006), and Singapore (Chow and Roth, 2006). On the contrary, observations carried out in Eilat, Israel, (Sofer and Potchter, 2006) and Kuala Lumpur, Malaysia (Elsayed, 2011), do not show a significant increase of the UHI intensity under calm conditions. However, the set of observations in Eilat was limited and wind speed during the monitoring was higher than 1.5 m/s, while in Kuala Lumpur the very high percentage of the observations were carried out during calm nights.

Almost all reported Asian and Australian studies agreed that the nocturnal UHI is better developed under clear sky conditions while during cloudy skies the UHI is still developed but it is seriously weakened. In Adelaide Australia, (Erell and Williamson, 2007), the UHI intensity was greater under clear sky conditions, however, intensities up to 4 K were observed under cloudy conditions close to 8 octas when wind speed was lower than 2 m/s. Almost similar conclusions are reported for Melbourne, Australia, where under low wind speeds, the UHI intensity decreased for increasing cloud cover. In particular, under calm weather conditions, increase of the cloud by one octa decreased the UHI intensity by 0.122 K. For wind speeds above 5 m/s, the UHI was still developed but an increase of the cloud cover from zero to eight octas caused an insignificant variation of its intensity. In Seoul, Korea, the influence of the cloud cover was less significant than the influence of the wind speed (Kim and Baik, 2005). The maximum of the UHI was observed under clear skies, 4.6 K, but a significant UHI intensity was recorded, 1.8 K under fully cloudy conditions (Kim and Baik, 2004). Other measurements for Seoul, Korea, report also that the maximum of the UHI intensity was observed under clear sky nights (Park, 1986). Measurements performed in Singapore have shown that cloudy conditions reduce the magnitude of the UHI intensity by 1.5–2.0 K (Nieuwolt, 1966). Higher magnitudes of the UHI intensity under clear sky conditions are also reported for Delhi, India (Mohan et al., 2013), Pune, India (Deosthali, 2000), and Ulan Bator, Mongolia (Ganbat et al., 2013).

5.4. Heat island in coastal cities

It is well proven that sea breeze developed in coastal cities has an important impact on the amplitude and characteristics of the local heat island, while it interacts strongly with it (Freitas et al., 2007; Ado, 1992; Yoshikado, 1994; Yoshikado and Tsuchida, 1996; Ohashi and Kida, 2002; Khan and Simpson, 2001; Gedzelman et al., 2003). Most of the existing studies conclude that the heat island intensity in coastal cities is reduced during the daytime of the warm period, because of the presence of the sea breeze that transfers relatively cooler air into the city and enhances wind speeds (Sakakibara and Emi, 2005). Several numerical and observational studies have investigated the specific interaction of the sea breeze system with the urban heat island. Most of them conclude that urban heat islands persist under the presence of sea breeze while having a serious effect on the pattern of sea breeze (Yoshikado, 1994; Lin et al., 2008). In particular, numerical studies for Tokyo, Japan, have shown that UHI creates a stagnation region that delays the flow of the sea breeze (Ado, 1992). Thus, heat island prevents the inland movement of the sea breeze and its cooling impact is much higher at the coastal front and decreases as distance from the coast (Sakaida et al., 2011; Yoshikado and Tsuchida, 1996; Ohashi and Kida, 2002). Concerning the impact of the urban heat island on the propagation speed of the local sea breeze studies in Sao Paolo, Brazil, concluded that urban heat island accelerates the flow of the sea breeze towards the city center and the increase of the speed caused by the presence of the city is close to 0.32 m/s, compared to the case where no city exists (Freitas et al., 2007). Similar conclusions are also drawn in (Khan and Simpson, 2001). However, because of the important convergent zone over the city, the font of the sea breeze stalls for 2 h over the center of the city and starts to propagate when the heat island disappears (Freitas et al., 2007). According to (Yoshikado, 1994), this effect is more pronounced in larger cities and when the city is substantially distanced from the coast and thus the local urban heat island has time to develop. Slightly contradictory conclusions are reported in (Gedzelman et al., 2003), where using numerical and experimental studies for New York it is found that during the warm period, sea breeze reduces and delays the circulation induced by the urban heat island and displaces it about 10 km inland (Gedzelman et al., 2003).

Studies on the impact of sea breeze are performed for several Asian cities and most of them are in agreement with the previous statements. The impact of the sea breeze seems to be important during spring and summer, and almost disappears during the rest of the time (Sakaida, 2014; Sakaida et al., 2011; Hua et al., 2008). In particular, in Korea and China, it is found that in coastal cities the amplitude of the UHI is weaker than in the inland cities (Sakaida, 2014; Hua et al., 2008). Similar results are also reported for Sendai and Tokyo, Japan (Sakaida, 2014; Sakaida et al., 2011; Ado, 1992), Visakhapatnam, India (Suryadevara, 2006), Jedah, Saudi Arabia (Abdullah and Abar, 1991), Tel Aviv, Israel (Saaroni et al., 2000), and Karachi, Pakistan (Sadiq and Ahmad, 2010), while in Kuwait City, the UHI is not developed at all because of the presence of the sea breeze (Nasrallah et al., 1990). On the contrary, the impact of sea breeze on UHI in coastal Malaysian cities, is found to be quite limited and this is attributed to the shadow effect caused by buildings that obstruct the flow of the sea breeze (Sani, 1990). The possible influence of buildings on the characteristics of the sea breeze is also studied in Sendai, Japan (Sakaida et al., 2011). As reported, dense buildings and the large number of roughness parameters have a useful influence and contribute to pull the sea breeze down to the ground level (Sakaida et al., 2011).

6. The impact of the topography, urban design factors and of the anthropogenic heat on the characteristics of the urban heat island

Man-made fluxes and the urban morphological and construction characteristics in a city determine at large its thermal balance (Giridharan et al., 2004, 2007; Doulos et al., 2004). In particular, the size and the density of the city, the type and the characteristics of the materials used in buildings and urban surfaces, the ratio of green zones, the land use, the sky view factor and the geometrical characteristics in urban canyons and semi-open spaces are the most considered parameters in existing heat island studies (Georgakis and Santamouris, 2006; Giannopoulou et al., 2010).

The specific impact of the materials used in the urban fabric on the ambient air temperature is very well studied (Doulos et al., 2004; Synnefa et al., 2006). Materials used in the urban fabric absorb and reflect solar radiation, store heat, emit infrared radiation and release sensible and latent heat through convection and evaporation processes (Stathopoulou et al., 2009). The optical and thermal characteristics of the materials, like the reflectivity to the short wave radiation, emissivity, thermal capacitance, conductivity and density define at large the thermal balance of materials and have a major impact on the distribution of the ambient temperature in cities. The impact of materials on the formation of the urban heat island is studied in many cities around the world and there is a major agreement that increased albedos contribute to lower UHI intensities (Synnefa et al., 2008). Many studies performed in Asian cities have also shown that the use of reflective materials helps in decreasing the magnitude of local heat islands (Sani, 1990; Giridharan et al., 2004; Rajagopalan et al., 2008). Extensive mitigation theoretical studies and real scale projects aiming to decrease the UHI intensity through the use of reflective materials are already carried out with significant results for many Asian studies. A full description of the specific projects and results is given in (Santamouris, 2014a,2014b).

The geometrical characteristics of the urban canyons, define the type and magnitude of air flow through them as well as the short and long wave radiation balance in the canyons (Niachou et al., 2008). Many heat island studies have investigated the impact of the geometrical canyon characteristics and in particular of the aspect ratio and the sky view factor on the intensity of the urban heat island, while several related expressions are proposed (Oke, 1973, 1981; Bottyan and Unger, 2003).

The specific geometrical canyon characteristics affect the magnitude of the short wave radiation reaching the street level, the long wave radiation escaping from the canyon and the characteristics of the air flow through the canyon (Georgakis and Santamouris, 2008; Bonamente et al., 2013; Santamouris et al., 1999). Characterization of the complex heat transfer phenomena in a canyon through the single use of the sky view factor or of the aspect ratio, seems an inadequate approach, especially in deep canyons where the lack of coupling between the undisturbed wind flow above the buildings and the canyon flow creates local air flow phenomena like double vortices (Santamouris et al., 1999). However, given that the sky view factor in a canyon is easily obtained using simple photographic techniques it is often used as an indicator to determine the magnitude of the heat island especially under calm weather conditions. For example, measurements performed in the city of Mosul, Iraq (Turki and Shaheen, 2013), concluded that the use of the sky view factor correlates very well with the ambient temperature. In parallel, measurements carried out in Hong Kong, China (Giridharan et al., 2007), in various types of canyons presenting different geometrical characteristics, show that during the daytime of peak summer partially cloudy days the intensity of the urban heat island tends to increase for SVF factors between 0.0 and 0.3 while beyond this value the change of UHI was negligible. During the late summer days, the UHI intensity found to increase for SVF values between 0.3 and 0.4, while for higher values the UHI tends to decrease. The above results have a local validity and are associated with the specific air flow and thermal conditions in the examined canyons.

Land use is highly linked to the distribution of the ambient temperature in a city. Results reported for Seoul, Korea (Kim and Baik, 2005), have shown that the various patterns of land use were a major parameter to determine the distribution of the surface air temperature in the city. Correlation of the maximum urban heat island intensities with the total evaporation surface in seven Japanese cities (parks, rivers, farms), shown that the higher the evaporation surface the lower the urban heat island intensity, (Fukuoka, 1997). In parallel, topography may have a serious impact on the local air temperature. Analysis of the topographical characteristics of Muscat, Oman (Charabi and Bakhit, 2011), has shown that the dark-colored mountains around the main valley absorb highly short wave radiation and contribute to increased ambient temperatures in the city while prevent the circulation of the sea–land breeze in the area.

Although the average anthropogenic heat flux is small compared to the summertime mid-day solar radiation, waste heat from urban anthropogenic activities plays an important role on the formation and magnitude of heat island phenomenon. Many experimental and modeling studies have documented that waste heat mainly from urban energy and transportation systems, and power generation, contribute to increased heat island intensities (Sailor and Lu, 2004; Khan and Simpson, 2001). Anthropogenic heat in an urban area depends on many factors as the spatial and temporal variation of the energy consumption, density of population, industrial activity, prevailing climatic conditions, transportation characteristics, and geographical location. Many studies have been performed to calculate the anthropogenic heat flux in urban areas and a value close to 100 W/m^2, is suggested as an average (Klysik, 1996; Grimmond, 1992). However, much higher values have been reported for various European and North American cities ranging between 20 and 250 W/m^2, (Oke, 1987; McGolrdich, 1980; Hosler and Landsberg, 1997; Taha, 1997; Steinecke, 1999). In Asia, studies from the Tokyo urban area, show that the anthropogenic heat flux in the city exceeds 400 W/m^2 in daytime, while the maximum value is close to 1590 W/m^2 in winter (Ichinose et al., 1999). Analysis of the anthropogenic heat distribution for central Beijing shows that at 8 AM local time, it ranges between 40 and 220 W/m^2 in summer and 60 and 300 W/m^2 in winter (Chen et al., 2007). Computer simulations carried out for the city of Taipei, have shown that an increase of the anthropogenic heat by 100 W/m^2, could increase the air surface temperature by 0.31 K (Lin et al., 2008). In Johor Bahru, Malaysia (Kubota and Ossen, 2014), the increased anthropogenic heat in an industrial zone developed an urban heat island of about 2 K even during the rainy days.

7. Heat island and city size

It is well accepted that urbanization affects the air surface temperature of cities (Karl et al., 1988; Karl and Jones, 1989; Turkes et al., 2002). Increase of the urban population is at least associated with a considerable increasing trend of the minimum ambient temperature and a minor increasing trend of the maximum temperature during the warm period (Engenglehart and Douglas, 2003; W. Liu et al., 2007; J. Liu et al., 2007). Urbanisation could affect highly the characteristics of the urban heat island as the urban built area and the anthropogenic heat flow in a city are increasing. In fact, increased population is associated with a higher number of buildings, pavements, urban structures, transport flows, energy consumption, and a lower ratio of free and cultivated land. A study relating the increase of the urban population with the mean annual intensity of the UHI for six major Asian cities during the period 1950–2000, found that the increase of the urban population increases considerably the intensity of the urban heat island, but with a different trend for each city (Kataoka et al., 2009). Analysis of the urban heat island intensity in the Yangtze River Delta cities in China (Yin et al., 2007), calculated on the basis of the annual average, annual average maximum, annual maximum and annual minimum ambient temperatures found a quite strong relationship with population for all cases. In parallel, a specific analysis for Shanghai, China (Wang et al., 1990a, 1990b) has shown a strong correlation between the intensity of the urban heat island and the number of operating busses in the city, the area of buildings, the area of paved roads, and the energy consumption in the city (Wang et al., 1990a, 1990b). In a similar way, a strong correlation between the minimum temperature UHI intensity and the expansion of the annual construction area is found for Beijing, China (W. Liu et al., 2007; J. Liu et al., 2007).

It is evident that the use of the population as a surrogate is convenient and incorporates many parameters influencing the magnitude of the urban heat island (Roth, 2007). However, there are many concerns about the appropriateness and the reliability of such an indicator given that climatic factors and anthropogenic flows in cities of the same size may be completely different. In particular, coastal cities benefit from the flow of sea breeze compared to inland cities of the same size. It is characteristic that because of the strong influence of the sea breeze no correlation is found between the heat island intensity and population growth in Kuwait City (Nasrallah et al., 1990). In parallel, the energy consumption and the magnitude of the anthropogenic heat released, vary substantially as a function of the economic and technological development in places that may present the same population size.

Despite these concerns, several urban climatic studies have investigated the impact of urbanization and city size on the magnitude of the UHI phenomenon (Oke, 1973; Kataoka et al., 2009, 2009; Fukuoka, 1983; Park, 1986; Kohji et al., 1986; Sakakibara and Kitahara, 2003; W. Liu et al., 2007; J. Liu et al., 2007; Wang et al., 1990a, 1990b; Yin et al., 2007; Coughlan et al., 1990). Most of the studies have proposed relations linking the maximum UHI intensity to the total number of citizens in the specific place. In particular Oke (1973), investigated the impact of city size on the UHI intensity for a number of small, medium and large size cities in Canada and Europe during cloudless calm nights and proposed two separate expressions for the North American and European cities linking the UHI intensity with the logarithm of the population. In his study on the relation of urban population and UHI intensity in Japan Fukuoka (1983), proposed a non-linear relationship presenting a much higher increasing slope for cities larger than 100,000 citizens, and of a smaller slope for cities below 100,000, than that proposed in (Oke, 1973) for N. American and European cities. Park (1986), presented relationships of a similar form for Korean and Japanese cities. He found that there is a bend in the regression line and the slope increased rapidly for cities above 300,000 inhabitants. For almost all considered cities, the growth rate of the UHI intensity with population was considerably lower compared to the N. American and European cities. A similar conclusion is also drawn for Australian and New Zealand cities, (Torok et al., 2001; Coughlan et al., 1990; Tapper, 1982). The impact of city size on the intensity of the urban heat island intensity for several Japanese cities is also investigated by Sakakibara and Kitahara (2003) and Sakakibara and Emi (2005), without however to find any bending point on the regression analysis as proposed by Park (1986). For cities above 300,000 inhabitants they found that the heat island intensity is considerably larger than that proposed by Park (1986). An analysis of the relation between the intensity of the urban heat island and the corresponding population for several Turkish cities (Tayanc and Toros, 1997), has shown that the correlation between urban heat island intensity and the corresponding population follows closely the relationship proposed by Oke (1973), for European cities.

Most of the previously presented empirical relationships are obtained using data collected for quite limited time periods, under different climatic conditions, using quite diverse monitoring protocols and reporting the urban heat island intensity for different ambient temperature statistics thus, the use of the proposed expressions has a strict local validity. In order to investigate the possible relationship of the urban heat island intensity and the city size in the 101 studied Asian and Australian cities, a specific analysis has been carried out and presented below.

To achieve the best possible homogeneity of the considered data for analysis, the available data set was split into two subsets on the basis of the duration of heat island measurements in each place. The first subset included all data with at least one complete year of measurements while the second one included the rest of the measurements. Most of the data in the second subset included limited time surveys performed using mobile traverses and non-standard fixed stations where the reported UHI intensity was the maximum temperature difference measured during the monitoring period. Almost all available data in the first subset were collected using standard fixed stations while the reported UHI intensity was either the average annual value, or the average annual maximum value or the measured annual maximum temperature difference between the urban and the reference stations. Hence, three clusters of data, analyzed separately, are defined for the first subset. Given that the number of small size cities where UHI data are available is reduced and the UHI characteristics in these cities differ substantially than those of large size cities, the analysis included only cities larger than 300,000 inhabitants.

Data on the specific size of the population for each considered city during the monitoring period are taken from the best possible reliable source available. The relationship between the reported UHI intensity and the population for the four considered clusters of data is given in Fig. 11. In parallel, the relationships proposed in Oke (1973), for North American and European cities, as well as those proposed in Park (1986), for Korean and Japanese cities are plotted for comparison.

As, shown, there is no correlation between the average annual urban heat island intensity and the urban population. The annual average value of the UHI masks and weakens possible important temperature differences that occurred between the urban and rural areas during a specific period of the year, i.e. the dry season, averaging against periods where heat island may be insignificant. Also, annual average values incorporate data obtained under diverse climatic and operational conditions that may favor or not the formation of the urban heat island (clam or windy days, etc), or intensify it (day or night, etc). Hence, the impact of the city size is not directly related to the annual average value of the urban heat island.

On the contrary, a significant correlation is achieved between the annual average maximum UHI intensity as well as of the annual maximum UHI intensity with the population. In both cases and given the reduced

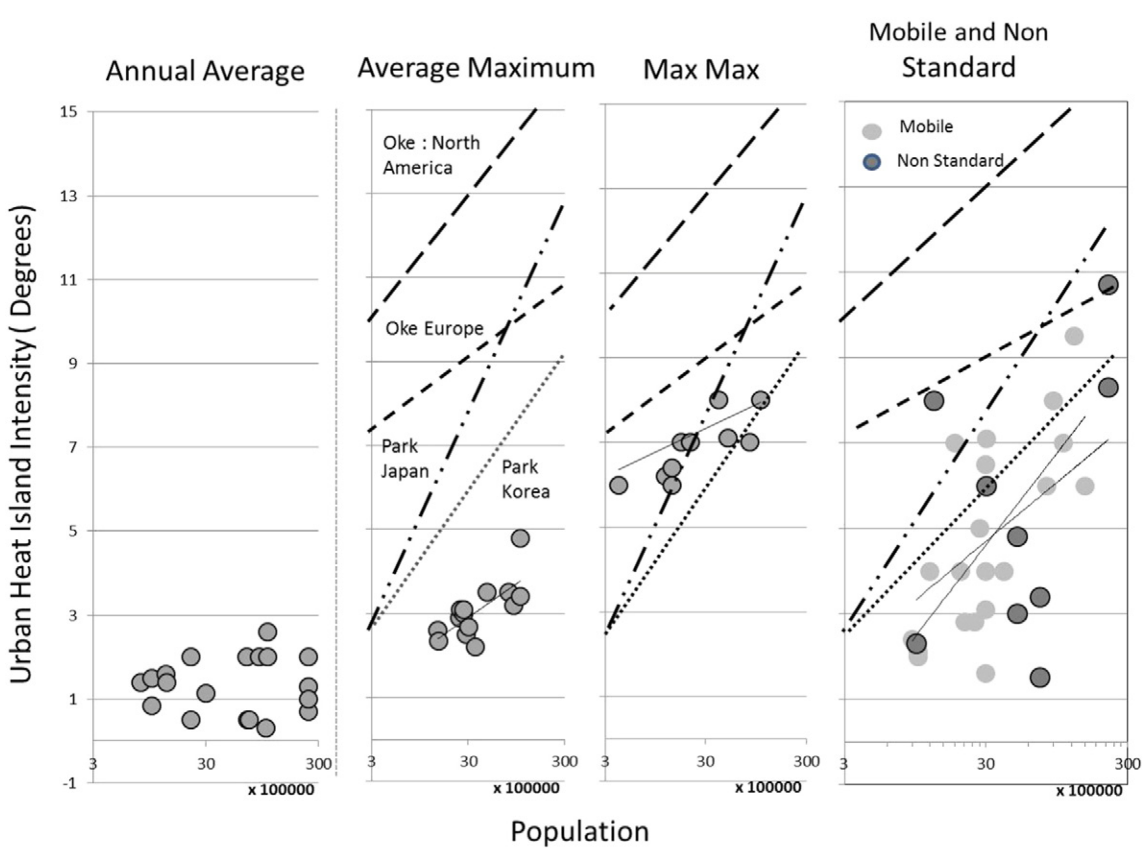

Fig. 11. Relationships between UHI intensity and population and existing formulas for North America, Europe (Oke, 1973), Japan and Korea (Park, 1986).

number of available data, an indicative logarithmic regression line is drawn. The r^2 for both cases varied between 0.55 and 0.65. When the obtained relationship between the average annual maximum UHI intensity and the population is compared against the expressions proposed in Oke (1973) and Park (1986) for North American, European, Korean and Japanese cities, it is clear that values of the UHI intensity given by the present study for cities are much lower. A possible explanation is that the present study uses data measured by standard meteorological stations while the relationships proposed in Oke (1973) and Park (1986) are obtained using automobile traverses. Standard meteorological stations are usually installed in thermally undisturbed zones of the city where the influence of buildings and other urban parameters is relatively limited and thus the magnitude of the urban heat island is quite reduced. On the contrary, measurements performed through automobile traverses are much more influenced by the urban structure and characteristics.

The obtained relationship between the maximum annual UHI intensity and population gives results at the same order of magnitude as the proposed relationships for Korea and Japan (Park, 1986). It has a slightly lower slope but the predicted magnitude of the UHI intensity for cities of the same size is quite similar for all three expressions.

When mobile measuring or non-standard fixed stations are used, the relationship between the reported urban heat island intensity and population is quite poor. Separate correlations have been obtained for experiments using mobile and fixed non-standard stations. In both cases there is an almost similar increasing trend however, it is not statistically significant. The corresponding regression lines have almost a similar slope as the relationship proposed in Park (1986), for Korean cities, however, the predicted UHI intensity is slightly lower for cities of the same population. The lack of acceptable correlation between the UHI intensity and population, can be explained by various reasons, like: a) some of the existing experiments are carried out under climatic conditions that do not fully enhance the development of heat island and the measured UHI intensity is low, b) other experiments are limited in their number of observations and many are carried out irregularly during the day or nighttime or both, c) the selection of the reference station was not done using always the same methodology and criteria, d) Some of the non-standard fixed stations are highly influenced by the surrounding urban structures and anthropogenic heat and in certain cases results may be biased.

Based on the above analysis the following conclusions can be drawn:

a) For data on urban heat island intensity measured using standard fixed measuring stations for more than one complete year, an important increasing trend is observed between the average annual maximum and the maximum urban heat island intensity with population.
b) Data collected in different places through mobile traverses and the use of non-standard fixed stations present important dissimilarities regarding the boundary and operational conditions under which measurements were performed and may not be considered as homogenous and reliable data set. In this case the correlation against population is weak and non-statistically significant.
c) Average annual urban heat island intensity should not be used to demonstrate the impact of city size on the magnitude of the urban heat island.
d) Existing relationships between the urban heat island intensity and population are obtained under diverse climatic and operational conditions and a direct comparison of results from other cities may be problematic. However, the overall comparative analysis permits to extract some conclusions of a qualitative nature. In particular, for all examined cases, the relationships proposed in Oke (1973), for North American and European cities predict a much higher UHI intensity than that obtained by the present analysis which is much closer to the relationship proposed in Park (1986) for Korean and then for Japanese cities.

8. Seasonal variation of the urban heat island

It is commonly accepted that the maximum heat island intensity is best developed during the warm period of the year (Oke, 1973; Morris et al., 2001; Mihalakakou et al., 2004). Observations carried out in many Asian and Australian cities have shown that this is valid for a number of cities like Melbourne, Australia (Erell and Williamson, 2007), Muscat, Oman (Charabi and Bakhit, 2011), Yangtze cities in China (Yin et al., 2007), Guwahati, India (Borbora and Das, 2014) and Karachi, Pakistan (Sadiq and Ahmad, 2010). However for climates characterized by dry and humid periods, the maximum urban heat island intensity is always presented during the dry season. In the tropical city of Singapore, the maximum UHI is observed during the driest period of June and the minimum during the wet period in January (Chow and Roth, 2006). In Seoul, Korea, the maximum magnitude of the heat island is presented during the dry seasons of autumn and winter while during the humid summer season it takes its minimum (Kim and Baik, 2005). The same is also valid for other five cities of Korea, Daejeon, Busan, Daegu, Incheon and Kwangju (Kim and Baik, 2004). Higher UHI intensities during the dry season between November and April are also observed for Bangkok, Thailand (Jongtanom et al., 2011). In the Chinese cities of Dandong, Jinzhou and Tieling, the annual variation of the UHI intensity follows a U shape, with a maximum in January and a minimum during the summer period (Li et al., 2012). Similar results are also reported for Beijing, China (W. Liu et al., 2007; J. Liu et al., 2007), where the UHI takes its maximum during the dry season of winter and spring and its minimum during the humid summer period. Finally, in Ulan Bator, Mongolia, the daily maximum UHI intensity during the winter period is 6.4 K, while the weakest one occurs during the summer season, 2.5 K (Ganbat et al., 2013).

9. Diurnal variation of the UHI intensity

It is generally believed that the urban heat island intensity takes its maximum during calm and clear nights (Arnfield, 2003; Schmidlin, 1989; Ripley et al., 1996; Tereshchenko and Filonov, 2001). This is attributed to the higher cooling rates in the rural compared to the urban areas that accelerate the temperature decrease in the rural zones, and increase the temperature difference between the city and its environment (Oke, 1982). Theoretical and experimental research carried out mainly in North American cities has shown that the maximum intensity of the UHI occurs 3–5 h after sunset (Oke, 1987). However, many recent field studies found that the maximum heat island intensity may occur at different times of the day, before and after sunset or midnight or even during the daytime, and this is mainly defined by the thermal balance in the specific urban and rural zones (Skoulika et al., 2014; Chow and Roth, 2006; Livada et al., 2002).

A significant number of observations regarding the diurnal pattern of the urban heat island are available for many Australian and Asian cities. In most of the cities, the maximum intensity of the urban heat island is observed during the late afternoon, nighttime or early morning, however in some cases, because of the specific thermal balance the maximum intensity is observed during the day period. In particular, in Adelaide, Australia the UHI starts to develop just before sunset and is well established 3–5 h later, while the maximum is presented after midnight (Erell and Williamson, 2007). In Bangkok, Thailand (Jongtanom et al., 2011), the maximum UHI intensity is observed during nighttime and in particular at 04:00 LST while the weakest maximum is observed during the day, 10:00 LST. In two other cities of Thailand, Chiang Mai and Songkhla, the maximum intensity is observed at 07:00 LST and 22:00 LST respectively (Jongtanom et al., 2011). In Muscat, Oman the maximum UHI magnitude is observed 6–7 h after sunset (Charabi and Bakhit, 2011), while in Beijing the maximum is observed at the late night period or evening (Miao et al., 2009; W. Liu et al., 2007; J. Liu et al., 2007), and the weakest during the day. In Delhi, India the UHI intensity takes its maximum during the late afternoon period and the night (Mohan et al., 2012), while in Ulan Bator, Mongolia the heat island intensity during the nighttime is five times higher than during the day period (Ganbat et al., 2013). In Jeddah, Saudi Arabia the UHI maximum appears during the early morning hours, 05:00 LST, and the minimum at 15:00 LST (Abdullah and Abar, 1991). In Seoul, Korea, the maximum heat island intensity is also presented during the nighttime (Kim and Baik, 2004, 2005), and in particular around midnight except during the winter period when the maximum occurs at 08:00 LST, because of the important release of anthropogenic heat during the cold period (Lee and Baik, 2010). Observations in five Korean cities, Daejeon, Busan, Daegu, Incheon and Kwangju, show that the maximum heat island is also presented during nighttime in all cities (Kim and Baik, 2004). In Naning, China, a strong heat island intensity occurs around midnight however, the peak occurs between 18:00 and 21:00 because of the important anthropogenic heat generated by the traffic (Huang et al., 2008). In Shuzhou, China (Zhang et al., 2011), the local maximum appears during the early afternoon while a second peak is observed at 05:00 LST.

The seasonal variability of the thermal balance in a city caused mainly by the variable magnitude of the anthropogenic heat released may affect the specific hour when the maximum heat island intensity is observed. Observations in Shanghai, China, show that during autumn and winter the maximum UHI intensity occurs during the night (Zhu et al., 2003), while measurements performed during the summer season show that the maximum intensity is more pronounced during the noon and afternoon period (Tan et al., 2010). In Kumamoto, Japan (Saito et al., 1990), the daily UHI maximum appears during the daytime because of the very high surface temperature of the absorbing materials used in the city, however a second peak is observed during the night period. In a similar way, the heat island intensity in Guwahati, India, is equally presented during the night and day periods (Borbora and Das, 2014). Observations carried out in Shenzhen, China, show that during the autumn and winter periods the UHI maximum occurs from noon to afternoon while for the rest of the year the maximum is observed between the afternoon and evening period (Zhang et al., 2008). Observations in Tel Aviv, Israel, show that the maximum UHI intensity above the buildings level is presented during the nighttime, while in the street level a stronger maximum appears both during the day and night periods (Saaroni et al., 2000). Urban temperature recordings measured during the summer season in Eilat Israel, show that the UHI maximum occurs during the afternoon period (Sofer and Potchter, 2006). In a similar way, measurements in Hong Kong, China (Giridharan et al., 2005) carried out during the summer period, show that the maximum of the UHI intensity is also presented during the daytime (Giridharan et al., 2005), while in the tropical city of city of Muer, Malaysia show that the UHI maximum occurs equally during the day, while a second peak is observed during the night period (Rajagopalan et al., 2014).

10. Daytime cool islands

The existence of daytime cool islands in cities is already reported in several urban climatological studies, (Runnalls and Oke, 2000; Oke, 1982; Steinecke, 1999; Unwin, 1980; Jauregui et al., 1992; Myrup et al., 1993; Figuerola and Mazzeo, 1998). Cool island conditions are observed in four Asian (Beijing, Kuala Lumpur, Seoul and Singapore), and two Australian cities (Adelaide and Melbourne). Lower urban temperatures may occur because of the less positive thermal balance in the specific urban zones than that of the reference rural areas. Several studies indicate that cool islands usually occur in deep and dense urban canyons (Erell and Williamson, 2007; Oke, 1982). In this case, cool islands can be attributed to the extensive shading in the canyons, the increased thermal admittance and the 'lack of capping inversions within the lowest few hundred meters of the urban atmosphere' (Oke, 1982). Reduced anthropogenic heat flux and shading in dense urban canyons where the incoming solar radiation can't penetrate are also the main reasons claimed by researchers that monitored the climatic conditions in Adelaide, Australia (Erell and Williamson, 2007). In this city, cool islands of about 2 K occurred during clear days with high ambient temperature, high solar radiation and low wind speeds. However, in Tel Aviv, urban cool islands are reported for urban areas other than deep canyons like open spaces, plazas, squares and wide roads mainly because of the influence of sea breeze penetrating in these zones (Mousavi-Baygi et al., 2010). The impact of specific synoptic conditions favoring the development of an urban cool island in Melbourne Australia is reported in Morris and Simmonds (2000). In Beijing, urban cool islands were observed during the morning period persisting until noon time (Miao et al., 2009). Lower urban temperatures were attributed to the important decrease of solar radiation in the city caused by the high concentration of aerosols and also the possible advection of warmer air to rural areas. In Seoul, observations reported in Kim and Baik (2005), indicate a weak cool island occasionally presented during the afternoon period, however, a second experiment in Seoul, described in Kim and Baik (2005), found that urban cool islands occur quite often during the day period and during the non-precipitation days of spring the frequency of occurrence was around 77%. In Kuala Lumpur, past climatological studies indicated the existence of many cool islands in the city, however, the rapid urbanization of the area has limited the cool zones into the boundaries of an urban park (Elsayed, 2011). In a similar way, cool islands in Singapore are observed in forested and less developed areas of the city (Chow and Roth, 2006), while the development of cool islands is also reported for the CBD area mainly because of the important shading caused by the tall buildings during the daytime and the proximity to a local river and the sea (Chow and Roth, 2006).

11. The Impact of the reference station selection procedures

The selection of the reference rural station to calculate the magnitude of the urban heat island intensity is perhaps the major source of potential errors (Runnalls and Oke, 2000). Rural areas around a city do not always present the same climatic characteristics because of the different topography, diverse proximity to the sea or different degree of urban influence. Urban heat island studies in Phoenix, US (Hawkins et al., 2004), have shown that differences in the configuration of the local topography and land covers influence the wind circulation and the local air flow and determine the distribution of the ambient temperature around the city. In parallel, in coastal zones the advection of warmer or cool air from the sea influences highly the temperature of coastal reference stations. Thus, the selection of an unsuitable reference station may not reflect the real temperature impact of urbanization.

The problem of temperature variability around urban areas because of the differences in topography, land cover and proximity to the sea is encountered in many urban heat island studies performed in Australia and Asia and various solutions to the problem are proposed. In Adelaide (Erell and Williamson, 2007), it is decided to use as the reference the ambient temperature measured in a green belt around the city, while in Melbourne, Australia (Morris et al., 2001), the average temperature measured at three local airports was used as the reference rural temperature. In Camberdown (Torok et al., 2001), Australia, the average of several rural stations is used to calculate the magnitude of the heat island and it is found that such an approach minimizes the local impacts on the estimation of the urban heat island intensity. In Muscat, Oman (Charabi and Bakhit, 2011), the magnitude of the urban heat island was calculated for every rural station. Because of the diverse selection of reference station, the intensity of the maximum urban heat island varied between 4.3 and 6.2 K. The impact of the selection of unsuitable rural stations on the amplitude of urban heat island in Tokyo Japan is studied in (Sakakibara and Owa, 2005). It is reported that the selection of an inland rural station as the reference one, results to an overestimation of the urban heat island intensity during the winter nights, while the selection of a typical countryside rural station results to an overestimation of the UHI intensity during the summer nights. The study concludes that proper selection of the reference rural station for coastal cities requires to be at the same distance from as the sea as the urban station.

Increase of the urbanization around the cities, influences the temperature of the reference rural stations (Karl and Quayle, 1988). An urban warming bias of about 0.06 K is calculated for the rural stations belonging to the United States Historical Climatic Network (Karl and Quayle, 1988), during the 20th century. According to the same source (Karl and Quayle, 1988), the warming trend of the rural stations is much higher in China, 0.24 K/30 years, while the corresponding warming trend for the urban stations is 0.36 K/30 years. The important increasing trend for both urban and rural stations in the Beijing area is also reported in (Ren et al., 2007). In particular, it is found that in the urban areas the highest tendency is observed for the minimum temperature while for the rural station the maximum temperature presented the highest increasing trend. Almost similar warming trends as in (Karl and Quayle, 1988) are reported for the Beijing rural stations in (W. Liu et al., 2007; J. Liu et al., 2007). The warming tendency for the rural stations was reported between 0.06 K/10 years and 0.11 K/10 years. It is evident that a suitable selection of a reference rural station should consider meteorological stations with the minimum possible influence of urbanization.

12. Conclusions

Experimental observations on the magnitude and the characteristics of the urban heat island are collected, classified and analyzed for 101 Asian and Australian cities and regions. Data are categorized using two criteria dealing with the experimental protocol employed and the type of information reported about the magnitude of the urban heat island. Analysis of the available information shows that studies based on the use of mobile traverses and non-standard measuring equipment usually report a significantly higher magnitude of the urban heat island as compared to studies employing standard fixed measuring stations and equipment. Mobile stations and non-standard measuring equipment are more suitable to perform observations in dense urban areas having a more positive thermal balance because of the strong influence of local urban parameters while standard fixed stations are mainly used in thermally undisturbed urban zones. A high fraction of the observations based on mobile traverses are carried out for a quite limited period, even one or two days and can't provide sufficient information on the seasonal variability of the phenomenon. In parallel, a high percentage of the studies employing standard fixed measuring equipment are based on data from a very limited number of urban stations, one or two, and may not represent adequately the spatial distribution of the UHI phenomenon in the specific city. The exact magnitude of the urban heat island intensity depends highly on the selection of the reference rural or suburban stations. Significant warming trends in the rural and suburban areas around cities are observed for many Asian cities which influence and in reality bias the reported urban heat island intensity and the global thermal impact of the urban environment.

The measured magnitude of the urban heat island in Asia and Australian cities is quite significant. It varies between 0.4 K and 11.0 K. The average UHI intensities reported by studies using mobile traverses and non-standard stations are 4.1 K and 5.0 K respectively. When standard measuring stations are used, the average annual intensity is 1.0 K, the average maximum 3.1 K, and the average absolute maximum is 6.2 K. Heat island intensity in the area has an important seasonal variability and the maximum is always presented during the warm period except in cities of humid climate where the maximum intensity is always measured during the dry season. In most of the cities the maximum UHI intensity is observed during the late afternoon, night or early morning period, however in many Asian cities the maximum intensity is measured during the daytime as a result of the very positive thermal balance developed during the day period, caused mainly by the increased release of anthropogenic heat. When, the diurnal thermal flows are quite reduced because of the extended shading in urban canyons, reduced anthropogenic heat and the possible cooling effect of sea breeze in coastal areas, the urban temperature may be lower than the rural one and cool islands may appear. Cool islands are observed in many Asian and Australian cities and are attributed to the strong influence of specific and diverse climatic parameters occurring for each city.

Despite the significant differences on urban heat flows and characteristics between cities of the same size and population, a significant relationship between the average maximum and the absolute maximum urban heat island intensity and the populations is obtained when data from standard fixed measuring stations are used. The specific relationships are in quite good agreement with similar expressions proposed for Japan and Korea but differ substantially from those proposed for North American and European cities. On the contrary due to the diverse characteristics of the experiments performed using mobile traverses and non-standard measuring equipment the corresponding relationships between the UHI intensity and the population are quite weak and non-statistically significant.

Urban heat island in Asian and Australian cities is better developed under calm and clear sky conditions. Most of the experiments have confirmed that higher wind speeds are associated with low urban heat island intensities while the threshold value of the wind speed over which UHI is drastically reduced varies as a function of the city characteristics. Coastal cities, seem to benefit highly from the presence of local winds, and in particular sea breeze. Although the presence of heat island is found to delay the flow of the sea breeze towards the city, most of the experiments confirm that there is an important cooling benefit for the city's climate. Clear sky conditions favor the development of UHI however under quite windy conditions the impact of cloud cover is quite limited.

Urban heat island represents a major local climatic phenomenon in Asia and Australia, increasing considerably the temperature of urban areas. This has important energy, environmental and social consequences while it deteriorates the quality of life of the citizens. Existing knowledge on urban heat island is quite rich but is overshadowed by various inconsistencies as related to the performed experimental and theoretical analysis. Therefore there is a need for an objective experimental and communication protocol to be followed in future UHI studies. Complete and accurate knowledge of the magnitude and the characteristics of heat island is a prerequisite for a proper and complete planning of urban mitigation and adaptation technologies.

Acknowledgments

I would like to thank Prof Costas Cartalis for his very useful suggestions and remarks.

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