Effects of Cities on Local Climates

Matthias ROTH *a

1. Introduction

For the first time, about half of the world’s population is living in urban areas (Population Reference Bureau, 2001). 95% of the growth over the next three decades will occur in less developed countries, 60% of which will be in Asia (especially China and India). By 2015, 16 of the world’s 24 megacities (cities with more than 10 million people) will be located in Asia. The urban transition now underway in Asia involves a volume of population much larger than any other region in the world and is taking place on a scale unprecedented in human history.

Many of these people will be added to cities whose infrastructure is often already at or beyond its limit which will lead to an inevitable decline in the quality of life and the urban environment. Several of these problems are directly or indirectly related to the climate of these cities. In mid-latitude cities, heat stress in summer can lead to increased mortality and loss of productivity. Increase in pollutant sources both stationary (e.g. industries) and non-stationary (e.g. vehicles) result in worsening atmospheric conditions. The situation is more dramatic in the less developed world and the tropics. Industrial areas are often located with little regard to ventilation and operate with little or no emission control. Many cities in the tropics experience weak winds and limited circulation of air which helps the accumulation of pollutants. High temperatures increase the production of secondary, photochemical pollutants and the high humidity contributes to a hazy atmosphere. In addition cities are a major source of greenhouse gases which are thought to be responsible for the observed global warming trend.

There are compelling practical issues relating to human health and well-being for which it is important to comprehend the physical basis of urban climates and thence to ensure a pleasant and healthy environment for city dwellers and to reduce the harmful effects of urbanization on large-scale climates. Some of the observed urban climate changes, e.g. temperature increase, have already occurred at a magnitude similar to that projected on a global scale into the future. Knowledge of urban weather and climate modification holds lessons for global climate change issues. The purpose of this paper is to summarize current knowledge of urban influence on the local climate and discuss practical implications of such understanding. Section 2 briefly introduces the background needed to understand why the presence of a city changes the local atmospheric environment. Examples of modifications are given in Section 3. The relationship

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between urban climate and global environmental change is discussed in Section 4, and Section 5 concludes with examples of efforts to mitigate some of the adverse effects.

2. Nature of the urban atmosphere

Urbanization, which includes residential, commercial and industrial developments initiates one of the most dramatic human-induced change of a natural ecosystem: a natural landscape, often containing transpiring vegetation and a pervious surface, is converted to a built, largely impervious landscape made-up of rigid, sharp-edged roughness elements. The introduction of new surface materials (such as concrete, asphalt, tiles, etc.), the construction of buildings and the emission of heat, moisture and pollutants dramatically change the following properties of the surface and the atmosphere above:

- **Radiative** Changes occur due to the introduction of new surface materials which have a larger range of albedo and emissivity values compared with vegetation; the 3-D arrangement of buildings and canyons interacts with radiation in more complex ways than a flat surface.
- **Thermal** The thermal mass of buildings is larger compared to natural surfaces thereby providing a massive reservoir for heat storage (daytime) and release (nighttime).
- **Moisture** Urbanization is associated with effective “sealing” of the surface, *i.e.* reduction of moisture available for evapotranspiration.
- **Roughness** Obstacles such as buildings, bridges etc. act as bluff bodies in the aerodynamic sense because of their impermeability, inflexibility and sharp edges. When exposed to the airflow they create strong positive and negative pressure differences over their surface, leading to flow separation and vortex shedding. This affects the transport of energy, mass and momentum to and away from the city surface. Turbulence is enhanced compared to the more homogeneous atmosphere over the rural surroundings.
- **Emissions** Emission of aerosols and greenhouse gases due to combustion of fuels, industry, cars, etc. affects the radiative transfer and act as condensation nuclei; waste heat and water vapour from combustion is added to the urban atmosphere.

A new set of ambient conditions is created which differs from that of the surrounding “undisturbed” rural areas. These changes are reflected in an altered energy balance – the basic and powerful framework used in the analysis of climate processes. It is therefore not surprising that, as urbanization proceeds, the associated weather and climate are often modified substantially. Every facet of every building, tree, etc. produces its own microclimate which all co-exist side-by-side. Spatial discontinuity occurs at all scales and advection is the norm. New microclimates evolve which in their aggregation result in unique regional climates for each city.
3. Urban effects on climate

In comparison with the surrounding landscape, the city is usually rougher, warmer and perhaps drier. This new set of surface conditions alters the physical characteristics of the urban climate. The most prominent modification involves the alteration of surface and air temperature which will be discussed in some detail below. Effects on other properties are probably less and not as well researched as those on temperature. Their treatment is therefore less comprehensive.

3.1 Heat island effect

Interest in urban climates began almost 200 hundred years when Luke Howard (Howard, 1833) first documented that cities appeared to be warmer than the surrounding countryside. This increase in surface and air temperatures over the urban area is still the most frequently observed and best documented climatic effect of urbanization. This condition has come to be known as the urban heat island (UHI). It is most pronounced at night under clear skies and light winds. It arises from differences in urban/rural cooling rates, i.e. less cooling in the city: daytime excess heat is stored in air and building fabric and released at night (slow because street canyons screen much of the cold sky).

The maximum difference in the urban peak temperature and the rural background temperature defines the UHI intensity $\Delta T_{u-r}$ or UHI max (Fig. 2). Over large metropolitan areas, there may be several plateaus, valleys and peaks in response to distinct intra-urban land-use such as parks, commercial and industrial developments as well as topographical features such as hills.

It is important to recognize that several types of UHIs can be defined depending on their location and height within the urban environment (Table 1). They are of course related but the processes involved in their genesis are different and so are their temporal dynamics. UHIs in the air are largest at night with a maximum in the city core (see below) and may even be negative by day.

**Table 1:** Simple classification scheme of urban heat island types (after Oke, 1995)

<table>
<thead>
<tr>
<th>UHI type</th>
<th>Location</th>
</tr>
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<tbody>
<tr>
<td>Air temperature UHI:</td>
<td></td>
</tr>
<tr>
<td>- Urban canopy layer heat island</td>
<td>Found in the air layer beneath roof-level</td>
</tr>
<tr>
<td>- Urban boundary layer</td>
<td>Found in the air layer above roof-level; can be advected downwind</td>
</tr>
</tbody>
</table>
Examples of air temperature UHI:

Most research has been restricted to cities in temperate climates. Observations show that the location of the nocturnal maximum UHI intensity roughly coincides with heavily built-up areas found in the center of cities. This is illustrated with two examples from Asian cities which also show many of the commonly observed features. In the case of Tokyo (temperate climate) the temperature is uniformly decreasing with distance away from the maximum (~14 ºC) observed around the commercial centres of Ueno, Shibuya and Shinagawa to a minimum (~10 ºC) observed in the more open and rural outskirts (Fig. 3). A similar picture is obtained in Kuala Lumpur (tropical humid climate) where the maximum (~31 ºC) is also associated with the city core and the rural surroundings to west and south-east are considerably cooler (~25 ºC) and separated by a sharp drop (cliff) in temperature from the built-up area (Fig. 3).

City size and air temperature UHI:

The magnitude of UHIs depends on the size and geometry of the city (Oke, 1973). Using population (P) as a surrogate of city “size”, UHI max is found to be proportional to log P when holding some controls constant: climate, topography, rural surrounds, weather (calm, cloudless), time of day (night) and height of traverse (1.5–2 m) (Fig. 4). This relationship works reasonably well for North America and European cities. Several tropical studies provide less than the full criteria and the tropical results increase scatter, probably related to wetness. The slope of the relation between city size and UHI max differs in different parts of the world. This is partly due to differences in the nature of the cities (i.e. street geometry, greenspace, heat release) but also due to differences in the cooling potential of their rural
surroundings (e.g. deserts, agricultural land, paddy fields, snow). Population is not a universal surrogate of great value but the relations have merit as first-order estimators of UHI max, in region of applicability and if P is related to site character UHI max puts an upper bound on values (Oke, 1999).

Examples of surface temperature UHI:

In contrast to air UHIs, surface UHIs are often greatest by day with a maximum in areas of large buildings or paved surfaces with a minimum at night. At regional and local scales, satellite sensors offer the ability to assess urban-rural differences and to give an integrated value of the urban ‘skin’ temperature (Figs. 5 and 6). It must be pointed out, however, that several methodological problems associated with the interpretation of these remotely-sensed data exist (Roth et al. 1989). Vertical surfaces, such as building walls, are under-represented by nadir remote sensors or systematically biased by off-nadir sensors which essential represent a 2-D, bird’s-eye view. Correspondence between dry (built) and moist (vegetated) surfaces with hot and cool areas is often quite dramatic (Fig. 6).

Figure 4: Relationship between population (P) and maximum urban heat island intensity (UHI max) for cities on different continents and representing different climate regions (Oke, 1999).

Figure 5: Urban heat island mapping at the city scale. Warmer surfaces are colored in red (from: http://Satellite.Zodiak.com/destination/frames_version/mapping/map_scales/building_scale.html)
Figure 6: Visible (left) and thermal infrared (right) images of sections from Baton Rouge, La. The yellow and red areas are hot, and generally correspond with roads and buildings; blue and green areas are cool and indicate water and vegetation. The solid blue band of color on the left side is the Mississippi River. The bright red areas in this image are about 65 °C; dark green and blue areas are around 25 °C (from: http://wwwghcc.msfc.nasa.gov/urban/urban_remote_sensing.html)

3.2 Humidity

Much less is known about urban effects on humidity. Urban/rural differences are small and the spatial pattern is complex. The consensus of mid-latitude studies suggests that the urban canopy air is usually drier (lower vapour density) by day, but slightly more moist (higher vapour density) by night. This pattern results from smaller vapour input as a result of a reduction in vegetation and hence smaller transpiration rates in the city compared to the greater rural evapotranspiration during the day. At night, a more humid environment is maintained in the urban area due to weak evaporation when the moisture content of the lower layers of the rural air is depleted by dewfall.

3.3 Airflow

It becomes obvious that urbanization affects the wind climate when one walks around buildings on a windy day. It is sometimes more sheltered and sometimes more gusty than an open site. The city as a whole affects the regional airflow. When winds are weak, thermal effects dominate and local-scale wind system resulting in a flow towards the warm city may be established. When winds are strong (> 5 m s⁻¹), the buildings of the city may act as a barrier, deflecting the flow around the center and slow the lowest layers as air crosses the city. This may result in changes in the wind direction due to reduced Coriolis turning and together with the convergence caused by uplift over the city disrupt synoptic weather fronts, cloud development and perhaps precipitation (e.g. Auer, 1981).

3.4 Precipitation

There is evidence to suggest that major urban areas cause changes in rainfall and increased occurrence of severe weather (e.g. Changnon, 1981, Cotton and Pielke, 1995). Uplift over the city due to convergence (see above), increase in cloud condensation nuclei from anthropogenic emissions and addition of moisture from industrial sources combine so that requirements for precipitation are anomalously present. Full understanding of the mechanisms thought responsible for enhanced rainfall, however, is not developed yet.
3.5 Turbulence
Modified surface heating and increased friction lead to perturbations in the mean wind and turbulence. These changes are most pronounced within canyons and just above where the introduction of sharp-edged buildings directly affects the airflow. The changed density and characteristics of the roughness elements alter the friction of the urban surface and therefore the vertical turbulent transport of heat, mass (e.g. moisture, CO$_2$) and momentum through increased mechanical and thermal mixing. Observational studies show that drag coefficients and turbulence intensities are larger (up to 50% for the latter) than their rural counterparts. The increased roughness and warmth of the city surface combine to produce a generally less stable atmosphere and promote stronger interaction between the near surface air and the rest of the UBL which results in an increase (doming) of the mixed layer. A comprehensive understanding of urban turbulence is important for many real-world applications such as understanding and modelling the dispersion of air pollutants or wind engineering practice for the design and construction of tall buildings.

4. Urban climate and global environmental change

The inadvertent modifications to urban climate may be used as analogues of the changes that humans cause at the global scale (Oke, 1997b). Obviously, the outcomes are not identical in their spatial scales. Nevertheless, the similarities in the magnitudes and the rate of climate change deserve attention as one considers how to react to global environmental changes.

4.1 Global warming
Is it possible that urban changes are responsible for global warming? Because cities are the source of most greenhouse gases and much of the aerosols that may lead to global warming they are indirectly responsible for the warming effect. Oke (1997b) suggests that 85% of the global total of anthropogenic CO$_2$, CFCs, methane and tropospheric O$_3$ originates in cities. The urban plumes of these substances extend hundreds, even thousands of kilometers downstream. Aerosols emitted by urban/industrial sources also have both direct and indirect cloud-radiative effects which cause or ameliorate changes in the global climate. However, the urban emissions do not directly warm the global atmosphere to any significant extent. The UHI is an essentially local phenomenon - urban areas cover much less than 1% of the earth’s surface and their extra heat content added to that of the global atmosphere is therefore insignificant.

There is, however, an important side issue. The measured global temperature is based on historical observations from weather stations, most of which are located in or near towns and airports. It is therefore possible that the global temperature record has been contaminated by readings from increasingly “urbanised” stations. Extensive efforts have been made to calculate the amount of urban temperature effect and to separate this “spurious noise” from the larger, non-urban climate signal. Karl and Jones (1989) suggest that the urban warming bias present in the entire US climate record was between 0.1-0.4 ºC from 1901 to 1984. This effect extrapolated to the global temperature record reduces to 0.01-0.1 ºC (Jones et al., 1989). More recently, Hansen et al. (2001) find evidence of a modest urban warming even in suburban and small-town air temperature records for US cities. They caution, however, that the inferred urban warming could be an artifact of inhomogeneities in the station records. The consensus which now seems to emerge is that the urban effects in the corrected global temperature signal are small.

At the local scale, however, urban dwellers have undergone a climate change of similar magnitude to that being observed on the global scale: 1–2 ºC over about one century (Fig. 7). Cities could therefore serve as useful “laboratories” in which to study the processes, effects and social influences of human activities. Urban populations and administration have experienced the same magnitude and speed of thermal change observed and predicted by climate
models. This means that they have also seen any biometeorological and societal effects and should be able to use that information to plan appropriate responses to any future change (Oke, 1997b).

![Figure 7: Long-term records of average annual near-surface air temperature: (a) for the globe, and station difference between an urban and a nearby less developed site near (b) Washington, DC and (c) Sao Paulo (from Oke, 1997b).](image)

4.2 Consequences of global warming

Several aspects of cities are temperature dependent and feedback upon the health of the inhabitants or the costs of running a city (Table 2).

<table>
<thead>
<tr>
<th>Climate impact</th>
<th>Cold</th>
<th>Hot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biological activity (plant growth, disease)</td>
<td>+</td>
<td>?</td>
</tr>
<tr>
<td>Human bioclimate (comfort, wind-chill, heat stress)</td>
<td>+ (W) / - (S)</td>
<td>-</td>
</tr>
<tr>
<td>Energy use (space heating, air conditioning)</td>
<td>+ (W) / - (S)</td>
<td>-</td>
</tr>
<tr>
<td>Water use (garden irrigation - pos. correlation with T)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ice and snow (transport disruption)</td>
<td>+</td>
<td>NA</td>
</tr>
<tr>
<td>Air pollution chemistry (weathering, photochemistry)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2: Impacts of urban heat islands, and/or a warmer base climate, on temperature-sensitive aspects of cities in cold and hot climate regions (from Oke, 1997b). + - beneficial; - - undesirable ('losers'); (W) – winter; (S) – summer; NA – not applicable; T - temperature
Biological activity

An increase in temperature usually stimulates biological activity which is mostly positive in cold climates where growing seasons are lengthened. In Tokyo, for instance an increase the emergence and increase of subtropical flora and fauna has been observed (The Japan Times, 2001). On the negative side, extra warmth may increase the range of insects carrying infectious diseases. The main vector of dengue for example is flourishing in mankind’s urban and suburban environments and has helped maintain the prevalence of this disease in Asian regions. The breeding behaviour of mosquitoes is very sensitive to temperature and only a small increase could result in an outbreak of this disease.

Human bioclimate

Inhabitants of cities in cold climates are likely to benefit in relation to human comfort and stress. Those in hot climates or those irregularly exposed to high temperatures will bear an increasing heat burden, however (Figure 8). Assuming future warming according to projections from global climate models, Kalkstein and Smoyer (1993) present mortality statistics which show dramatic increases of heat-related deaths for many cities. Similarly, the number of victims of heat stroke in Tokyo has nearly tripled since 1985, and is correlated to an increase in air temperature and the number of “tropical” nights (The Japan Times, 2001). Using climate warming scenarios and recognized thresholds for human comfort, it is clear that the population likely to be most affected is that in tropical climates.

Energy use

If the global climate becomes warmer, cities in cold climates can expect to save fuel for space heating. Cities in hot climates, however, will most likely face extra energy use for air-conditioning (Fig. 9). Air-conditioning use has significant related issues. First, cooling the interiors of buildings results in the release of hot air which contributes to an extra heat load outside which may lead to an additional demand for air conditioning. Second, depending on the power source used for air conditioning, extra fuel use is likely to increase the emission of greenhouse gases which in turn contributes to global warming.

Figure 8: Relation between maximum air temperature and mortality in Shanghai from 1980 to 1989. Above a threshold of about 34 °C, heat deaths increase sharply. Shading proportional to density of data points. (Oke, 1997b adapted from Kalkstein and Smoyer, 1993).

Figure 9: Relation between electricity power load at 16:00 hours and average daily temperature in Los Angeles for every day in 1986 (Oke, 1997b adapted from Akbari et al., 1989).
Air pollution

Atmospheric chemistry is strongly related to temperature. This is especially true for tropospheric ozone concentrations. Hydrocarbons are important precursors for the production of ozone. Their primary anthropogenic source is traffic. When mixed with NO and NO₂ (which are also produced by the combustion of fuel) they interact with the UV part of the sunlight and ozone is formed. This photochemical reaction is strongly stimulated by temperature (Fig. 10). There is also the possibility that extra natural hydrocarbon release from shrubs and trees can increase production of oxidants.

Figure 10: Relation between daily maximum air temperature and daily maximum ozone concentration in Connecticut. Shading proportional to density of data points (Oke, 1997b).

5. Applications of UHI Research

Relatively little of the large body of knowledge concerning urban climate has found its way into the urban planning process. However, if climatic factors were considered in future building, settlement or town planning it may be possible to reduce some of the negative effects predicted following an increase in the UHI effect (Table 2); this would be particularly beneficial to cities in tropical climates.

Examples of climate applications at the building scale are plentiful and often incorporated in traditional architectural building forms which are very specific to local climate conditions. Similar examples of climate input to the design of groups of buildings and whole settlements are not as readily available. Oke (1984) lists a few cases for cities in extreme climatic environments (mostly having cold winters) where plans have been drawn up to address specific problems such as very wet, snowy and windy conditions. In extreme climates, the role of the climate is dominant and is naturally given high priority in the planning process. The reason why climate is included in the planning of developments is often to address the following 4 concerns (after Oke, 1984):

- Wind (to avoid problems associated with wind loads on structures; concern with energy loss from buildings; street-level winds which may be dangerous to pedestrians; etc.)
- Solar radiation (to avoid mutual shading of buildings or maximize the solar energy potential through building orientation; need for shading to reduce solar load; etc.)
- Precipitation/runoff (adequate flood control, storm water routing and drainage system)
- Air pollution (to prevent the negative impact of pollutant emissions in the vicinity of sources; ventilation of entire building groups or cities)

Because of the current demands to create a more proactive process to join together knowledge on the urban climate, planning and design concepts, the US Environmental Protection Agency in concert with the Department of Energy’s Lawrence Berkeley Laboratory produced two major design concepts for mid-latitude cities with hot and relatively dry
summers (Garbesi et al., 1989; Akbari et al., 1992): (1) The use of light-coloured surfaces to enhance the reflection of incoming solar radiation to reduce solar heating during daytime and hence decrease the need for cooling. (2) Planting of trees to produce cooler temperature through shading and evaporative cooling.

Using a numerical, meso-scale meteorological model, Kinouchi and Yoshitani (2001) calculate the cooling effect due to an increase in the amount of roof-top vegetation in Tokyo from the current 24% to 40%. The near surface air temperature is predicted to decrease by 0.6 ºC as a result of increased evapotranspiration and reduced heat conduction into the buildings. The model also predicts that the region of cooler air will be advected over the less urbanized surroundings in the afternoon.

5.1 Park-induced coolness

On a larger scale, vegetated parks are also likely to be cooler than their surrounding built environment. This is demonstrated in remote sensing images of the surface temperature of cities which show marked coolness of vegetated surfaces in general and parks in particular (e.g. Honjo and Takakura, 1986, Roth et al. 1989 and Gallo et al., 1993).

Temperate climate cities

Influence of surface coolness upon the air can be found in maps of urban heat islands (e.g. Oke, 1989, Spronken-Smith and Oke, 1998). Like the urban heat island effect, the thermal contrast between a park and its urban surroundings is best developed on calm, cloudless nights with the nocturnal coolness of the park being established soon after sunset and reaching its maximum cooling near sunrise. Depending on the size of the park the coolness is typically between 1-2 ºC at night but can reach up to 5-6 ºC under ideal conditions and for some cities (Vancouver: Spronken-Smith and Oke, 1998. Sacramento: Spronken-Smith and Oke, 1998; Tokyo: Hamada and Mikami, 1994). The actual magnitude depends on park type (substantial tree canopy: maximum cooling in afternoon; open grass parks: max cooling near sunrise), whether it is irrigated, nature of surrounding landscape and macroscale climate. The area of lower air temperature associated with the park reaches beyond its border by about one park width.

Tropical climate cities

Literature from cities in tropical climates is sparse. This is surprising given the potential of parks to cool and thereby provide relief from excessive heat loads. In Tuscon, a hot and dry city, Spronken-Smith (1994) observed the air of the largest park in the city to be up to 6.8 ºC cooler than its suburban environs. In Kuala Lumpur, a hot and humid city, parks are 4-5 ºC cooler than nearby commercial areas in the afternoon (e.g. Sham 1991) with only a 1 ºC difference found in the evening between well-treed parks and their urban surroundings. In Madras, India, Sundersingh (1991) reports that at night parks may provide cooling of up to 4 ºC. In cities with uncomfortably hot summers, urban parks offer the potential to cool neighbourhoods, which is particularly important because reduction of only a few degrees can be critically important in terms of human health and comfort.

Universal solutions are probably not possible. An increase in humidity due to excessive use of trees may have adverse effects in humid climates because they add moisture to the already humid air. They may also reduce the ventilation of houses around which they grow. Because of the sun-earth geometry, roofs are extremely important in tropical building climate. Shade trees should be tall and have a broad enough canopy to shade the roof as well as the walls, otherwise the accompanying loss of ventilation due to reduced turbulent transport will lead to oppressive conditions (Oke, 1989).

Recommendations

Systematic research into the benefits of UHI mitigation efforts is still scarce. Questions to be addressed include:

- Is there an optimum proportion of the city to devote to vegetation
• Is there an optimum arrangement of such greenspace
• Is there a preferred orientation for roads and buildings to maximize solar radiation influences
• Are there optimal height/width ratios for street canyons to maximize energy conservation or pollutant dispersal.

Further measure to improve the urban environment and save energy include:

• reducing emissions
• switching to fuels with less GHG side effects
• greater use of passive heating and cooling technology.
• intelligent use of trees to shelter and shade
• increased use of light-coloured surfaces in hot cities
• more compact city design and greater use of mass transport

Addressing these issues, however, depends on the political will of local and national governments and is often not possible because funds are limited and may be used to resolve more immediate needs, especially in less developed countries.

References


