# Urbanization and global environmental change: local effects of urban warming

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*This paper was accepted for publication in January 2007*

## Introduction

The extent and rate of global environmental changes, whether greenhouse gas-induced warming, deforestation, desertification, or loss in biodiversity, are driven largely by the rapid growth of the Earth's human population. Given the large and ever-increasing fraction of the world's population living in cities, and the disproportionate share of resources used by these urban residents, especially in the global North, cities and their inhabitants are key drivers of global environmental change. Here attention is directed to the impact of cities on climate. The focus is not on the effects of cities on global-scale climate, rather the effects globally of cities at regional and local scales. Distinct urban climates at these scales have long been recognized (dating back to Howard 1833). Locally, they are of greater magnitude than projected global-scale climate change and enhance the vulnerability of urban residents to future global environmental change. Moreover, interventions at these scales have the potential to mitigate broader environmental change both directly and indirectly.

The links between urbanization and global climate change are complex (Sánchez-Rodríguez *et al.* 2005; Simon this issue). In the context of enhanced global warming, cities affect greenhouse gas sources and sinks both directly and indirectly. For instance, urban areas are the major sources of anthropogenic carbon dioxide emissions from the burning of fossil fuels for heating and cooling; from industrial processes; transportation of people and goods, and so forth. Svirejeva-Hopkins *et al.* (2004) suggest that more than 90% of anthropogenic carbon emissions are generated in cities. The clearing of land for cities and roads, and the demand for goods and resources by urban residents, both historically and today, are the major drivers of regional land use change, such as deforestation, which has reduced the magnitude of global carbon sinks.

While predicting climate change and its impacts at a global scale is still highly uncertain, local effects of urbanization on the climate have long been documented (see descriptions in Landsberg 1981). Surface and atmospheric changes associated with the construction and functioning of cities are profound. New surface materials, associated with buildings, roads, and other infrastructure, along with changes to the morphology of the surface, alter energy and water exchanges and airflow. Combined with direct anthropogenic emissions of heat, carbon dioxide and pollutants, these result in distinct urban climates (Landsberg 1981; Oke 1997).

One of the best-known urban effects of such development is urban warming; globally cities are almost always warmer than the surrounding rural area (Oke 1973). The magnitude of urban warming is highly variable over both time and space. On average, urban temperatures may be 1–3°C warmer, but under appropriate meteorological conditions (calm, cloudless nights in winter) air temperatures can be more than 10°C warmer than surrounding rural environments (Oke 1981). However, in some regional settings, for example in arid environments, cities with large amounts of irrigated greenspace (parks, suburban vegetation) may actually be cooler than the surrounding dry areas (see the results of Grimmond *et al.* 1993, for example, for Sacramento, California, USA).

The underlying physical causes of the urban heat island are complex (Table 1). For any neighbourhood in any city, the relative balance of controls depends on the nature of the urban environment, human activity, and meteorological conditions.

Urban climatologists commonly characterize the morphology of a city in terms of the height, width and density of buildings (see Figure 3, in which sky view factor is defined). These properties, in combination, affect the loss of long wave radiation at night and therefore cooling rates, the solar access during the day and thus the diurnal pattern of heating, and airflow and wind speed at street level.

**Table 1** Causes of urban warming and examples of mitigation strategies

| Urban heat island causes | Mitigation strategy |
|---|---|
| *Increased surface area* | |
| Large vertical faces | |
| Reduced sky view factor | |
| Increased absorption of shortwave (solar) radiation | High reflection building and road materials, high reflection paints for vehicles |
| Decreased longwave (terrestrial) radiation loss | |
| Decreased total turbulent heat transport | Spacing of buildings |
| Reduced wind speeds | Variability of building heights |
| *Surface materials* | |
| *Thermal characteristics* | |
| Higher heat capacities | Reduce surface temperatures (changing albedo and emissivity) |
| Higher conductivities | |
| Increased surface heat storage | Improved roof insulation |
| *Moisture characteristics* | |
| Urban areas have larger areas that are impervious | Porous pavement |
| Shed water more rapidly – changes the hydrograph | Neighbourhood detention ponds and wetlands which collect stormwater |
| Increased runoff with a more rapid peak | |
| Decreased evapotranspiration (latent heat flux, $Q_E$) | Increase greenspace fraction |
| | Greenroofs, greenwalls |
| *Additional supply of energy – anthropogenic heat flux – $Q_F$* | |
| Electricity and combustion of fossil fuels: heating and cooling systems, machinery, vehicles. | Reduced solar loading internally, reduce need for active cooling (shades on windows, change materials) |
| 3-D geometry of buildings – canyon geometry | District heating and cooling systems |
| | Combined heat and power systems |
| | High reflection paint on vehicles to reduce temperature |
| *Air pollution* | |
| Human activities lead to ejection of pollutants and dust into the atmosphere | District heating and cooling systems |
| | Combined heat and power or cogeneration systems |
| Increased longwave radiation from the sky | |
| Greater absorption and re-emission ('greenhouse effect') | |

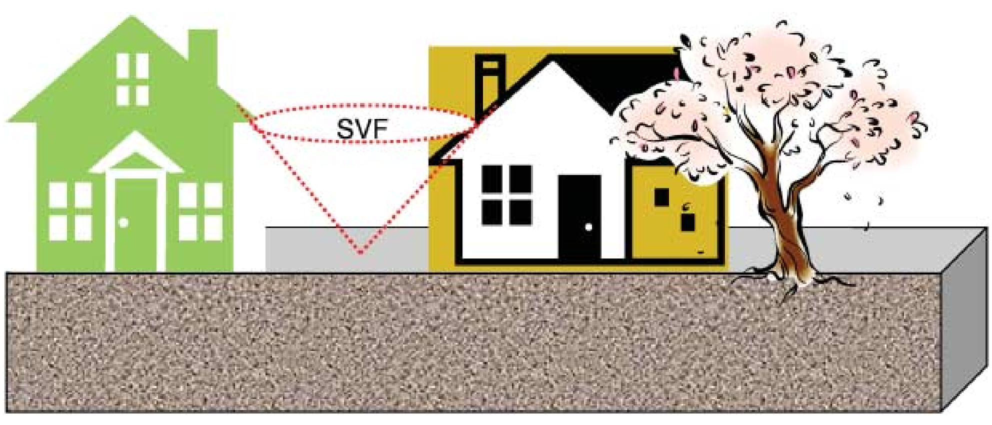


**Figure 3** The sky view factor – a commonly used measure by urban climatologists to quantify the openness of a site within an urban setting that has important implications for incoming and outgoing radiation (solar and terrestrial) and thus heating and cooling patterns

**Plate 1** Photographs by the author of Melbourne, Australia (top); Oklahoma City, USA (lower left); Ouagadougou, Burkina Faso (lower middle); and Marseille, France (lower right) to illustrate variations in materials and morphology of urban landscapes both within and between cities. These result in distinct spatial and temporal patterns of urban warming

The radiative, thermal and hydraulic properties of construction materials differ markedly from those of bare rock, soil, vegetation and water, their pre-existing counterparts. In many, though not all, cities the area covered by vegetation decreases. Thus the fraction of solar energy driving evapotranspiration (the latent heat flux), rather than warming the urban fabric and air (the sensible heat fluxes), decreases. However, the properties of building materials differ widely (Plate 1). For example, roofing materials – asphalt tiles, ceramic tiles, thatch, slate, and corrugated steel/iron – have very different radiative properties (albedo, emissivity) and conductive properties (thermal admittance, conductivity) which greatly affect energy uptake and release and thus heating/cooling patterns. Other facets of buildings, for example, walls, are constructed of materials with equally different properties, which have profound effects on heating and cooling patterns and the resulting building and air temperatures.

## Spatial and temporal dynamics

Within a city, urban–rural temperature differences show significant spatial and temporal variability. Temperatures from one side of a street to the other, from a park to an industrial neighbourhood, or one suburb to another may be significantly different, and the nature of these differences changes through time. Generally, the greatest intra-urban temperature differences are associated with clear skies and low wind speeds. The clear skies allow maximum solar radiation receipt during the day, thus enhanced heating of vertical surfaces and roofs. Under cloudy and windy conditions there is likely to be less solar gain and greater mixing, so that differences in air temperatures are reduced. Typically the greatest urban–rural temperature difference is observed 2–3 h after sunset. Given that the rate of radiative cooling is influenced by the sky view factor, narrower streets (smaller sky view factors) result in reduced longwave radiative loss and remain warmer than more open (high sky view factor) areas. Cities have higher building densities in the centre, so warmer temperatures tend to be found in these locations. Changes in wind direction, especially under low wind speed conditions, can displace these maxima downwind. The locations of parks (vegetated) or other wide open areas can be influential in creating complex patterns.

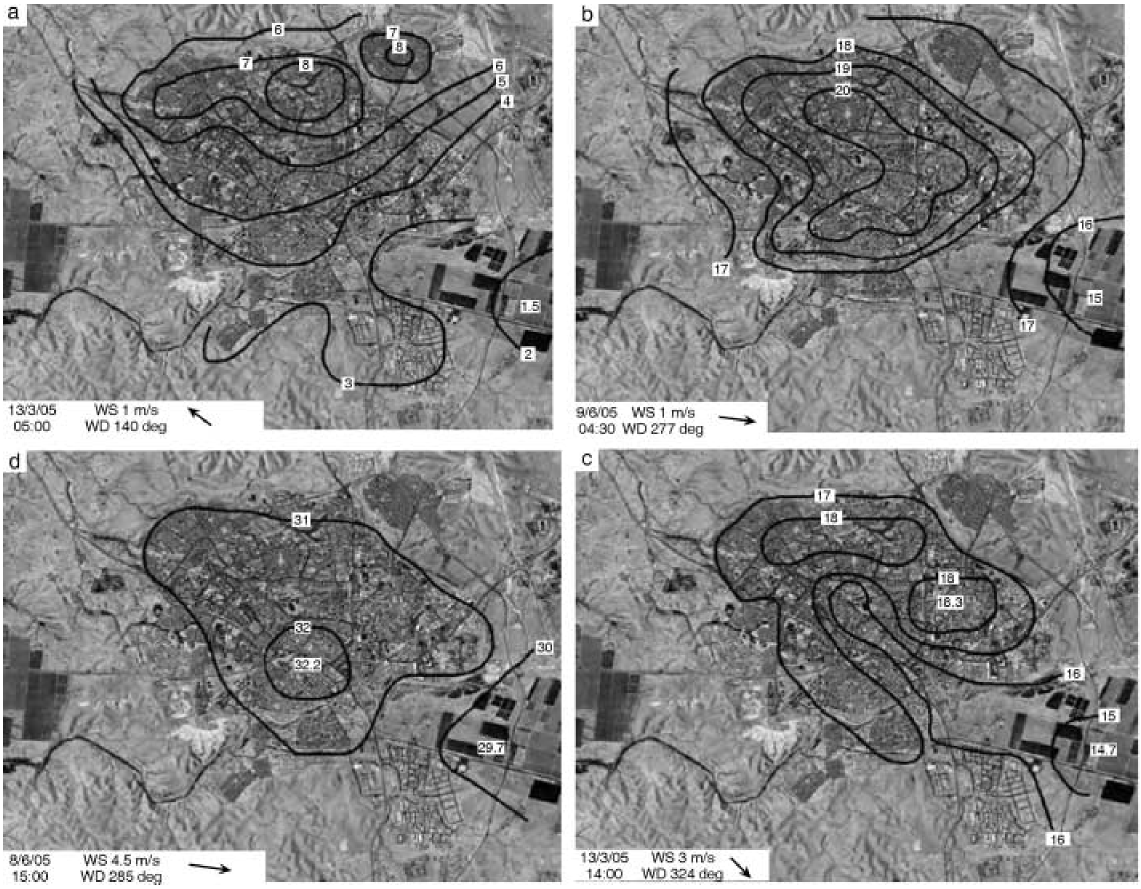


**Figure 4** Spatial and temporal dynamics of urban warming: Beer Sheva, Israel. The impacts of urban development and meteorological conditions are evident. Top left – dawn in winter; top right – dawn in summer; lower left – midday in winter; lower right – midday in summer
*Source*: Adapted from Potchter *et al.* (2006)

The magnitude of the temperature range across a city can be very large. The range typically is greater for surface temperatures (e.g. as seen by a satellite such as ASTER) than for air temperatures, given that air temperatures respond to mixing. When these spatial patterns are studied over time (seasonally, diurnally), the location of the maximum temperature varies (e.g. Potchter *et al.* 2006; Figure 4).

Urban areas are dynamic, thus urban temperature patterns change over longer periods. Some cities develop over time through processes of very deliberate planning, others in a more *ad hoc* way. The form of urban development also varies. For example, in China, where there is very rapid growth in urban populations, new construction tends to be of tall buildings (Whitehand and Gu 2006); in India, by contrast, this is not the case. This has implications not only for the nature of the cities and the environmental conditions within them, but also the spatial extent of new development (regional land use change) and commuting distances of city residents. Also important are the ways in which old buildings are refurbished and brownfields developed. The former may involve reroofing, refitting interior heating and cooling systems, painting the exterior or covering a building with new materials. All these changes have impacts on the micro and local thermal environment.

## Impacts

Urban warming has important implications for human comfort, health and well-being. Many examples exist of the vulnerability of urban populations, most often the elderly and the poor, associated with heat waves; for example in India in 1998 and France and Spain in 2003 (Souch and Grimmond 2004). Future climate scenarios, which predict an increase in summertime maximum temperatures and also in the frequency and magnitude of extreme conditions, suggest greater risks in the future. Warmer conditions in cities will also increase demand for air conditioning. More air conditioners generate more heat and have significant effects on the local-scale external climate, with implications for human comfort and the demand for cooling. At a larger scale, greater use of air conditioning results in more greenhouse gases through increased electricity generation. Significant growth in the use of air conditioning in North America, Europe and Asia has been documented and recent simulations indicate the resultant increase in energy demand will more than offset reductions in energy demand for heating under cold conditions (Hadley *et al.* 2006).

## Mitigation

Understanding the causes of the urban heat island effect allows insight into strategies for mitigation. This has broader implications in terms of the management of energy resources. Peak energy demand for many regions of the world is now in the summer rather than winter. On occasions, utility companies are now unable to meet demand under these conditions and blackouts or rolling-blackouts result. For example, during some of the warmer periods of the summer of 2006, energy supply in London and Los Angeles was not able to meet demand and power cuts resulted. Mitigating enhanced urban temperatures, and thus reducing energy demand, has significant implications.

A wide range of strategies is being considered to mitigate urban warming (Table 1). The scales at which these can be applied vary; for example, individual building versus a neighbourhood, new development versus redevelopment/retrofitting. Some mitigation strategies involve changing the material properties of individual buildings (e.g. Akabari *et al.* 2001), others to the spatial arrangement (separation of individual buildings). Changes in materials have the advantage that they can be used on current buildings, so do not require the costs or time of new development. Moreover, significant developments in new building materials mean that many that have high reflectivity and modified emissivity no longer need to be 'white'. Thus individual preferences in terms of colour can be retained (Cool Roof Rating Council 2006). In many cases, new materials may cost no more than the traditional alternatives. Hence cost is not a barrier to integration of 'cool' building materials.

Many strategies benefit multiple aspects of urban environmental change. For example, the addition of water detention ponds and wetlands reduces peak urban runoff, which has the advantages of reducing the need to engineer larger systems to deal with flash floods and/or manage the release of untreated water downstream. With careful design of a wetland area, the quality of the stormwater can also be enhanced as well as providing the open areas of parks (higher sky view factors) and enhanced evaporation. Additional social, cultural, and psychological benefits from 'natural' space can accrue too. Also, new residential developments (e.g. Lynbrooks in Melbourne, Australia) employ water-sensitive urban design that involves the use of grey water to irrigate residential vegetation (Mitchell *et al.* 2002). This reduces the demand for water to be diverted into a city for irrigation purposes.

Other strategies involve developing district heating and cooling (DHC) using combined heat and power (CHP) or co-generation systems. These aim to reduce the emissions of carbon dioxide and other air pollutants (IEA 2006) and have been developed for building to (small) citywide scales (they can generate several kilowatts to hundreds of megawatts of electricity). Technological changes are increasing the viability of these systems; notably reducing energy losses in the transmission process, and by recapturing waste heat and energy to avoid warming the air unnecessarily. The captured heat can be used to meet heating requirements, provide cooling using advanced absorption cooling technology, and also to generate more electricity with a steam turbine.

## Final comments

Clearly the direct contributions of urban warming to global climates are small. Urban areas cover only a small fraction on the Earth's surface and their moisture, thermal and kinematic effects extend downwind only a few kilometres. However, the greenhouse gas emissions from the construction and operation of cities are large and increasing; the gases from urban areas are the dominant anthropogenic sources. Moreover, the warmer conditions in many cities result in greater energy and resource consumption by the inhabitants to offset the effect and also make urban populations more vulnerable to heat waves and other extreme conditions. Thus it is critical that cities and the drivers of urbanization are central to global environmental research. Urban areas and urban populations will continue to grow in size and number. Existing urban areas will experience redevelopment and refurbishment. The decisions made about how this will occur will impact upon the people living within the buildings, neighbourhoods and cities. In combination, they will have global implications and consequences.

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# Climatic perturbation and urbanization in Senegal


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*This paper was accepted for publication in January 2007*

## Introduction

Senegal benefits from a Sudano-Guinean climate and thus from more favourable ecological conditions in the southern part of its territory. Furthermore, the temperate climate of the Atlantic seaboard has played an important role in the establishment of most of its major cities. The resulting imbalances between North and South, East and West, both eco-geographically and with respect to economic potential, significantly influence the internal mobility of the population. Reflecting these factors, Senegal's current population of almost 11 million is distributed very unevenly across the country's total area of 196 722 km$^2$.

Changing climatic conditions have stimulated this mobility and contributed to reinforcing the role