How is urbanization altering local and regional climate?

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How is urbanization altering local and regional climate?

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Urbanization has profound effects on climate. The materials and morphology of the urban surface, along with emissions from domestic, commercial and transport activities, result in changes in local climate often greater in magnitude than projected global-scale climate change. Cities are commonly 2-3 °C warmer than their surrounding environments, with the greatest differences at night and in winter. Such urban climate effects increase the vulnerability of residents to future environmental change, making cities prime sites for climate mitigation and adaptation. This chapter describes the major processes influencing urban climates at a range of scales, and illustrates these with data from London, one of Europe's most densely populated cities and home to over 8.2 million people.

1. Cities compared to rural landscapes

Major surface and atmospheric changes are associated with the construction and functioning of cities. Materials used for buildings, roads and other infrastructure, along with the three-dimensional form of the urban landscape, alter the radiative, thermal, hydrologic and aerodynamic properties of the surface, the airflow, and the energy and water exchanges. Direct anthropogenic emissions of heat, carbon dioxide and other pollutants also modify the urban climate (Figure 1).

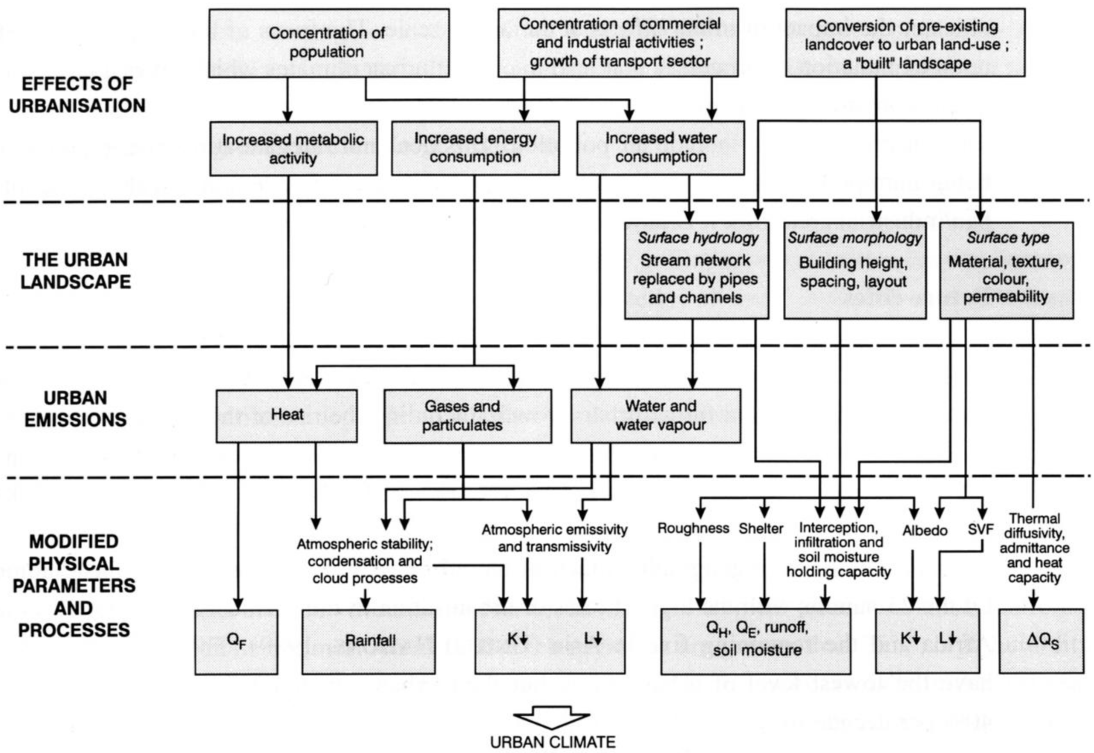


Figure 1: The effects of the urban landscape and urban emissions on key parameters and processes, resulting from urbanisation. Source: Cleugh and Grimmond (2012)

Urban development typically replaces natural or agricultural vegetation with surfaces that are impermeable and inflexible to the movement of water and air. Buildings, often arranged in relatively regular rows or grids, channel and accelerate airflow, and their sharp edges can introduce highly turbulent wakes and vortices (Kastner-Klein et al. 2004; Xie et al. 2005). Networks of pipes, channels and canals replace or supplement natural drainage systems, further modifying exchanges of water and heat.

Building material properties, architectural styles and the layout of cities differ considerably (e.g., Herold et al. 2004, Kotthaus et al. 2014). Materials used for a certain type of facet (e.g., roofing materials such as asphalt, ceramic tiles, thatch, slate, steel or copper) have a wide range of radiative (albedo, emissivity) and conductive (thermal admittance, heat capacity) properties, which affect heat retention and loss. Together, these have direct implications for energy uptake and release by the buildings, indoor and outdoor temperatures, and, thus, heating and cooling demands (Kikegawa et al. 2003) and carbon emissions.

Although vegetation cover in many cities is small, 'greenspace', i.e., parks, gardens, shrubs, trees and even green roofs and walls, have a particularly important influence on heat, water and carbon exchanges, and, thus, on temperature and humidity. Some suburbs of Western cities meet the definition of a forest (Oke 1989) and irrigation enables urban greening in arid regions (Shashua-Bar et al. 2011). The juxtaposition of built and vegetated elements is fundamental to the creation of urban climates, and it is critical to represent this adequately in numerical models (Grimmond et al. 2011).

2. Scales of urban climate effects

Climate variables, whether air temperature, humidity or wind speed, vary significantly both within and between cities. Air temperatures, for example, differ from one side of a street to the other (sunlit versus shaded), from a park to an industrial neighborhood or from one suburb to another. These differences also change through time. For any application, identifying the relevant scale is absolutely critical: micro, local or meso-scale (Figure 2).

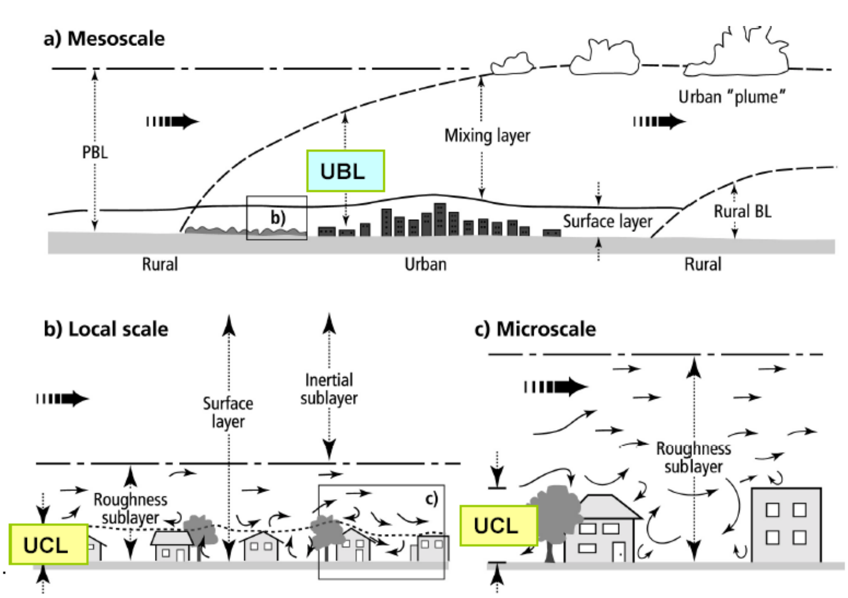


Figure 2: Key spatial scales in the urban atmosphere (adapted from Oke 1997).

The fundamental elements at the *micro-scale* (<10^2 m) are individual buildings and trees. As buildings are typically sharp-edged, rigid and impermeable, they alter the wind-flow and turbulence. The large thermal capacity of buildings enhances daytime heat storage and subsequently night-time release. In combination, building shapes and materials control how radiation is absorbed, reflected and (sometimes) transmitted. While building exteriors are designed to limit moisture exchanges (notably to restrict water entry), heat exchanges do occur by conduction through all the exterior walls and by convection through gaps, vents and chimneys. How the individual buildings are operated, either by inhabitants or businesses, affects the timing and magnitude of these exhaust heat and gas emissions.

Multiple urban canyons, (two rows of buildings with a transport corridor, e.g., a street or alley way), create *city block*, *local*- or *neighborhood-scale* (10^2 – 10^4 m) areas within the city (Figure 2). The building heights (H), and widths (W) of the spaces between allow these areas to be characterized with respect to differences in radiative, convective heat and momentum exchanges. Cities are aerodynamically rough and therefore reduce overall wind speeds and ventilation in the urban canopy, with important implications for air quality, temperature and human exposure.

Micro-scale features are blended in mean turbulent flow above the roughness sub-layer (Figure 2) at the local-scale. With increasing spatial extent (land use zones across several kilometers), the urban surface starts to have an influence that extends beyond the immediate group of buildings into the overlying boundary layer. Examples include a residential area dominated by similar style housing, an industrial area dominated by warehouses, or the central business district of a city with high-rise buildings.

At the largest urban spatial scale, the *meso-scale* (10^3 – 10^5 m), the urban boundary layer (Figure 2) reflects the influence of all the different neighborhoods; i.e., the entire city. Thermal and chemical characteristics are transported downwind, impacting a larger region extending beyond the city.

The regional setting of a city, for example, if it is next to a large water body (whether lakes - Chicago, Geneva; or oceans - Los Angeles, Vancouver, Shanghai, Tokyo) or in a mountain-valley system (e.g., Salt Lake City, Phoenix, Mexico City, Innsbruck), influences how it interacts and modifies regional thermal circulations and can cause re-circulation of air pollutants into the city and/or to surrounding areas. Such complex wind-flow regimes can generate multiple convergence zones, which modify precipitation and cloud patterns (e.g., Yoshikado and Kondo 1989). These are embedded in the larger weather patterns of expected fronts and high/low pressure systems, the latitudinal variations in solar radiation and the moderation from maritime/continental influences that control larger-scale climates.

To illustrate effects at different scales, wind speed measurements from various settings and heights in London during a particularly windy period are shown in Figure 3. Within the urban canopy, the wind is significantly reduced but, as in all areas, increases with height. Such strong winds can cause significant damage to infrastructure and loss of life.

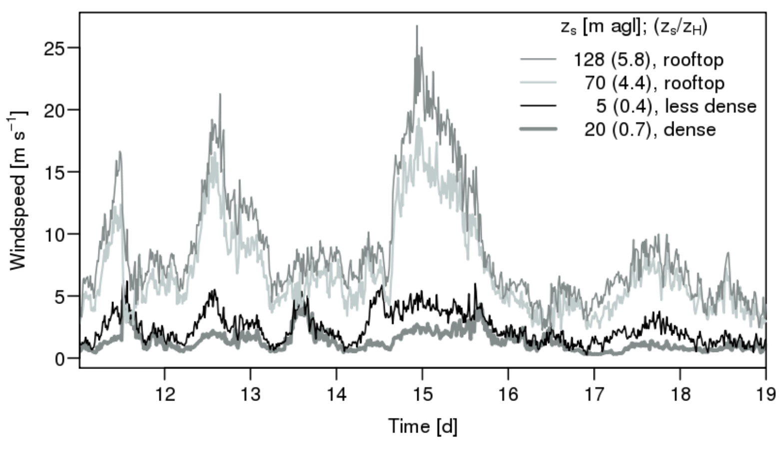


Figure 3 – Measured wind speeds (m s^{-1}) at various heights in central London during a particularly windy period in February 2014. The four sensors are locatad at height, z_S, above ground level (agl). Two are below roof level, that is below the mean height of the buidlings (z_H) (i.e. z_S/z_H <1) or withinand an urban canyon. The sensor in the more dense area has a lower wind speed despite being higher above the ground. The other two sensors are located well above the mean building height (z_S/z_H > 1). The mean height is determind here from the building heights within 1 km of the site of the anemometer.

3. Urban energy exchanges

Modification of energy, water, momentum and carbon exchanges between the urban surface and atmosphere create distinct urban climates. Each of these exchanges can be written as a statement of conservation (of energy, mass, etc.) for a typical volume at the various scales described above (Figure 2). For energy this is defined as (Oke 1987):

$$Q^* + Q_F = Q_E + Q_H + \Delta Q_S \quad (1)$$

with inputs of net all-wave radiation (Q^*) and anthropogenic heat (Q_F). The outputs are the energy to evaporate and transpire water through evapotranspiration (latent heat flux Q_E), and to heat the air (sensible heat flux Q_H), and urban volume (net storage heat flux ΔQ_S). Both biophysical and human factors regulate these exchanges. While Equation 1 is applicable at any spatial scale in the urban environment, it does assume that the net lateral transport of energy, due to advection, is negligible at the scale under consideration (see Pigeon et al. 2007 for discussion of this issue).

Observations in cities, key to understanding these exchange processes, remain fewer in number than in other environments. In the last decade, a range of cities with contrasting climatic and topographic settings, varying population density, socio-economic status and urban design have been studied (see Lietzke et al. 2014 for review). From these, the variability of flux exchanges both within and between cities and controlling factors have become evident (Loridan and Grimmond 2012). The key elements of these are described below.

3.1 Urban radiation balance

The incoming short-wave radiation (diffuse plus direct beam radiation) is reduced in urban areas, varying from minor reductions (~ 5%) in those cities with low aerosol concentrations to much larger reductions (up to ~ 30%) in cities that have high levels of particulate pollution (e.g., Rome and Athens) (Mallet et al. 2013).

To illustrate urban effects on incoming solar radiation, data are presented for three sites in southern England (70 to 100 km apart at similar latitude): central London (Kotthaus and Grimmond 2014a,b); a suburban neighborhood in Swindon (Ward et al. 2013); and a woodland site (Alice Holt) (Wilkinson et al. (2012). Full details of the sites, the instrumentation and comparison of the data are presented by Ward et al. (2014). Experiencing broadly similar synoptic conditions, differences between the sites reflect local urban or non-urban controls. Observations of incoming solar radiation at the three sites (Figure 4) illustrate general agreement in seasonal (winter-summer) and synoptic patterns (cloudy-clear) but with a reduction of solar radiation receipt in central London, the most urbanized of the sites with the poorest air quality.

Very high concentrations of greenhouse gases (especially carbon dioxide, CO_2) and aerosols occur in urban areas where they are released from numerous sources (Crawford and Christen 2014). They increase atmospheric absorption and, hence, lead to elevated temperatures and often increased absolute humidity levels. Thus, the urban atmosphere experiences an enhanced greenhouse effect, over and above that occurring at the global scale and greater incoming long-wave radiation.

Low urban albedo (e.g., total reflectance of 0.08 to 0.20 out of 1.00) for suburban and urban landscapes (Taha et al. 1997) is attributed to the radiative characteristics of urban construction materials and radiative trapping within street canyons. The net effect is greater short-wave radiation absorption compared to a non-urban landscape receiving the same global radiation. Similarly, the reduced sky view factor impedes long-wave radiation losses, so net long-wave radiation receipt is typically increased. Local-scale changes in building materials and urban design can be used to modify the radiation balance (Taha 1997). However, generally, spatial differences in the net all-wave radiation are surprisingly small (Schmid et al. 1991, Arnfield 2003, Lietzke et al. 2014).

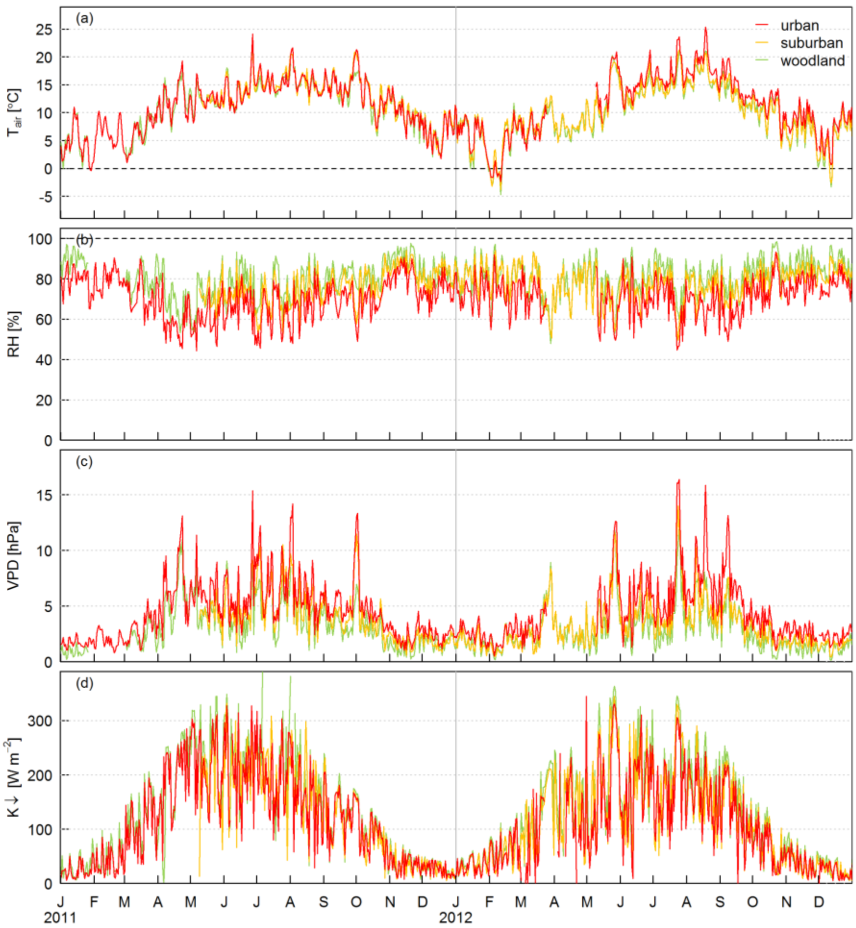


Figure 4: Mean daily air temperature, relative humidity, vapour pressure deficit and solar (short wave) radiation for a two year period from an urban (red central London (Kotthaus and Grimmond 2014a,b), suburban (orange, residential Swindon, Ward et al., 2013) and rural (green Alice Holt deciduous forest (Wilkinson et al. 2012))site in southern England. All sites experience broadly the same synoptic conditions; differences represent urban/non-urban effects. Gaps in the data are due to missing observations.

The micro-scale radiation regime of an individual element (e.g., person or tree) or facet (e.g., wall, roof or pavement) is highly variable in space and time and closely related to its surroundings; e.g., albedo of urban impervious materials may range from 0.05 to 0.54 (Kotthaus et al. 2014). The urban form (or morphology) creates shadows and reduces sky view factors; thus, tall buildings can reduce the albedo because of radiative trapping, while if clad with highly reflective, non-Lambertian materials such as glass and metal, which are often used in modern architecture, they can also generate strong specular reflections and glare (Shih and Huang 2001a,b). As one example, the façade of a new skyscraper in the City of London reflected sufficient radiation to create surface temperatures warm enough to melt plastic parts of cars parked nearby (Guardian 2013). The effects of highly reflective urban surface materials are illustrated with data of outgoing radiation at a rooftop site in London (Figure 5). This shows the clear impact of a roof window. Radiation levels are crucial for human comfort (Erell et al. 2014).

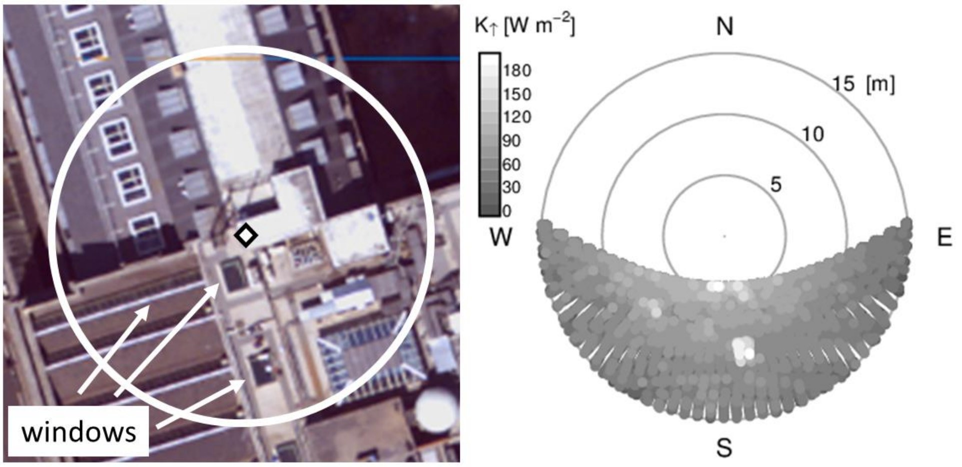


Figure 5: Effect of surface materials on reflected short wave radiation (a) circle shows 80% field of view (15.2 m radius) for the radiation sensor; (b) median reflected short-wave radiation observed (2012), by solar azimuth angle and distance of maximum, specular reflection R_s. Full details of analysis and definition of R_S in Kotthaus and Grimmond (2014b). Aerial photo (NERC ARSF 2008)

3.2 Urban heat storage and anthropogenic fluxes

The change in heat storage, ΔQ_S, in all elements of the urban canopy layer (air, biomass, soil and built) is a dominant term in the urban energy balance (Equation 1). This flux is, however, very difficult to measure directly (Offerle et al. 2005). It can be approximated by the sum of the heat fluxes conducted through the solid-air interfaces (i.e., walls, roofs, pavement and roads, trees, lawns and gardens) (Arnfield 2003) or estimated as a residual in the energy balance when all other terms are measured (see Roberts et al. 2006 for discussion).

By day, the flux consumes between 20 and 30% of the net all-wave radiation in suburban land use, and up to half of the net radiation in heavily urbanized sites, such as found in Mexico City (Oke et al. 1999), London (Kotthaus and Grimmond 2014a) and industrial areas of Vancouver (Grimmond and Oke 1999). By night, the net loss of radiation from the urban canopy is typically balanced by the heat storage (and Q_F) term and can lead to positive sensible heat flux exchanges (with implications for nocturnal atmospheric stability). From estimates using the residual approach, ΔQ_S for 20 cities across North America, Africa, Europe and Australia are presented in Figure 6 (grey squares). The data are normalised by the incoming (short-wave and long-wave) fluxes so relative patterns are evident (otherwise controls of latitude and synoptic conditions on the total amount of energy would dominate). Over the course of the day, ΔQ_S is out of phase with the incoming radiation, leading to a non-linear, hysteresis $\Delta Q_S / Q^*$ relation (evident in Figure 6, particularly notable for Miami and Tucson).

Anthropogenic heat flux (Q_F) from stationary and mobile sources can be important in the urban energy balance. Q_F is difficult to measure directly so most estimates are derived from energy use statistics or surrogates, such as traffic numbers; alternatively Q_F can be estimated as a residual in the urban energy balance (see Sailor 2011 review).

While the average diurnal range of Q_F is estimated to be between 0.7–3.6 W m^{-2} for all urban areas globally (Allen et al. 2011), a value that is relatively small, this flux is highly scale dependent. It is much larger for small areas with dense built infrastructure in the center of major cities. For example, Ichinose et al. (1999) documented fluxes > 1000 W m^{-2} in Tokyo. Using a top-down approach for Greater London (Iamarino et al. 2012), the relative impacts of building emissions (Q_{Fb}), road traffic (Q_{Ft}) and metabolism (Q_{Fm}) are clear (Figure 7). The combined overall annual average flux is 10.9 W m^{-2}, but in the City of London values reach 210 W m^{-2} (annual average). The commercial/service sector, which covers only 2.5% of London's area, has annual average fluxes > 50 W m^{-2}. If shorter time periods are considered, the peak values can be much larger. Thus, anthropogenic heat fluxes can be large relative to radiative inputs, especially in winter. The timing of human activities (such as commuting, heating of buildings, cooking of meals, etc.) and their variations between work and non-workdays all have a large impact on Q_F and its diurnal pattern and, therefore, on the input of additional energy to the urban system.

3.3 Turbulent latent and sensible heat fluxes

Urban influences on Q_E and Q_H fluxes are large including enhancement through the aerodynamically rough urban canopy and strong dependence on surface water availability (e.g., from precipitation, irrigation). The Bowen ratio ($\beta = Q_H/Q_E$) provides a key indicator, which varies with vegetation (type, amount) and water availability. More energy is partitioned into sensible heat fluxes (Q_H) in dense urban areas if vegetated areas are small, while evaporation usually becomes more important with an increasing proportion of green surface cover (e.g., suburban areas).

Typically large urban storage heat fluxes in the morning (partially because of the increased heating of the vertical surfaces due to absorption of incoming solar radiation) and the evaporation of surface water (dew, nocturnal irrigation), if present (Grimmond and Oke 1991), result in a time lag of the sensible heat flux in urban areas compared to natural surfaces (Grimmond and Oke 1999, Grimmond and Oke 2002). In dense urban areas, the turbulent sensible heat flux generally remains positive (see Figure 6), i.e., an energy source to the atmosphere throughout the day and night (Grimmond and Oke 2002, Kotthaus and Grimmond 2014a). This heating, which results in a persistently strong net upward motion of warm air, has an important influence on the atmospheric boundary layer in cities with implications for air quality, larger-scale meteorological processes and health (Bohnenstengel et al. 2014).

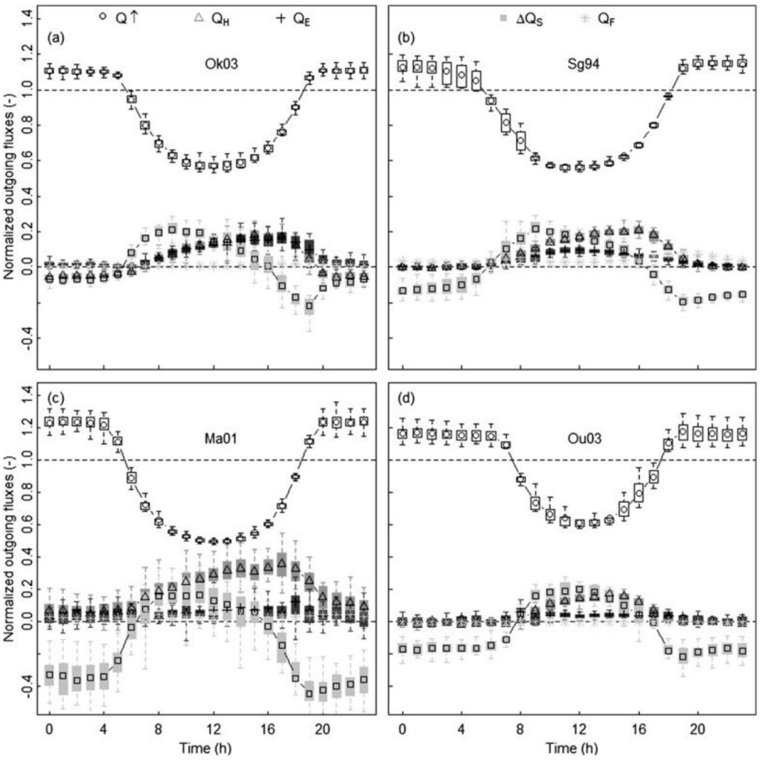


Figure 6: Energy balance fluxes normalized by incoming (short- and long- wave) radiation. Mean diurnal pattern of the ratios (symbols) with box plots for data by Loridan and Grimmond (2012 Full descriptions of each site (codes below) and the appropriate source references see Loridan and Grimmond (2012). Sites: (Ok03 (WH)) Oklahoma City, OK, USA, residential; (Ou03) Ouagadougou, Burkina Faso, residential; (Sg94) San Gabriel CA, USA suburban and small commercial (MA01) Marseille, France central city

The most variable flux within and between cities is the latent heat flux: ranging from almost zero to values greater than the surrounding rural landscapes (Grimmond et al. 1993) when the study area is well watered with abundant vegetation (e.g., urban gardens, Oke 1979 or parks, Spronken-Smith et al. 2000). As evapotranspiration impacts energy, water and carbon balances, this term has been manipulated to passively mitigate urban heating and cooling demand, and, thereby, energy consumption (e.g., Mitchell et al. 2008) (see further examples below).

4. Urban water balance

The urban water balance is expressed in mass (kg or as mm) exchanges per unit time (Grimmond and Oke 1991):

$$p + I + F = E + \Delta r + \Delta W \qquad (2)$$

where the inputs are precipitation *p* (including dew, fog, hail, rain and snow), piped water supply (*I*) (released indoors and outdoors), and water released with combustion (*F*). The output terms are evapotranspiration (*E*), runoff (□*r*) (waste and storm water) and changes in stored water (ΔW) in the urban canopy (air, biomass, soil and built components) (see Lietzke et al. 2014 for a more extended discussion of the urban water balance). When expressed this way the water balance is assumed to relate to a volume with vertical dimensions from within the soil up to the urban canopy airspace. The lateral dimensions can apply to a single household, a neighborhood (equivalent to the local-scale defined above), or a catchment defined by topography and/or the pipe supply network.

All terms in Equation 2 are impacted by urbanization, with direct implications for the urban climate. The dominant changes occur because of enhanced water supply (notably) and increased runoff associated with the greater impervious cover and piped networks (Grimmond and Oke 1986). While reduced vegetation cover may lower evapotranspiration, a more secure and enhanced water supply can sustain large rates of evapotranspiration. In fact *E* can often be the largest output term in the urban water balance, exceeding the runoff (e.g., Grimmond and Oke 1986). In the absence of water restrictions, a plentiful water supply can generate higher evaporation rates in suburban areas than in rural landscapes (e.g., Sacramento, USA, presented by Grimmond et al. 1993).

Urban climate and hydrology are linked directly by the evapotranspiration term, the mass flux (*E*) in the water balance and the energy used in the phase change of liquid water to vapour (Q_E) in the energy balance (i.e., $Q_E = L_v E$ where L_v is the latent heat of vaporization). Thus, the urban climate can be modulated by manipulating the water balance, for example by sustaining evapotranspiration through importing water (*I*) and/or harnessing and reusing runoff (□*r*). Managing the urban water balance is a key potential strategy to mitigate excessive urban heating (Steeneveld et al. 2011). For a detailed discussion of urbanization and climate as it relates to precipitation see *Mitra and Shepherd* in this volume.

5. Urban carbon balance

Vegetation's assimilation of the greenhouse gas CO_2, during photosynthesis requires photosynthetically active radiation (PAR) and releases water vapour. Thus, there are close links between the urban carbon, energy and water balances. The control volume can again be used to define a carbon balance:

$$F_{CP} + F_{CF} = F_{CR} + F_{CM} + \Delta S_C \qquad (3)$$

where the inputs of CO_2 are F_{CP} assimilated through photosynthesis by vegetation, and F_{CF}, the import of fossil fuels. The CO_2 emissions are from heterotrophic (animals including people) and autotrophic (plants, algae) respiration (F_{CR}) and human activities (F_{CM}). The latter includes transport, space heating/cooling, other combustion of fuel (e.g., for cooking) and industrial emissions. The size of the net change in storage (ΔS_C) depends on both the temporal and spatial scales considered and whether a gain or loss of CO_2 occurs within the urban volume of interest. As for energy and water, the control volume, although relatively straightforward in theory, requires careful definition of the boundaries in practice.

As urban areas significantly perturb the regional and global carbon budget, understanding the drivers is critical to addressing global climate change. The ability to measure directly the net CO_2 exchanges in urban landscapes is important in assessing progress on reducing carbon emissions (see the overview by Christen 2014).

With both anthropogenic and biogenic controls, urban carbon exchanges have a complex dependence on surface cover (Velasco and Roth 2010, Grimmond and Christen 2012, Järvi et al. 2012, Nordbo et al. 2012, Ward et al. 2015). In most urban environments, the biogenic sources are much smaller than the anthropogenic ones. However, when plants are actively growing (and, thus, sequestering CO_2) there may be a balance with respiration (i.e., $F_{CP} \cong F_{CR}$) or even a net uptake of carbon (see, for example, the summer months in Baltimore, Crawford et al. 2011).

The urban climate, notably, the urban heat island, solar radiation (in terms of the amount of diffuse versus direct radiation), irrigation, enhanced levels of CO_2 and atmospheric deposition of nitrogen, affects the biological processes of photosynthesis and respiration in urban canopies. The phenology of urban vegetation (i.e., time of leaf growth and leaf-fall), which is different to rural surroundings (Gazal et al. 2008, Neil et al. 2010) and the enhanced size of urban vegetation because of elevated CO_2 concentrations (documented in Baltimore by George et al. 2009), affect net CO_2 sequestration.

Cities are clearly significant net sources of carbon dioxide, with emissions closely related to the fraction of the surface covered by impervious materials (buildings and roads) (Grimmond and Christen 2012). Although urban greenspace does sequester some of the CO_2 emissions from vehicles and other urban sources, recent observations (e.g., Coutts et al. 2007, Crawford et al. 2011, Ward et al. 2015) indicate this sequestration is insufficient to offset the emissions on an annual basis. Diurnal and seasonal variations in net CO_2 fluxes are dominated by the cycle of human activities and emissions from vehicles and space heating. Net emissions are larger during weekdays and during cold periods (such as the winter months when additional heating is required). The annual emissions of CO_2 (cited by Velasco and Roth 2010) for Tokyo, Mexico City, Melbourne and Copenhagen vary between 8 and 15 kg CO_2 m^{-2} y^{-1} (i.e., 80 and 150 t CO_2 ha^{-1} y^{-1}). These emissions are about 10 times the CO_2 sequestered by a mature and productive forest (Falge et al. 2002, Law et al. 2002).

The interconnection of water, heat and carbon exchanges is well illustrated by the study of Pataki et al. (2009), who concluded that the greatest benefits from urban tree-planting programs come not from carbon sequestration but rather from the modification of the urban energy balance, notably shading at the micro-scale, evaporation at the local-scale and the impacts these have on energy demand.

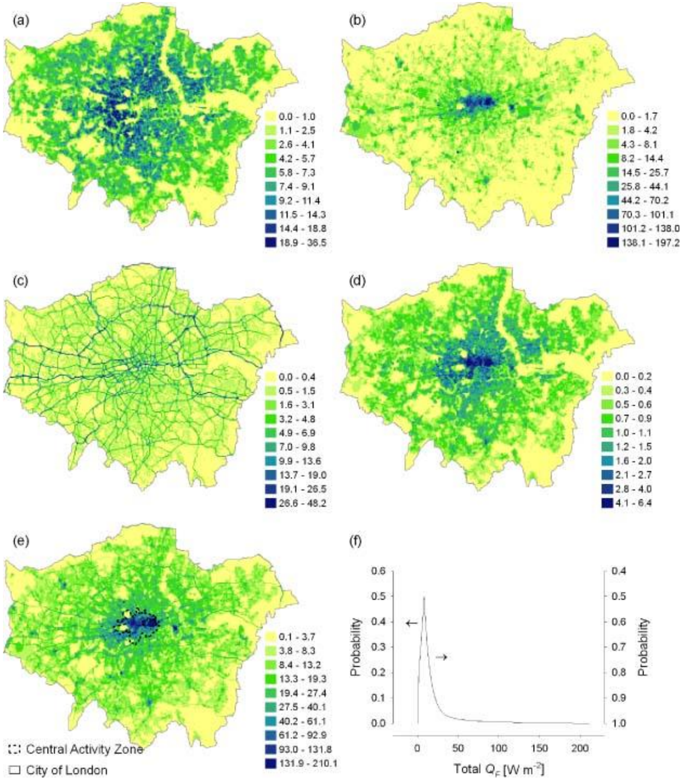
6. Resulting effects and implications of urban climates

The most widely recognized and studied urban climate phenomenon, the urban heat island **(**UHI), refers to the frequent observation that urban areas are warmer than their surrounding regions. Canyon air temperatures tend to exhibit the greatest difference two to three hours after sunset, although daytime heat islands are also observed (evident in the temperature profiles for London, Swindon and Alice Holt forest shown in Figure 4).

The strength of the canopy air temperature UHI (defined as $\Delta T_{U\text{-}R}$, where *U* and *R* refer to urban and rural, respectively) can be as large as ~10ºC on individual nights (Oke 1981). Typically, the peak is within the city core and declines with distance towards the urban/rural boundary. The greatest intra-urban temperature differences tend to be associated with clear skies and low wind speeds. The clear skies allow maximum solar radiation receipt during the day, thus enhancing heating of vertical surfaces and roofs. Cities usually have higher building densities in the center, so warmer temperatures tend to be found in these locations. The maxima can, though, be displaced downwind, with the location changing seasonally depending on winds (e.g., sea breeze circulations in Tokyo, Honjo et al. 2012). The locations of parks or other open areas can also create complex temperature patterns. However, the cooling effect of parks does not typically extend long distances downwind (Eliasson and Uppmanis 2000, Nagatani et al. 2008). In extremely cold climates, the maximum urban warming is associated with intense anthropogenic heat use (e.g., Hinkel et al. 2003, Malevitch and Klink 2011).

From the enormous number of studies of the UHI (e.g., within Santamouris 2007), it is evident that great care must be taken in the methods of observation and analysis (Stewart 2011). There are, in fact, many types of UHIs (Voogt 2004): near-surface urban canopy layer heat islands, subterranean urban heating effects (e.g., Allen et al. 2003), boundary layer heat islands (e.g., Bohnenstengel et al. 2011) and radiative surface heat islands (e.g., Jin et al. 2005). Remote sensing-based studies of the UHI are numerous, but determination of the surface temperature remains challenging because of limited view angles, coarse spatial resolution (mixed land cover in pixels), difficulty in obtaining the surface emissivity and atmospheric corrections (Roth et al. 1989, Voogt and Oke 2003, Dousett and Gourmelon 2003, Kotthaus et al. 2014).

Understanding the causes of the UHI allows insight into strategies for mitigation with broader implications for management of energy resources. The mitigation strategies are applicable at scales ranging from individual buildings to neighborhoods (see examples in Table 1), and can be used in new developments, or to retrofit or refurbish existing building stock. Approaches taking construction. However, new developments can alter the orientations or separations of buildings, the variability of building heights or land cover proportions and patterns. Such modifications can have environmental benefits at multiple scales, from individual buildings to neighborhoods, and may even help to reduce CO_2 emissions from power generation elsewhere. advantage of material properties (e.g., Saadatian et al. 2013, Santamouris 2013) can be used on existing buildings (e.g., application of specialised coatings, exchanging roofing material) so are often more cost and time effective than completely new



Alternative strategies to cool urban areas include adding water detention ponds and wetlands that enhance evaporation rates during the day and create more open areas to enhance cooling at night given their larger sky view factors. These have other benefits too, such as reducing peak urban runoff and reducing the need for construction of large infrastructure to protect against flash floods and/or manage the release of untreated water downstream. They can also improve water quality and provide social, cultural and psychological amenities with benefits from the creation of 'natural' space. New residential developments can employ water-sensitive urban design that involves the use of greywater to irrigate residential vegetation (Coutts et al. 2013) that reduces the demand for water to be diverted into a city for irrigation purposes.

Figure 7: Spatial variability of heat emissions (average for 2005–2008) at 200×200 m^2 resolution by sector: (a) domestic, (b) industrial, (c) road traffic, (d) metabolism and (e) total (classes by Jenks natural breaks) and (f) folded cumulative distribution function of total Q_F. Values in W m^{-2} (Iamarino et al., 2012).

The enhanced warmth of urban areas, the reduced vegetation cover and the presence of engineered structures designed to remove water rapidly from cities all have influences on a city's atmospheric moisture. The data from the urban-forest transect in southern England (Figure 4) illustrate this clearly. The synoptic influences are common to each site, but superimposed are the urban effects related to both moisture and temperature. Higher vapour pressure deficits and lower relative humidities are evident in central London. In winter, if conditions are dry, water release from combustion-related sources can be important in creating an urban moisture excess (e.g., Holmer and Eliasson 1999, Kuttler et al. 2007).

Table 1. *Causes of urban warming and examples of mitigation strategies (adapted from Grimmond 2007)*

Urban heat island causes	Mitigation strategy
Increased surface area	
Large vertical faces	
Reduced sky view factor	
Increased absorption of short-wave (solar) radiation	High reflection building and road materials, high reflection paints for vehicles
Decreased long-wave (terrestrial) radiation loss	Spacing of buildings
Decreased total turbulent heat transport Reduced wind speeds	Variability of building heights
Surface materials – Thermal characteristics	
Higher heat capacities	Reduce surface temperatures (changing albedo and emissivity)
Higher conductivities	Improved roof insulation
Increased surface heat storage	
Surface materials – Moisture characteristics	
Large proportion of impervious surface cover	Porous pavement
Shed water more rapidly – changes the hydrograph	Neighborhood detention ponds and wetlands which collect stormwater
Increased runoff with a more rapid peak	Increase greenspace fraction
Decreased evapotranspiration (latent heat flux, QE)	Green roofs, green walls
Additional supply of energy – anthropogenic heat flux – QF	
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 and buildings to reduce temperature
Air pollution	
Human activities lead to ejection of pollutants and dust into the atmosphere	District heating and cooling systems
Increased long-wave radiation from the sky	Combined heat and power or cogeneration systems
Greater absorption and re-emission ('greenhouse effect')	

7. Concluding comments

Urban areas cover only a small fraction (< 5%) of the Earth's surface (Schneider et al. 2009). Their moisture, thermal and kinematic plumes remain distinct only a few kilometers downwind, although aerosol and gaseous releases are distributed much more widely. Many of the processes instrumental in creating urban climates are the same drivers of global anthropogenic climate change: regional-scale land use changes; increased energy use; and increased emissions of climatically-relevant atmospheric constituents. Thus, cities aid in the understanding of anthropogenic climate change and are also critical agents in moderating its effects. Understanding how urban surface properties affect radiation, energy, water and carbon exchanges can support mitigation and adaptation efforts centered around deliberate manipulation of surface climates, for example, through building design and materials or the use of vegetation. Cities and the drivers of urbanization are central to global environmental research. Urban populations and areas 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 not only those living within the buildings, neighborhoods and cities, but in combination will have global implications and consequences.

Key messages:

- Urbanization has profound effects on climate. The materials and morphology of the urban surface, along with emissions from domestic, commercial and transport activities, result in changes in local climate often greater in magnitude than projected global-scale climate change
- Urban climates have been studied for a long period; a rich literature with data, concepts, models and theories exists to inform current work
- Ultimately, urban climate effects are due to changes in surface-atmosphere energy, water and carbon exchanges; these can best be understood through the frameworks of energy, water and carbon budgets
- Understanding the scale-dependent nature of urban climates is fundamental to understanding, representative measurement programmes, and modelling of current and future cities for any application
- Cities are critical agents in moderating future global climate change; the materials used in their construction, building and neighborhood design and residents' behaviour all have profound effects on climate within and beyond a city's boundaries

Future research needs:

- More attention needs to be directed to understanding urban atmospheric dynamics in tropical cities where a large and ever increasing fraction of the world's population lives
- Attention also needs to be directed to towns and medium-sized cities as well as megacities, with specific attention to the scaling of effects and processes across the full range of urban environments
- New methods need to be developed to measure water, energy and carbon exchanges in dense urban settings increasingly characteristic of Asian cities, where current methods and theory are challenged by very tall buildings
- High-resolution numerical models need to be further developed to resolve and link canyon, neighborhood and city-scale conditions
- Integrated studies are needed of energy, water and carbon exchanges to better understand interdependences and the implications of interventions to mitigate urban climate effects

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