Global Warming and the Urban Heat Island

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Keywords: urban heat island · climate change

Introduction

The aim of this paper is not to present an exhaustive synthesis of the literature addressing global warming and the urban heat island; rather, it is to shed light on some common misperceptions and to address this issue by presenting a number of different perspectives and by highlighting some of the topics that require further research. By 2005, in the most developed countries of the world, ∼74% of the population lived in urban areas. Between 2005 and 2010, the world's urban population is predicted to grow at an annual rate of 1.96%. By 2015, cities with over 10 M inhabitants ("megacities" – see also Kraas, this volume) will account for 9% of the total urban population (http://esa.un.org/unup/, [as of 10 Nov 2006]). However, urban growth incorporates two other trends: income growth and spatial growth or sprawl (Kahn 2006). The flight to the cities has been exacerbated not only by the effects of desertification, reductions in biodiversity and soil fertility in the rural areas, and the effects of globalization, especially in third-world nations (Handay et al. 1992, cited by Oke 1997), but also by income growth, especially in developed countries. As income grows, the urban population tends to sprawl (Kahn 2006).

According to Mills (2006), the new urban *utopia* is the sustainable city, whose impacts upon the environment are minimized without bringing about a reduction in the quality of life of the urban dwellers (Newman 1999; Kamp et al. 2003). Sustainable development is therefore the most important aim of the urban planning process (Barton 1996), because severe environmental problems, such as poor air and water quality, noise and thermal stresses, are especially likely in cities. Today's urban sprawl has led to worsening environmental problems, as more area is sealed over (i.e., becomes impermeable through paving or building construction), less green area remains, and water and energy consumption increase (Kahn 2006). As a result, ever more serious local, regional and even global threats have been emerging (Oke 1997; Decker et al. 2000).

Many titles in the scientific literature refer either to global warming (GW) or to urban climate, the latter including in particular the issue of urban heat islands (UHI). However, there are few papers or books that address the relationships between GW and UHI. Differences in temporal and spatial scales, research methods and data sets, as well as the lack of a comprehensive theoretical framework, are responsible. However, a better understanding of the role urban areas play in GW is an urgent concern, so that one might fight the negative consequences of GW and to take necessary measures to mitigate those consequences or to adapt to new climate conditions. On the other hand, the impact

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Written for this collection and originally published in:
J.M. Marzluff et al., *Urban Ecology,*

of GW upon urban thermal climates is also poorly understood and is often the object of many overly simplistic and erroneous ideas.

Global Warming

Climate change is defined by the Intergovernmental Panel on Climate Change (IPCC 2001) as any change in climate over time, whether due to natural variability or as a result of human activity. Ever since the formation of the Earth, there has always been considerable temperature variability over time, as is attested by both natural and documentary sources. The mean global temperature has increased by 0.6° (±0.2°C, 99% CL) during the 20th Century. Warming has been more significant over land than over the ocean, and most intense in the winter and in the Northern Hemisphere. In turn, the daily temperature range has been decreasing. Over the last millennium, colder and warmer periods have alternated, mostly due to natural forcing factors: for example, a "Medieval Warm Epoch" was followed by a "Little Ice Age" that lasted from around 1300 until the 1850s (Brázdil et al. 2005). From then onwards, the temperature has been rising, although not in a continuous and uniform manner. This temperature increase has been particularly intense during 1910–1945 (centered in the North Atlantic) and from 1976 onwards, particularly in the middle- and high-latitude areas of the Northern Hemisphere (except for the NW Atlantic areas) (Drogue et al. 2005).

According to many studies (e.g., IPCC 2001) the latter temperature rise has been exacerbated by human activity, namely through the emission of greenhouse gases. Moreover, the increase in mean temperature that occurred during the 1990s was the highest in the 20th Century. Global temperature anomalies (in relation to the 20th Century mean) in the early years of the 21st Century seem to confirm that warming is continuing – the single greatest anomaly took place in 2005 (+0.61°C; the warmest year of the 20th Century was 1998, at +0.58°C); [see at http://lwf.ncdc.noaa.gov/oa/climate/research/anomalies/anomalies.html]. According to IPCC (2001), a worldwide increase of 1.4 to 5.8°C (depending on the scenario) is expected to occur from 1990–2100. An update of the IPCC report was released in early 2007.

The Urban Thermal Effect and the Urban Heat Island

Tables summarising the climatic effects of urban areas have been presented elsewhere – e.g., Landsberg (1981), Oke (1988), Kuttler (2004) and in the present volume by Kuttler and Endlicher et al. Here, we focus on the effects of urban areas upon urban temperature, specifically upon the air temperature in the urban canopy layer.

Urban climate is a consequence of regional, local and urban geographical features (Lowry 1977). In most cases, due to the non-existence of pre-urban data, the "urban thermal effect" is calculated by comparing data from urban and nearby rural meteorological stations. The UHI is the best documented instance of inadvertent human climate modification (Oke 1987). It is exemplified by those urban areas where the surface, sub-surface or air temperatures are higher than the corresponding temperatures in surrounding rural areas. The UHI occurs most strongly during night time (see also Kuttler, this volume). Oke (1987) summarized the main modifications of the energy balance that lead to UHI formation. UHI intensity is defined as the difference between the highest air temperature recorded in the urban canopy and the lowest recorded in the surrounding rural areas. This apparently simple definition is actually not simple, and is applied in many different ways in different case-studies, due to differences in methods used in the collection of the data (such as relying on data from meteorological station[s] vs carrying out field measurements) and/or differences in the selected thermal parameter (minimum temperature, daily temperature range, maximum temperature, annual or monthly mean temperature), among other factors. These methodological differences are critically important and often render generalization difficult or impossible.

Consequences of Global Warming to the Urban Heat Island

Warmer cities have been frequently associated with global warming (the former being referred to as either a cause or a consequence of the latter). However, a large number of questions have arisen, and remain, with regard to the relationship between these two phenomena. "In many instances, the urban climate effects are similar to, and maybe even greater than, those changes predicted from global climate models (GCM)" (Grimmond 2006). Lombardo (pers. comm.) states that air temperature in São Paulo (Brazil) increased by ~2°C during the last century, that is, by ~3x the increase in mean temperature of the planet.

On the other hand, global warming may not necessarily bring about an increase in UHI intensity: urban-rural temperature differences may remain constant even in an overall warmer world (Oke 1997). UHI intensity could even decrease during global warming, due to the likely increase in vertical instability conditions and the subsequent dissipation of urban heat (Brázdil & Budíková 1999). Future UHI trends will also depend on the frequency of the synoptic conditions (e.g., anticyclones) and weather types (calm and cloudless weather) that favour high-intensity heat islands (Oke 1987; Morris & Simmonds 2000). Indeed, Beranová & Huth (2005) found that the long-term changes in Prague's UHI are associated with variations in the synoptic circulation types. The intensity of the UHI has increased the most (from 1961 to 1990) under prevailing anticyclonic conditions in every season except for spring. That increase also depends on the prevailing airflow directions. The analysis of data stratified in accordance with the circulation conditions indicated that the intensification of the UHI is generally higher under anticyclonic conditions and a S + SW flow (+0.27°C/decade in the winter).

The London Climate Change Partnership report (LCCP 2002) predicts not only the intensity of the UHI in London (particularly in the warm season), but also the number of days during which the UHI is expected to be >4°C – both under the B2 and A2 IPCC scenarios and through the use of statistical downscaling techniques (Wilby & Wigley 1997; Patz et al. 2005). However, there are several limitations with regard to global and regional climatic modelling and the use of downscaling techniques. This is especially so whenever the downscaling concerns urban areas: additional problems arise due to the difficulty of (1) representing urban areas in regional models and (2) collecting detailed data concerning the urban features for every pixel. As argued by Lamptey et al. (2005), additional observational and modelling studies are still lacking. Furthermore, for warmer regions, if global warming causes increased air conditioning in cities, then more anthropogenic heat will be released and the UHI will increase further still (Auliciems 1997). Conversely, in colder areas there will be a reduction in energy use for heating, but "... early snowmelt will increase the thickness of the thawed layer in summer and threaten the structural stability of roads, buildings and pipelines" (Hinkel et al. 2003).

Moreover, the current changes in the magnitude of the urban thermal effect cannot be expressed solely in terms of UHI. In some cases, there is a decrease in UHI over time alongside an increase in the areas affected by urban warming, due to urban sprawl. In both Europe and North America, the greatest growth in both "core" urban area and population growth took place one century ago. "Much of the population shifts now underway involves movement away from concentrated urban areas and into extensive, sprawling metropolitan regions, or to small- and intermediate-size cities. (...) This means that the imprint of urban areas on climate is increasing" (Grimmond 2006,p. 223). Tereshchenko & Filonov (2001) predicted that UHI intensity in Guadalajara (Mexico) will decrease due to "megalopolization", but the area affected will be larger. In New

Jersey (Rosenzweig et al. 2005), even if UHI intensity does not increase, “UHI like” conditions and temperature extremes will expand in dense suburban areas.

The Influence of Cities upon Global Warming

A Direct Impact upon Global Warming?

The increase in temperature of cities all over the world does not have a direct impact upon global warming. This is because urban areas cover $<1\%$ of the world’s land surface and urban effects upon air temperature “. . . only extend downwind for at most tens of km and dilution renders the impact on global climate negligible” (Oke 1997, p. 278). Furthermore, the energy released by human activities is only 10^{-4} that received on Earth from the Sun (Crutzen 2004).

Indirect Impact Through Increasing Emissions in Urban Areas?

Cities are, however, the most important source of greenhouse gases**.** Globally, 85% of the total anthropogenic CO_2, CFCs and tropospheric ozone are produced in or near urban areas (Oke 1997), as a result of “. . . higher living standards and higher demand for transportation, energy, water, and other resources and services” (Kahn 2006). The high density of pollutants in UHI plumes affects atmospheric chemistry and climate on a larger scale (Crutzen 2004). As the sensible heat fluxes increase, the ascending vertical atmospheric motion may intensify, leading to more unstable conditions (Lamptey et al. 2005; Makar et al. 2006) and to the carrying upward of water and pollutants into the middle and upper troposphere, with potential regional (and global?) consequences (Crutzen 2004; Sherwood 2002).

Cities are also a major source of airborne particulate material, which has a distinct climatic effect. IPCC (2001) includes computations of direct and indirect radiative forcing effects of different types of aerosols. Aerosols generally tend to slow the increasing temperature trend, with the exception of fuel organic carbon aerosols (there is also great uncertainty about mineral dust aerosols).

Urban Influences upon Global Temperature Trends?

Very different opinions can be found in the literature with respect to the urban influence upon the temperature trends. Some of those differences may reflect differences in methods and in data used. For example: (1) Several thermal parameters have been used (e.g., minimum and maximum temperature, daily temperature range, several period averages). (2) The approach varies according to the spatial scale of the research. In global or continental studies, the degree of spatial generalization is greater and therefore urban influence seems less important (Jones et al. 1999); [but note: some controversy remains (Peterson 2003) about the classification of meteorological stations as either “urban” or “rural”]. When seeking to identify the temperature trends of a city or a few cities, it is easier to collect metadata from each meteorological station in order to look for the non-climatic causes of the observed trends. Brázdil & Budíková (1999) and Beranová & Huth (2005) in Prague, and Quereda-Sala et al. (2000) in Spain are examples of research at a more detailed spatial scale. (3) Methods used to assess the urban influence may also differ. Three such methods are described below:

Method 1 – comparing series from “urban” and “rural” meteorological stations (or groups of stations). IPCC (2001) compared trends from rural stations (selected per the classification by the Global Historical Climatology Network - GHCN) with those from a larger group of stations (which included urban ones). Karl et al. (1988) and Peterson (2003) used data from several groups of US stations, the latter using 40 clusters of stations (including urban, sub-urban and rural ones), to show that the choice of different criteria to classify the cities leads to different results (see Fig. 1 in Peterson 2003). Shimoda (2005) compared rural and urban stations in Japan, whereas Brázdil & Budíková (1999) and Beranová & Huth (2005) compared Prague's urban stations with surrounding rural stations;

Method 2 – comparing the series produced by meteorological stations (which may reflect the influence of the urban effect) with the series resulting from the reanalysis carried out by the National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) (Kalnay & Cai 2003; Zhou et al. 2004);

Method 3 – other authors used indirect criteria (Parker 2004; Parker et al. 2006). Because most studies (mostly carried out at middle-latitudes) show that the UHI increases under low wind speed and is greatest during night-time (Oke 1987), these authors compared trends of minimum temperature values from 264 urban meteorological stations under calm conditions with those under windy conditions.

Perhaps partly as a result of the differences in the methods used to assess the urban influence, in the scale of the analysis and in the thermal parameters used, these studies have yielded different conclusions, as described below.

"Large Scale Warming is not Urban"

The title of this paragraph is the same as that of a paper in Nature by Parker (2004). Parker concluded that "... urban warming has not introduced significant biases into estimates of global warming. The reality and magnitude of global-scale warming is supported by the near-equality of temperature trends on windy nights with trends based on all data".

However, uncertainties exist, for example:

(i) Parker does not state whether the relevant stations were urban or rural, nor how many of each there were;

(ii) according to Parker, "... the main impact of any urban warming is expected to be on minimum temperature"; however, the highest values of UHI typically occur a couple of hours after sunset (Oke 1987) – not at dawn, when the minimum temperature is most likely to occur. Besides, in some cities such as Shanghai (Chen et al. 2003) and Belgrade (Unkaševi¢ et al. 2005), there has been an increase in the maximum temperature that is probably due to the UHI;

(iii) as argued by Pielke & Matsui (2005), the UHI does not depend solely on the wind speed, but also on "... thermodynamic stability, aerodynamic roughness, and the vertical gradient of absolute humidity. (...) Parker's [2004] conclusions, therefore need further analysis and interpretation before they can be used to conclude whether or not there is an influence of urban warming on large-scale temperature trends";

(iv) the wind speed parameter used in that paper to select the nights in which the UHI was expected to occur was the daily mean wind speed, which is in fact an estimated (i.e., not actually measured) parameter based on the NCEP-NCAR reanalysis. Although these daily average reanalysis wind speeds are generally sufficiently correlated with the limited available observing-station wind speeds, it does not seem to make much sense to draw conclusions with regard to the UHI occurring at dawn based on the daily average wind speed;

(v) finally, there are some cities [(mostly but not exclusively in areas with irregular topography or near sea/lake shores), such as Nice (Carrega 1994), Eilat, Israel (Sofer & Potchter 2006), Lisbon Spain (Alcoforado & Andrade 2006; Alcoforado 1992, Andrade 2003), Fribourg Germany (Roten et al. 1984) and Calgary CA (Nkemdirim 1976)] where intensity of UHI does not increase linearly with reduction in wind speed from the prevailing direction.

Under very calm wind conditions, these cities are prone to thermally-induced breezes that frequently create urban cool islands or weaken the UHI.

In turn, the IPCC report (2001) concludes "... that estimates of long-term (1880 to 1998) global land-surface air temperature variations and trends are relatively little affected by whether the station distribution typically used by the four global analyses is used, or whether a special effort is made to concentrate on rural stations using elaborate criteria to identify them."

Peterson (2003) considers the urban influence to be insignificant in the USA. He compared 40 clusters of stations (191 urban, 85 rural, 18 suburban). After adjusting for biases in the data caused by the differences in altitude, latitude, time of observation, instrumentation and non-standard settings, he could not find any significant impact of urbanization across the *in situ* temperature observation network in the US. He argues that this is due to "micro and local-scale impacts dominating over the mesoscale UHI", combined with the fact that observations are less frequent in areas, such as industrial ones, that are usually warmer than rural areas. His work illustrates the need to acquire detailed knowledge of the sites and settings of the meteorological stations from which data are used.

Peterson (2003) presents Figure 6 of his paper as being a portrait of a "real" urban thermal field, but that figure in fact represents the spatial variation of surface temperature, rather than that of the air temperature – and surface temperature responds in a much more direct way to the physical properties of the substrate than does air temperature, the variation of which is much less dependent upon microclimatic factors. Besides, it seems to us that what this author calls "the ruralization of urban areas", as opposed to the "urbanization of rural areas" is a reflection of urban sprawl - a process that causes the UHI to be an outdated concept in the case of certain cities.

Based on the series produced by the National Observatory of Athens, Founda et al. (2004) found that cities are not influencing global temperature trends. They note that annual mean air temperature increased by 0.047°C/decade over the last century, most significantly during the warm season, and that the increase in the daily maximum temperature was greater than that in the daily minimum temperature. They also claim that, during the 1990s, "... a sudden temperature rise was observed during both the warm and the cold seasons ..." which attenuated the differences between the maximum and minimum temperatures and between the warm and cold seasons (p. 36). Yet, the UHI in the historical center (where the meteorological station is located) has not evolved uniformly over time, and, in particular, the urbanization rate (building density, population growth) has not undergone any recent increases, which is why these authors have concluded that this last temperature rise was not due to an increase in the urban effect. However, it is important to bear in mind that other factors may cause the UHI to increase, such as increased release of anthropogenic heat associated with rises in energy consumption.

"Large Scale Warming is Caused by Cities"

In some studies, global warming is almost ignored as the effect of the cities "encroaching upon observatories" (Quereda-Sala et al. 2000) becomes regarded as increasingly important. Two studies from Mediterranean Spain serve as examples. In their study of ten Spanish 1st order Mediterranean observatories (mostly located in cities), Quereda-Sala et al. (2000) state that "... the assumption of temperature stability in the Spanish Mediterranean should not be rejected, once systematic changes in air temperatures only occurred in highly urbanized areas". In turn, García-Barrón et al. (2004) have identified a positive trend in the minimum temperature series for Badajoz over 1864–1984. In 1984 the observatory was relocated from the historical city center to the University Campus. From 1984 onwards, the minimum temperature exhibited a negative trend until 1999, whereas the maximum temperature has exhibited a positive trend ever since.

Large Scale Warming is Also Urban

Other papers highlight the impact of the urban effect upon temperature trends while taking into account the changes over time in the conditions surrounding the climatological stations (Oke 1997), or show that the UHI intensifies as cities grow – e.g., Madrid (Yagüe et al. 1991), Seoul (Kim & Baik, 2002) and Tucson (Comrie 2000, in Beranová & Huth 2005).

Indeed, we need to somehow check whether the city under study has influenced the temperature change and to isolate that urban effect from the global temperature rise, that is, to extract the urban bias from the long-run temperature series. The papers on this subject show quite different and even contradictory results. We find that those differences are partly due to differences in the methods adopted to extract the urban bias, and partly due to the data used (number and type of stations, temperature parameter, period).

One method used to extract the urban bias, particularly when working with a large set of series, includes taking population growth into account. It is used mostly because it is easily available. According to Jones et al. (1989) "Although population growth is an indirect measure of urbanization and the urban warming effect, it is the only statistic that is readily available for most regions of the world". However, the usefulness of the demographic information is highly dependent on its reliability and "[T]he areal basis of reporting population statistics is often at an inappropriate scale" (Oke 1997). An illustration of this point comes from Portugal: the meteorological stations *Sintra/Granja* (located on a military base far from the nearest densely urbanized area) and *Lisboa/Geofísico* (in the Lisbon city center) are both presented in the NCDC database as being associated with a population of 1.1 M (i.e., the population of the Lisbon metropolitan area). How can this type of reliability problem be controlled for at the global scale? The fact is that errors such as these can lead to wrong conclusions with respect to the impact of the urban effect upon the air temperature. Moreover, the use of population size as a criterion for estimating the urban effect is also subject to controversy; the magnitude of the urban effect may be more closely associated with the level of energy consumption (e.g., cal/person/year), which depends on other socio-economic factors (Brázdil & Budíková 1999, re. Prague; Chen et al. 2003, re. Shanghai). Remember, the population of numerous cities in "developed" countries has recently tended to stagnate or even decrease. For example, the population of the seven largest French cities grew by 82% from 1955 – 1990, but is expected to increase by only 9% over 1990–2015 (http://esa.un.org/unup/). Nevertheless, this does not necessarily imply a reduction in the thermal effect. Other factors, such as "the urban area land use modifications" (Changnon 1999), and the characteristics of the urban structure and the area of the city (Oke 1973, 1987; Changnon 1999) may influence the urban effect upon temperature, regardless of whether or not there is a population increase. Changnon (1999) has used deep soil temperature data, which he claims to provide "an unbiased measure of the natural temperature trend" and has compared its observed trend with that of the adjusted air temperature series (which used the population size to extract the urban bias) presented by Karl et al. (1988). He concluded that the urban influence is much larger than estimated by Karl et al., making it clear that population is not the best parameter to use to extract the urban bias from the temperature series.

A second method consists of calculating the differences between the trends recorded in the urban and rural stations of the same area. This may yield interesting results, provided that some questions are explicitly considered. The homogeneity of the series must be checked, in order to make sure that the data are comparable. The classification of the stations as "urban" or "rural" must be very carefully made (Peterson 2003). Finally, the number of stations used, the selected temperature parameter and the choice of the periods for analysis will also influence the results. For example, Brázdil & Budíková (1999) and Beranová & Huth (2005) both studied Prague using data from the Prague/Klementinum meteorological station. However, the studies gave quite different conclusions, due to differences in the periods for which the trends were calculated and to the use of different "rural" stations. This example clearly shows that great care must be taken in interpreting the “figures” of the urban influence upon the “global” temperature variation over time. Furthermore, the use of mean values by most authors conceals the differences between the day/night trends and between trends under different synoptic conditions.

Kalnay & Cai (2003) compared the trends of actually observations from the US with data from the NCEP-NCAR reanalysis. They concluded that changes in land use patterns (mainly due to urbanization) have had a very significant influence upon air temperature trends (0.027°C/decade). Those conclusions have been disputed, because the series had not been homogenized (e.g., Parker, 2004, 2006; Peterson, 2003). Zhou et al. (2004) used an improved version of the Kalnay & Cai (2003) method (including data homogenization) to estimate the impact of the urban effect in China: “. . . The average differences in maximum and minimum temperature trends between observed and R-2 [Reanalysis 2] data are −0.016 and 0.116°C per decade, respectively”.

Assessing the Impacts of Global Warming in Urban Areas

IPCC (2007) includes more recent figures and reviews forecasts with respect to global warming, as well as some downscaling references to a number of different regional areas - downscaling being particularly troublesome in urban areas. Moreover, in the elaboration of forecasts, “. . . there exists a hierarchy of causal relationships with uncertainties at each level of the hierarchy (Carter 2001), such as those associated with the assumptions concerning (i) the main socio-economic and technological drivers of environmental change; (ii) the future emissions of greenhouse gases and aerosols into the atmosphere; (iii) the future composition of the atmosphere; and (iv) the future radiation balance of the Earth, . . . each [of which] is subject to additional uncertainties attributable to imperfect data and models as well as the inherent indeterminacy of predictions” (Carter 2001, p. 48). As regards estimating future impacts of climate changes, Carter (2001) argues further that there should be “. . . more emphasis on the presentation on uncertainties [at each stage of impact assessment] – both for stakeholders and for fellow scientists” (p. 49).

Regardless of the high level of uncertainty surrounding climate change forecasts, particularly at regional and local levels, it is likely that the impacts of climate change upon human life and activities will be considerable. Although most of the foreseen consequences are not exclusive to urban areas, they will be felt most intensely in cities (Patz et al. 2005; Lindley et al. 2006), due to (1) the socioeconomic and demographic characteristics of urban areas, (2) the concentration of infrastructures and (3) the cumulative effect of global warming and urban warming that can be expected . “In central London the UHI effect could add a further 5 to 6°C to temperatures during summer nights” (LCCP 2002).

The main consequences of the temperature rise in urban areas consist of its impacts upon the human health, the ecosystems, and consumption of water and energy. Some of the main direct impacts of global warming include an increase in mortality and morbidity due to the increase in the frequency and intensity of heat waves (even allowing for enhanced acclimatization) and, on the other hand, a decrease in winter mortality, associated with warmer winters. Some authors (e.g., Kalkstein & Greene 1997), have studied several large American cities and argue that the mortality increase in the summer will be greater than its decrease in the winter. Others consider that in the case of medium- and high-latitude cities, the decrease in winter mortality due to GW will be greater than the increase in summer mortality due to the heat waves (Martens 1998, based on the analysis of several cities located in different climatic zones; Keatinge et al. 2000, for Europe; Donaldson et al. 2003, for London). Others (Dessai 2002) only mention the summer increase. In tropical cities (e.g., Singapore, Caracas), an increase in mortality is expected to occur due to GW (Martens 1997). Other indirect effects of GW include increased production of aero-allergens associated with higher temperatures (Epstein & Rogers 2004; Wayne et al. 2002; McMichael et al. 2006); increases in air pollution (particularly ozone and other photochemical pollutants: Cardelino & Chameides 1990; Stone 2005); increased vector-borne infections (Epstein & Rogers 2004; Epstein 2004; Wayne et al. 2002; McMichael et al. 2006); sea-level rise; and increases in the frequency and magnitude of extreme meteorological events (besides heat waves), including hurricanes and flash-floods, which can have particularly bad consequences in urban areas (LCCP 2002, 2006; Smith 1999; Suarez et al. 2005; Bloomfield et al. 1999). Moreover, synergies occur in urban areas between the various different hostile factors: for example, combining high temperatures, more air pollution and more aeroallergens (Epstein 2004), can leave city inhabitants in a particularly vulnerable position (Kalkstein 1997; Lindley et al. 2006).

Urban ecosystems, such as cities' green areas, will also be affected by GW: species composition may change, exotic species may be favoured (Dukes & Mooney 1999; Wilby & Perry 2006) and the phenological rhythms of plant species may be modified (e.g., Seoul, Ho et al. 2006). Certain urban ecosystems, such as the intertidal ecosystems of the Greater London area (Wilby & Perry 2006), will also be affected by sea-level rise.

Furthermore, urban temperature rises will lead to increased energy consumption for refrigeration and air conditioning in summer (Shimoda 2005; Solecki et al. 2005) and decreased energy for heating in winter. The overall balance will depend on local conditions (LCCP 2002, 2006).

Discussion and Conclusions

Throughout this text, attention has been drawn to the fact that there is a wide gap between the various types of studies that address the issue of temperature change at different spatial scales – particularly between those that address the issue of global warming and those focusing on urban warming resulting from the urban heat island.

The large number of papers addressing the issue of global warming have used a variety of data sets, computational methods and climate models to estimate temperature trends. Despite these differences, the vast majority concur: since the temperature trends of the last century cannot be explained by internal variability of the climatic system (IPCC 2001), part of the observed global warming is human-induced and largely due to the increase in the emission of greenhouse gases. Even if the level of anthropogenic influence were to be radically reduced, there would still be a climatic response to the past emissions that would project itself far into the future (Lindley et al. 2006).

In the time since Howard's works on London's climate, the methods and techniques of urban climatology have improved greatly (see Kuttler, this volume), and many papers now address this subject. Urban climatology has emerged as a new scientific field, with both theoretical and applied objectives (Oke 1987, 2006; Grimmond 2006; Mills 2006). Even though several other climatological parameters are modified in and by the cities, attention in this present writing has been restricted to temperature change. Due to increases in soil sealing, decreases in evapotranspiration, the evolving characteristics of the urban fabric, and increasing anthropogenic heat flux, among other reasons (Kuttler, this volume), urban surface and air temperatures have been on the rise. This fact is usually quantified by using UHI intensity.

However, using UHI intensity as the sole relevant parameter in assessing the magnitude of the urban thermal influence raises several questions. First of all, UHI can be computed in very different ways, as discussed above. Moreover, as urban areas continue to sprawl, UHI may not be the best parameter for showing the increasing influence of urban areas upon local, regional (and global?) climate. This is because "urban" stations are often located in old city districts, far from the present growing urbanization processes; and also, many "rural" stations are becoming increasingly integrated into sub-urban, or even fully urban, settings. In those cases, the increase in those areas' anthropogenic influence upon the temperature trend may not be visible in variations of UHI intensity over time. The methods to be used in assessing the evolution of the urban thermal influence over time should thus be the object of serious discussion by the scientific community.

Over the last few decades, an association has been drawn between warmer cities and global warming. It is true that the urban temperature rise now observed in several cities is similar to that predicted by global climate models to occur on a global scale in the next 50 or 100 years. However, a great deal of uncertainty remains with regard to the effects of global warming upon urban temperatures, on the one hand, and the influence of urban areas upon global warming, on the other. A survey of many studies indicates that the conclusions are indeed varied and that a number of problems remain to be addressed with regard to assessing and forecasting both the urban "reaction" to GW and the influence of the cities upon GW. Importantly, the results of various studies cannot be easily compared, due to the wide variety of data sets and analysis procedures used. Further discussion of these aspects by the scientific community therefore seems warranted.

Our goal was not to present a synthesis of all the literature addressing this subject; rather, it was to survey a number of relatively recent papers and thereby not only extract some of the main conclusions, but also highlight some of the problems and questions that, up until now, are yet to be given a clear and unanimous answer and which should be the object of further reflection and discussion.

Main Conclusions

In the works studied and cited for this present work, all authors agree that the energy balance in urban areas is modified due to human construction and activities, and that, as a result, the subsurface, surface, and air temperatures are higher than in surrounding areas.

Most authors agree with the following statements regarding the influence of urban warming upon regional (and global?) warming:

a) Urban anthropogenic heat fluxes do not have a direct impact upon global warming, because urban areas cover $<1\%$ of Earth's land areas and the amount of energy released by man is much less significant than the energy received by Earth from the Sun.
b) Cities are a very important source of anthropogenic greenhouse gases and thereby contribute indirectly to global warming.
c) Warming of urban atmospheres exerts a slight influence upon the computation of global warming (except in the case of those authors that use large data sets and work at the planetary or hemispheric scale).

   Most authors agree with the following statements about the influence of global warming upon urban warming:
d) The impacts of global warming (including its impacts upon human well-being and health, various ecosystems, and on levels of energy and water consumption) may be exacerbated in urban areas.
e) Depending both on their latitude and on their regional climate, cities will either be losers or winners from global warming (Oke 1997). From the point of view of the human bioclimate, the high-latitude cities will probably be the winners, and low- and mid-latitude cities, especially in the summer, will probably be losers. Warmer cities are, in general, likely to experience an increase in the levels of photo-oxidant air pollution and water consumption, so from that point of view all the cities will probably lose. As regards energy consumption, the only winners will be cities in colder climatic zones and, in the winter, those at intermediate latitudes. However, additional climate-related problems may arise in high-latitude cities as a consequence of GW.
f) The consequences of GW will exhibit considerable regional variability and will depend on the future frequencies of the various synoptic situations and weather types. For example, an increase in vertical instability associated with higher temperatures can partially offset urban warming.

Some Issues that Remain to be Addressed

The first issue concerns choosing the best methods for extracting urban bias from temperature series, bearing in mind that, during the 20th Century, urban areas have been engulfing a large number of the historic 1st order meteorological stations. One method consists of statistical modelling, seeking to correlate temperature increase with population size. This method is subject to "... some debate, since changes can occur independently of population and there are limitations to population statistics" (Voogt 2004). A second method compares series from rural and urban stations located in the same general area (e.g., Brázdil & Budíková 1999, and Beranová & Huth 2005). Although this method seems to yield the best local results, its application is very difficult at the global scale. Ultimately, the best solution may involve construction of large data sets, including appropriate metadata so that one can correct the series, and the use of standard computation methods.

Yet another problem is assessing the degree of uncertainty involved in discussing and forecasting the consequences of urban/global warming. Uncertainty is present whenever each causal relationship involved in global changes is computed and projected, as well as whenever those projections are used as inputs to assess impacts (from the global emission scenarios and the projections regarding radiative forcing to the climate projections and the analysis of regional scenarios and impacts) – and, of course, feedback mechanisms occur at and between all of these levels (Carter 2001).

To sum up, it is very important that the research in this area continues to be improved, in order for it to be possible to accurately assess and forecast urban temperature trends, and to produce better estimates and forecasts of global warming that take into account the urban data sets.

Although we cannot at this stage accurately quantify urban influences upon global temperature trends, measures must be taken to mitigate the negative consequences of both urban warming (including upon human well-being and health, and upon urban economies) and global warming, which will be felt with greatest intensity in the urban areas (the impacts of sea-level rises upon low-lying cities is an example). On the other hand, measures aimed at capturing the benefits of climate change should also be taken (Lindley et al. 2006). Special attention should be devoted to the situation of the low-latitude cities, most of which are located in developing countries where the urban population is growing at very high rates. Indeed, those are the cities that, from any perspective, will surely be the losers from urban and global warming. We can be sure that local measures taken there will have an impact upon the political measures aimed at decreasing global warming.

Acknowledgments We are grateful to Professor Rudolf Brazdil, for the comments he kindly made about a previous version of this text and to Teresa Vaz, for her intelligent help in the literature search.

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