Climate of cities

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Climate of Cities

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Introduction

Urban areas create distinct local and micro-scale climates. Commonly cited effects are summarised in Table 1. What this summary does not make clear, however, is that urban climates vary significantly both within and between cities, and through the year. Urban climates result from changes in the urban surface (materials, architectural styles, fraction of built and vegetated cover etc.) and the activities of the cities' inhabitants (generating heat, greenhouse gases, aerosols etc.) as they move around, work and live in the city. Ultimately, urban climates are due to the surface-atmosphere exchanges of energy, mass and momentum (represented conceptually in Figure 1). Understanding these exchanges, and the effects of a particular urban setting on their spatial and temporal dynamics, are key to understanding urban climates at the scale of the city, neighbourhood or individual street or property level, and to predicting and mitigating negative effects. This chapter describes these energy and mass exchanges and highlights key urban controls with data and examples.

Global, regional and local effects

Cities, towns and settlements cover only a small fraction of the Earth (<2 % of the land surface). Thus, in terms of direct surface changes individual cities do not impact global weather or climate patterns. However, 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, cities and their inhabitants are key drivers of global climate change. Cities affect greenhouse gas sources and sinks both directly and indirectly. Urban areas are the major sources of anthropogenic carbon dioxide emissions from the burning of fossil fuel for heating and cooling; from industrial processes; transportation of people and goods etc. Moreover, the demand for goods and resources by city dwellers, both historically and today, are the major drivers of regional land use change such as deforestation. While the exact values are subject to debate, it is widely suggested that more than 70% of anthropogenic carbon emissions can be attributed to cities. Thus despite their small surface area globally, the effects of cities are significant regionally and globally, as well as locally.

A city's geographical setting influences both its climate and its effects on climate. Latitude has an influence through basic solar forcing; continentality influences seasonal extremes; and the sequence of expected fronts, low pressures systems, and other synoptic scale influences, affect the ranges of meteorological conditions a city experiences. These all influence the design of a city (e.g. building styles and materials) and the behaviours and activities of inhabitants (their demands for heating, cooling etc).

At the meso-scale, the geographic setting of a city will influence regional wind systems forced by topography (e.g. mountain–valley) or the presence of water bodies (e.g. sea or lake - land breezes). These in turn affect such things as the redistribution of air pollutants. The presence of the city itself can, under some synoptic conditions (e.g. anticyclones), create regional winds, the so-called rural-to-city breezes (e.g. in Paris documented by Lemonsu and Masson 2002). Cities also influence areas downwind. They are a source of warm, polluted air and can modify precipitation patterns (Lowry 1998, Shepherd et al. 2002, McLeod et al., 2017).

Within a city, neighbourhoods with similar land-use and land-cover, generate distinct local scale climates (Stewart and Oke, 2012). These are a function of the shape and spacing of buildings and their materials, amounts of vegetation, and human activity. Repeated patterns, based on features such as the height of the buildings, width of the canyons between them, the shape of roofs, and the areal fraction of vegetation can be clearly identified (Figure 2). Urban climatologists commonly characterise cities at this scale in terms of the height, width, density of buildings, the fraction of greenspace, and amounts of heat released by human activities (Table 2). Many numerical models simulate urban climates at this scale (e.g. the Weather Research and Forecasting Model WRF, Meso-NH) (see further description in Grimmond et al. 2010, Chen et al. 2011).

Within neighbourhoods, arrays of micro-scale climates exist. At these smaller spatial scales (10^0 – 10^1 m), a person walking down the street can experience a range of conditions: the sunlit or shaded sides of the street; the channelling or blockage of wind by a building; the influence of a park or shade trees.

Thus, key to an understanding of urban climates, is a clear understanding of spatial scale, both horizontal and vertical (Figure 2). Fundamental in any study of urban climate is the question as to 'what is actually of interest' – the overall effect of the city, conditions in a neighbourhood, or the climate of an individual house or garden. Confusion results if this is not clear and if there is a spatial mismatch between the entity of interest, observations collected or used, or the spatial resolution of models run to simulate or predict effects.

The surface energy and water balance

The surface energy balance provides a powerful framework within which to understand urban climates. The available energy at any location, urban or rural, to evaporate water, to heat the air, or heat the ground, is dependent on the balance of radiative fluxes. This simple statement of the conservation of energy can be defined (Oke 1988):

$$Q^* = K^* + L^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow \qquad \text{Units: W m}^{-2}$$

where Q* is the net all wave radiation, K the short wave or solar fluxes, L the long wave or terrestrial fluxes, with the arrows indicating whether the flow of energy is towards (↓) or away (↑) from the surface. The net all wave radiation, with the additional source of energy in cities from people's activities, the anthropogenic heat flux (Q_F), drives non-radiative exchanges between the surface and the atmosphere (Oke 1988):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \qquad \text{Units: W m}^{-2}$$

where Q_H is the turbulent sensible heat flux (heating of the air), Q_E is the turbulent latent heat flux (linked to E evapotranspiration (mm of water) through the latent heat of vaporization), ΔQ_S is the net storage heat flux (heating of the urban volume), and ΔQ_A is the net horizontal advective heat flux (Figure 1). For the energy balance, the sign convention is that fluxes away from the surface are positive on the right hand-side. The radiative fluxes towards the surface are positive.

4. Net all-wave radiation

Key factors influencing each of the radiative fluxes in any city are defined in Table 1. These factors are separated into those common across all land covers/land uses (column 2), and those influenced more specifically by urban conditions (column 3).

Latitude influences the typical incoming shortwave or solar radiation (K↓) at the top of the atmosphere and its seasonal variation. The synoptic and regional settings influence the probability of cloud and the nature of air pollution within the region, thus affecting solar radiation received at the surface. Increased concentrations of aerosols (e.g. from industry, clouds) alter scattering and therefore the relative amounts of direct and diffuse radiation received, as well as the overall transmissivity of the atmosphere and the shortwave flux received at the surface.

The nature of the surface, both materials and morphology, alters the albedo (α) (reflectivity) of the surface, and thus the outgoing shortwave radiation (K↑). In a city, if surface materials are kept constant, taller buildings result in lower 'bulk' albedo if street widths are kept constant (larger height: width ratios – H:W) (Aida 1982, Kanda et al. 2005). Lighter and drier materials tend to have higher albedos than darker or wetter building fabrics. For many urban settings, considerable attention has been directed to the development of urban building materials (paints, roofing covers etc) which have higher albedos to reduce the radiative loading of urban areas and thus mitigate urban heat islands (Santamouris et al. 2011).

Net longwave radiation (L*) similarly is dependent on atmospheric conditions, through influences on incoming longwave radiation (L↓), and surface conditions on outgoing longwave radiation (L↑). Surface materials and morphology influence the surface temperature and emissivity. The trapping of longwave radiation in areas with low sky view factors (larger Height to Width ratios of buildings and vegetation) results in increased L*. Developments of cool materials, noted above, take account the spectral response of short and long wave-length radiative fluxes.

While the influence on individual fluxes can be significant and can vary largely at the micro or local scale, overall the effects tend to balance out and the net radiative flux in cities tends to be close to that documented in nearby rural settings (Oke et al. 2017).

Figure 3a-c provides a comparison of radiative fluxes at two sites (Marseille and Miami). A comparison is also shown between clear sky and all sky conditions (Figure 3b,c). These data give a sense of the magnitude and diurnal course of fluxes.

Anthropogenic heat flux

The anthropogenic heat flux is an additional energy term introduced in the urban energy balance to account for energy that is released in cities. This flux derives largely from buildings, whether industrial, commercial or residential (for lighting, heating, air conditioning, industrial manufacturing, etc), transportation, and that energy attributable directly to human metabolism (Grimmond 1992, Sailor 2011). Dense urban areas with tall buildings that intensively use energy for air conditioning/heating in the summer/winter result in significant amounts of energy being released into the urban environment. In central London, for example, fluxes of over 100 W m^{-2} have been calculated (Lindberg et al. 2018). In areas where the buildings are smaller and less dense, and there is minimal use of heating and cooling, values for Q_F are less than 5 W m^{-2} (Lindberg et al. 2018). In terms of the mobile transport sources of heat, key controls are the nature of the vehicle fleet (e.g. balance of trucks versus cars and the fuel used), the density of traffic (e.g. major versus minor roads), the volume of vehicles and commuting behaviours (e.g. related to employment hours, when schools are in session etc). Heat released directly by metabolism is controlled by where people are likely to be (e.g. work, home) and their levels of activity (e.g. active or resting).

Turbulent sensible heat flux

The turbulent sensible heat flux is driven by the net available energy, the gradient in air temperature between the surface and the air above it, and the ability of the air to transport the energy away from the 'warm' location (towards or away from the surface). Atmospheric stability is a measure of the ability of the air to mix– typically classified as unstable, neutral and stable. Under unstable conditions lots of vertical motion helps to move heat away from the surface. Under such conditions, large positive Q_H fluxes are expected. Under neutral conditions, the buoyant transport of heat is suppressed, and Q_H tends to be close to zero. Such conditions are common under overcast, windy conditions or in the evening. Under stable conditions there is net transport of sensible heat towards the surface.

Typically, in cities in the summer unstable conditions prevail during the daytime and mildly unstable or neutral conditions at night. In high latitudes in the winter, for example in Scandinavia or northern European cities, Alaska, northern Canada, or in areas of very low urban density, negative Q_H values can be observed.

The relative importance of the sensible heat flux for three contrasting cities is shown in Figure 3. These illustrate clearly the typical diurnal course of the flux and key differences between residential areas of cities related to the nature of the building fabric (a key control on the storage heat flux) and the available moisture/fraction of greenspace (a key control on the latent heat flux).

Turbulent latent heat flux

The turbulent latent heat flux is dependent on the availability of moisture at the surface and the ability of the atmosphere to move the moisture away from the surface. For the latter, the influence of atmospheric stability and wind fields discussed above apply. Thus, a critical control is the strength of the moisture gradient. Unlike the spatial pattern of surface temperatures in a city, where differences always are present, albeit with varying contrasts, in urban environments it is possible to have areas/times where there is no surface moisture (e.g. a totally sealed parking lot with no vegetation a long period after rain) and areas where it is freely available (e.g. irrigated parks, ponds). Street cleaning, allowing/banning/regulating garden irrigation *etc.* can significantly modify water availability and thus rates of Q_E. When irrigation bans are put in place to conserve water, rates of evapotranspiration drop accordingly (Kokkonnen al., 2018). Typically, the central business district of a city has less vegetation and residential areas greater vegetation and patterns of Q_E reflect this (Figure 4) (see also Ward et al., 2017). Even in the driest urban settings, water is present and urban evapotranspiration does occur (see for example the fluxes from Ouagadougou shown in Figure 3).

Of course, latent heat flux rates also are influenced by the frequency and intensity of precipitation events, and the methods used to detain or rapidly drain rainwater away. In many urban areas water is retained in neighbourhood detention ponds (particularly common in USA) (see Chapter XX this volume) or recycled into local wetlands (see

Chapter XXX this volume), or held at individual properties (increasingly common in Australia) to irrigate vegetation or for internal water use. Under very humid conditions, small moisture gradients will reduce evaporation rates. Immediately following rain, or early morning after dewfall, there can be large latent heat flux values for a short period of time (e.g. Kotthaus and Grimmond 2014).

As the latent heat flux is the energy equivalent to the evaporation term in the water balance (see Chapter XX this volume), the size of the flux influences not only the partitioning of the convective energy fluxes (Bowen ratio (β) = Q_H/Q_E) (heating air: evaporating water), but also other water balance fluxes such as ground water recharge.

The spatial patterns of atmospheric moisture (various measures of humidity) within cities are also influenced by temperature patterns (see Chapter XX this volume), as well as the surface moisture status and latent heat fluxes. Typically, urban areas are described as having an atmospheric urban moisture 'deficit' compared to surrounding rural areas (see, for example, the studies cited in Kuttler et al. 2007). This is because of the limited vegetated surfaces, the enhanced air temperatures (which increases the amount of moisture required to saturate air), and engineered pipe networks designed to rapidly remove precipitation from urban areas. Care needs to be taken when comparing moisture metrics as there are a number of different measures (e.g. relative humidity, specific humidity, dew point temperature, absolute humidity, vapour pressure) and these may be a function of other variables (e. g. pressure, temperature) as well as actual moisture content change in the air.

Net heat storage flux

Typically, the heat storage flux is considerably larger in urban areas relative to rural surroundings (e.g. Grimmond and Oke 1999a). This flux is the net uptake or release of energy (per unit area and time) by sensible heat changes in the urban canopy air layer, buildings, vegetation, and the ground. Given that in cities there is a significant amount of mass to heat up and cool down, plus there are vertical faces of buildings that are being directly heated in the morning (east facing walls), middle of the day (south facing in the northern hemisphere, north facing in the southern hemisphere) and in the afternoon (west facing walls) the flux is significant - up to 40-50%, compared to more typical values of 5% in rural areas. Moreover, there is a distinct diurnal trend in cities. The flux is typically larger in the morning, before solar noon, as heat is moved away from the surface into the building volume. However, by mid- to late afternoon heat is being transferred back towards the surface and released into the atmosphere. This helps to maintain a positive sensible heat flux in cities in the evening and at night (noted above) which results in a warmer air temperature. This large conductive heat store also helps to increase the energy available for longwave radiative exchanges (see discussion above).

Key characteristics of the urban environment that influence the size of the storage heat flux are the surface materials, morphology and thermal mass. The surface materials influence the ability of the heat to be conducted in to (and out of) the urban fabric. As conduction is not as efficient as convection, typically there are steep thermal gradients relative to the surface temperature. Very high surface temperature are frequently observed in cities (e.g. by thermal remote sensing), but away from the surfaces (e.g. inside building cavities or air temperatures) the range of temperatures are considerably less. Thus, just as with the radiative characteristics of built materials, the thermal characteristics (heat capacity, thickness of layers, density) of built materials provide opportunities for architects, planners and engineers, to manipulate the energy exchanges both internally and externally for a building, thus affecting urban climates at micro- to local scales. The morphology (spacing, heights, and orientations) of buildings also have a key influence on initial solar gains by the surface and on radiative trapping.

Net Heat Advection flux

Advection, the net horizontal flow of energy, into and across a city results from spatial differences of surface characteristics. Contrasting surface temperatures, moisture availability or roughness will create a spatial gradient, which drives horizontal transport of energy. The setting of a city, next to water, for example, will dictate the magnitude of these exchanges (into or out of) a city at the larger scale. Within the city, patchiness of urban surfaces (e.g. at the lot or neighbourhood scale) affects horizontal energy exchanges and mixing (Crawford et al. 2017). For example, on a hot summer's day, well irrigated grass next to a road or other paved surface will result in advection. This induces spatial variability of evapotranspiration rates in parks (Spronken-Smith et al. 2000). Such patchiness and advection have important implications for the stress of vegetation in urban settings.

Wind Fields

Underlying an understanding of any of the convective heat exchanges already described (Q_H, Q_E) is the need to know about urban wind fields. One very distinct characteristic of cities is the roughness elements - the objects that the air has to flow over. These are both bluff bodies (e.g. buildings) and porous elements (e.g. vegetation). Clearly, porous objects occur over most land surfaces, so it is the bluff bodies and their characteristics that are important in creating distinct wind environments in cities. As air flow is three dimensional (towards an object, at right angles to the object, and vertically - usually referred to as u, v, w components, respectively), it is the response of the wind in each of these directions that is important to urban wind fields at the micro-scale.

The presence of bluff bodies force air to go up, over and around the edges of the objects. This can cause an increase in wind speeds at points upwind and a cavity of low flow behind the object(s) (Figure 5a). With an increase in the number of objects (e.g. increasing building density), the surface reaches a peak in roughness, which is associated with the largest roughness length for momentum. After that, any further increase in density is associated with effectively lifting the 'surface' higher. Under such conditions the canyon flows are little influenced by above canyon cross flow (Figure 5a). The zero-plane displacement length for momentum, the mean level of momentum transfer between the flow and the roughness elements, continues to increase with increasing building height. Thus, the roughness length and zero-plane displacement length are neighbourhood scale characteristics which will vary across a city. At the scale of the whole city, the city itself will act as regional scale bluff body causing flow to be deflected around it.

At the micro-scale wind fields can be complex and result in wind directions and wind speeds that are quite different from those that are above the roughness sublayer (Figure 5c). This can mean that a small change in measurement height results in quite different wind components (u, v, w) being observed. Because of the complexity of this, extensive efforts have directed to the modelling of airflow and dispersion at these scales to be able to predict the movement of pollutants released within a canyon (Hertwig et al. 2018) under different stability conditions.

Air Pollution

Urban areas are well known for having other mass exchanges, those involved in air pollution, which can have major impacts on human health and well-being, and also affect vegetation. Many of the sources of anthropogenic heat are also sources of air pollution. These pollutants are normally classified as primary (those directly emitted) or secondary (resulting from chemical interactions e.g. ozone). Primary pollutants often of concern are sulphur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO) and carbon dioxide (CO_2), and volatile organic compounds (VOCs). From a health perspective, the chemical characteristics of the substances released, along with the physical properties of the aerosols themselves, are important. Particulates are particularly relevant in considerations of respiratory problems. Increasingly data on PM_{10} (which refers to particles which are less than 10 μm in diameter), $PM_{2.5}$ (<= 2.5 μm in diameter) and PM_1 (< 1 μm in diameter) are documented throughout urban environments.

The presence of the particles or aerosols in the atmosphere also influences physical atmospheric processes; e.g. radiative transfer, scattering, absorption. The presence of these particles is fundamental to precipitation processes (they act as condensation nuclei and freezing nuclei), but their chemical composition can lead to secondary pollutants through, for example, oxidation processes and change the chemical composition of precipitation (e.g. wet deposition). The exact urban impact depends on: what type of particles are released, at what temperature and velocity (which will influence their transport); the meteorological conditions at the time of the release; where they are released (e.g. tailpipe of a vehicle, from a tall industrial stack); and the previous chemical state of the atmosphere (which will influence the atmospheric chemical reactions that can occur).

Final comments

In the previous sections the nature of the processes that occur in any urban setting of any size and location are discussed. Note the urban heat island is discussed separately in Chapter XX.

In terms of the dominant seasonal controls, the urban energy balance in tropical cities will be affected most by changes in precipitation conditions, whereas for high latitudes the most distinct differences occur because of major differences in solar radiation availability and variations in albedo (related to snow cover). Mid-latitude cities typically will have strong seasonal variations associated with changes in radiation receipt also (exacerbated by winter-time snow).

Across a city, significant changes in energy partitioning will occur because of varying surface characteristics. Key is the amount of active vegetation, which typically results in a decrease in Bowen ratio (Q_H/Q_E) as greenspace, particularly irrigated greenspace, increases. Increasing the built fraction increases the probability of unstable conditions at night and positive turbulent sensible heat flux.

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Table 1: Controls on urban climate are dependent on location as well as urban specific characteristics (these are explored in detail in Oke et al. 2017)

Variable	General controls	Urban controls/effects
Incoming solar radiation (K↓)	Latitude; Synoptic conditions/ cloud cover	Air quality/Industrial sources influence scattering
Outgoing solar radiation (K↑)		Surface materials; Surface morphology/geometry
Incoming long wave radiation (L↓)	Synoptic conditions/ cloud cover	Air quality/Industrial sources affect absorption
Outgoing long wave radiation (L↑)		Thermal properties of materials; Radiative properties; Surface morphology/geometry
Net all-wave radiation (Q*)	Latitude; Synoptic conditions/ cloud cover	Materials & Morphology, Air quality
Sensible heat flux (Q_H)	Temperature gradient; Atmospheric stability; Synoptic conditions	Building volume; Built fraction
Latent heat flux (Q_E)	Moisture gradient; Atmospheric stability; Synoptic conditions	Fraction greenspace; Irrigated surfaces; Enhanced runoff; Detention ponds
Storage heat flux (ΔQ_S)		Materials & morphology urban surface; Orientations walls; Mass/volume urban surface
Anthropogenic heat flux (Q_F)	Latitude; Continentality; Regional setting	Heating/Cooling requirements; Industrial activity; Socio-economic conditions; Population/Building density; Transportation routes & methods
Air temperature	Latitude; Continentality; Regional setting	Materials & morphology of urban surface Release of anthropogenic heat; Air quality
Humidity	Latitude; Continentality; Regional setting – proximity to water bodies	Reduced vegetation; Fewer moist surfaces Localised releases (industrial sources) as bi-product combustion; Urban air temperature
Wind field	Synoptic conditions	Building & tree density; Morphology buildings & roofs affect roughness & displacement lengths, Channelling through urban canyons
Precipitation	Latitude (solid, liquid); Synoptic conditions; Topographic variations	Air quality/industrial-traffic sources ->cloud condensation nuclei; Roughness elements/surface heating -> convection

Table 2: Parameters commonly used to characterise cities. Each subscript refers to a separate parameter. Subscript f = roof; r = road; w = wall; v = pervious; t = tree; H = building; g = grass, s=soil, m = momentum; h = heat, u=urban, c= canyon.

Category	Parameter	Name
Radiative	$\alpha_{f,r,w,v,t,g,c}$	Albedo
	$\varepsilon_{f,r,w,v,t,,c}$	Emissivity
Roughness	$z0m_{,c,u}$; $z0h_{,c,u}$	Roughness length for momentum and heat
	$d0_{f,r,w}$	Zero-place displacement height
Thermal characteristics	$c_{Pf,r,w,v,t,g,s}$	Volumetric heat capacity
	$K_{f,r,w,v}$	Thermal conductivity
	$nl_{f,r,w,v,s}$	Number of layers
	$dl_{f,r,w,v,s}$	Layer thickness
Urban morphology	$z_{H,g,t,u}$	Mean height
	W_X	Averaged building separation/canyon width
	L_X	Average width of buildings
	SVF	Sky view factor
	L_Y	Mean block length
	az	Mean long axis azimuth of walls
	λ_F	Frontal area index
Plan area	$\lambda_{f\ v,g,t,H}$	Fraction of area
Urban area classification		Oke (2006), Loridan and Grimmond (2012), Stewart and Oke (2012)