Chapter 9
Integrating Urban Climate Knowledge: The Need for a New Knowledge Infrastructure to Support Climate-Responsive Urbanism

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9.1 Introduction

Cities affect climate at a hierarchy of scales and decisions that are made to manage these climates do not always recognise the interdependencies between these scales. This is partly because the relationships between the climate drivers at city scales are complex but it is also a product of the history of urban climate research and application that has resulted in a fragmented knowledge base that is difficult to integrate. As a result, solutions to one climate problem at one scale can present a problem elsewhere; as an example, air-conditioning systems to cool an indoor space contribute to heating the outdoors. In this short contribution we outline some of the climate issues that arise at urban scales from narrowly focussed solutions to urban energy management. In particular, we focus on the relationship between the indoor and the outdoor climates in cities and argue for the development of a body of knowledge that integrates urban climate science knowledge across multiple fields of study. This is needed to support comprehensive policies that seek to create more sustainable cities that create liveable and healthy indoor/outdoor city climates while contributing to global sustainability. Here, our focus is on the fundamental link between natural and anthropogenic energy exchanges and climate impacts in cities and we draw upon examples from the City of London to support our points.

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9.2 Cities, Energy and Climate Changes

Rees and Wackernagel (2008) argued that although cities cannot be sustainable, they are a key to achieving sustainability. This proposition captures the conundrum posed by cities; on the one hand, as individual entities, the land-cover change and resource demands of cities means that they rely on the productivity of landscapes elsewhere and, on the other hand, their relatively compact form and high population density offer opportunities for efficiency that would not be possible otherwise. Currently, the urbanised landscape of the Earth's land is less than 3%, yet cities are collectively responsible for over 70% of CO_2 emissions (Seto et al. 2014). This suggests that much of the global mitigation policies should be focussed on cities as major drivers of global climate change where there are management systems that can implement change at relevant scales. However, until very recently, the focus of climate change policies has been at national levels and on the major sources of energy demand (e.g. transport, industry and buildings), even though much of this demand is spatially 'bundled' in cities. The importance of urban areas in the global context has changed considerably with the emergence of international consortiums of cities that are focussed on mitigation and adaptation strategies and encourage knowledge exchange.[1] The most recent IPCC assessment report recognises the potential role of human settlements by linking aspects of urban form and functions and states that key 'drivers of energy and GHG emissions are density, land use mix, connectivity, and accessibility. These factors are interrelated and interdependent. Pursuing one of them in isolation is insufficient for lower emissions' (Seto et al. 2014). Compact city policies that encourage higher population and built densities are advocated to make cities more energy efficient. In practice this is often used to support policies for the more efficient use of serviced land by building closely and vertically.

Separately from global climate change concerns, the climates in cities have been a subject of study for a very long time. We might usefully divide these into studies of indoor and outdoor climates and the (mis)management of natural and anthropogenic energy fluxes.

9.2.1 Indoor Climates

Much of the energy consumed by a city is used in buildings for managing the internal climate and supporting the occupants. In many buildings the large proportion of this energy is used for space heating and cooling to balance internal and external energy loads. The amount of energy required depends on the ambient climate and

[1] For example, C40 is a network of the world's megacities committed to addressing climate change. C40 supports cities to collaborate effectively, share knowledge and drive meaningful, measurable and sustainable action on climate change (https://www.c40.org/).

the degree of control on the indoor climate to ensure thermal comfort (De Dear 2004). Innovations in architectural and engineering practices have revolutionised building and building practice such that building form and function can be considered to have been liberated from its climate-driven form (e.g. Lehmann 2010). Historically, settlements accounted for natural resources in their layout, which regulated building height and spacing to permit (or limit) access to daylight and sunshine. The result of these historical design decisions is often embedded in the urban landscape including road width, plot size and building dimensions. Modern buildings have minimised their dependency on passive resources through technological innovations that rely increasingly on mechanical controls. As a result, in large buildings (such as modern office blocks and apartment buildings) great emphasis is placed on the envelope as the interface with the outdoors and its ability to regulate energy gains and losses to the building. The heating, ventilation and air-conditioning (HVAC) systems are designed to manage the internal climate within acceptable limits. In current thinking, a building can achieve high efficiency through this fabric-first approach that achieves energy efficiency through the design of envelope and the efficiency of HVAC systems. This approach can be complemented by availing of renewable energy (such as photovoltaic cells) on-site.

Buildings are significant consumers of energy and as a result are a focus of climate change mitigation;[2] in the EU buildings accounted for 40% of the final energy consumption and 60% of electricity consumption in 2016, two-thirds of which was expended in residential buildings.[3]

9.2.2 *Outdoor Urban Climates*

The urban effect on the outdoor climate in cities is an outcome of characteristics of form and function. Form describes the land cover (e.g. the fractions of vegetative and impervious cover), the fabric (the characteristics of manufactured materials used to construct the paving and buildings) and the geometry (the corrugated nature of the urban surface). Urban functions describe the throughput of materials, energy and water that are needed to sustain the urban system. Many of these resources pass through the city in degraded form and much is expended as waste gases and particulates into the overlying atmosphere. Together, urban form and functions modify the exchange processes at the surface-air interface and generate extreme spatial and temporal variations in microclimates across the urban landscape. These effects extend through a deep (>1 km) layer of the overlying air but are most profound near the ground, in the spaces between buildings and below roof level (known as the urban canopy layer). The best known of these urban climate effects is the urban heat

[2] See Building Regulation Standard (Conservation of fuel and power: Approved Document L) at https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-l.

[3] https://www.odyssee-mure.eu/publications/policy-brief/buildings-energy-efficiency-trends.html.

island (UHI), which results in warmer surface and air temperatures within the canopy by day (surface) and night (air). The UHI impacts the public health, especially during warm weather events, and impacts the heating/cooling energy needs of buildings. The urban impact on climate varies considerably across the urbanised landscape but the magnitude is usually greatest in city centres characterised by high building densities, little green cover and high daytime occupancy. Although there is a substantial body of literature on how urban planning and design decisions affect the local climate (e.g. Grimmond et al. 2010), there is little evidence that this knowledge is incorporated into practice (e.g. Mills et al. 2010); this has been referred to as a post-war knowledge circulation failure (Hebbert and Mackillop 2013).

The links between global and local climate changes are synergistic and many of the projections of global climate change, such as increased frequency of heatwaves, will be enhanced by the UHI (Li and Bou-Zeid 2013). Climate change policies on the outdoor urban climate largely focus on increasing the adaptive capacity to offset projected changes through various greening strategies.

9.2.3 Redefining the Urban Canopy Layer

The partitioning of the near-surface urban environment into indoor and outdoor climates with distinct management policies can result in undesireable climatic outcomes. In the urban realm, the emphasis on buildings as independent entities with responsibility for managing its internal energy use can have unintended impacts on the nearby outdoor spaces and other buildings. Similarly changes to the urban context (by modifying building dimensions and/or greening outdoor spaces) surrounding an individual building will impact its ability to meet its energy needs efficiently. Balancing the needs of both the indoors and outdoors in an urban setting requires an integrated perspective that can bring together expertise that is fragmented into many different fields of study (e.g. building engineers, architects, meteorologists, designers and planners), each of which has its own language and methods that inhibits communication. A potential starting point is to simply consider the outdoor and indoor climates in cities as parts of a single layer of the atmosphere linked by natural (and enhanced) energy/mass exchanges and extend the definition of the meteorological concept of 'urban canopy layer' (UCL) to include the indoor space.

The etymology of the UCL in boundary-layer meteorology is based on its equivalence with the architecture of forests, which separates the climates found above and below the leafy forest canopy. From the vantage above the forest canopy, the relevant plane where energy and momentum exchanges are concentrated is located above the ground at the top of the canopy. Below the canopy top, exchanges at the ground surface are greatly altered by the overlying leafy 'roof' which limits short-wave radiation receipt and long-wave radiation loss. Within the forest canopy layer it is not possible to understand the climate impact of trees in a forest simply as the sum of the individual trees, as their interaction through mutual exchanges (e.g.

shading and sheltering) produces a unique climate that affects the responses of each tree.

The equivalent canopy layer in urban meteorology is defined as the outdoor space between the buildings below roof level. Apart from the different 'architecture' of the canopy itself, buildings are hollow and are a ubiquitous energy source as heat is added/removed as needed to maintain an indoor temperature suited to its needs. Ironically, to ensure a near-uniform microclimate, the building waste energy must be disposed into the outdoors contributing to the urban climate effect, which in turn impacts the energy needs of the building itself. Moreover, the mutual shadowing and sheltering of buildings in an urbanised landscape affect the energy performance of each building. Finally, unlike the forest, much of the ground between the buildings is paved and is also an enhanced energy source as a result of waste energy emitted by traffic.

Fundamentally, the layer between the ground and the rooftop level is a zone of human occupation. Redefining the urban canopy layer to include both the indoor and outdoor space below roof level would overcome many of the difficulties that arise because of the partitioning of this space into separate areas of study. The boundary at the top level of this UCL includes the solid roofs of buildings and the open interface between them. The wall facets are the shared boundary separating the indoors and outdoors and, like the top of the UCL, can be open to air exchanges (infiltration, natural ventilation and HVAC intake and exhaust), radiative transfer and heat conduction. While the indoor environment is highly regulated, the outdoor space may be partially managed (through landscaping, choice of fabric, traffic control) or unregulated. This perspective has the advantage of describing the entire urban landscape using the same context; the challenge is to assemble the underpinning scientific knowledge. Here we outline a perspective and methodology that is used to explore the relationship between urban form and energy (mis)managment in indoor and outdoor environments.

9.3 Urban Climate Management

Urban form management on the wider environment can be evaluated and usefully applied to the study of indoor and outdoor climates has been demonstrated Urban form, that is the dimensions and layout of buildings, has been shown to have a dramatic impact on the outdoor climate between builidngs and to impact the ambient environment of individual buildings (e.g. Ratti et al. 2005; Salat 2009; Kolokotroni et al. 2012; Futcher et al. 2018; Salvati et al. 2020). Nonetheless, current methodologies for assessing urban energy sustainability focusses on individual buildings, which can achieve impressive energy credentials without considering their impacts on neighbouring buildings or adjacent outdoor spaces (e.g. loss of sunshine, wind effects, etc.). In most jurisdictions there is no legal framework or guidance for conducting a microclimatic assessment of these impacts and no basis for examining the aggregate impact of buildings on the atmospheric environment. In the UK the exception is the right to daylight, which is enshrined in law as an easement (that is, a right to cross over someone else's land for a specific purpose), and must be taken into account when a new construction affects the daylight resources of neighbouring buildings. However, there are no mandatory criteria to assess potential impacts on the surrounding urban landscape more generally and nor are assessments part of planning and/or policy guidance. As a result, city landscapes are developing in such a way that the emerging morphology, which will have significant long-term impacts for on the outdoor and indoor climate are not taken into account.

The current approach to the environmental management of our cities focusses on the aspects of indoor and outdoor spaces (e.g. zero-carbon buildings, vehicle emission standards, urban greening) often in isolation. An integrated approach would account for the interdependencies between urban built form and impacts. It would also consider the urban commons and the use, preservation and access to our collective shared resources (e.g. daylight, ventilation, air quality) to create healthy environments and encourage more sustainable urban practices. A shared understanding of the urban climate at all scales (macro to micro in both the vertical and horizontal) requires clear definitions of building energy interdependencies and a common set of methods and teminology to support knowledge exchange. Urban building energy models (Reinhart and Davila 2016), which permit the analysis of neighbourhoods rather than buildings and account for the mutual interactions between buildings and outdoor spaces as a shared environment, offer a pathway toward an integrated science. Ideally these urban building energy models would be coupled with climate models that could simulate the environmental impacts of design decisions.

9.3.1 Case Study: The City of London

Our case on the need for an integrated science of the urban landscape for climate management has been formed through studies of the outdoor impacts of the emerging urban landscape in the City of London, which occupies a space of just over 3 km^2 or less than 0.2% of the Greater London area (Table 9.1).

It is distinguished within London by its occupation patterns that are strongly linked to commercial functions; during the daytime its population swells to nearly 500,000 but there are just over 8000 residents. The reliance on commercial functions is seen in the intensity of energy consumption, much of it for space cooling in buildings that have large internal energy gains. The desire to maximise floor space and the availability of modern construction techniques have seen a radical change in the historic urban form including:

- Tall and very tall buildings that occupy small plots and are inserted into a relatively low-lying urban setting
- Deep-plan buildings that fill large floor plates and replace courtyard forms

Many of these building types use curtain wall systems that permit large uninterrupted areas of glazed facades (Fig. 9.1). While all of these buildings are designed

Table 9.1 A comparison of the energy and occupancy profiles for Greater London (32 boroughs and City of London) and the City of London. Data are from 2014 and sourced from https://data.london.gov.uk/

Property	Greater London		City of London	
Area (km^2)	1594.69		3.15	
Daytime population	8,676,835		360,075	
Residential population	8,538,689		8072	
Population density (day) Persons per km^2	5441		114,330	
Population density (residential) Persons per km^2	5354		2563	
Energy density GWh per km^2	82.78		1033.07	
Energy use (kWh) per capita (day)	1521.45		903.58	
Energy use (kWh) per capita (residential)	1546.06		40,306.77	
Total energy use (GWh)	132,013.5		3253.6	
Commercial energy use (GWh)	48,279.3	36.6%	2986.0	91.7%
Domestic energy use (GWh)	53,249.2	40.3%	57.4	1.8%

Fig. 9.1 High-rise buildings of the City of London by Tristan Surtel (25 April 2018) at https://commons.wikimedia.org/wiki/File:City_of_London_seen_from_Tower_Bridge.jpg#file under a Creative Commons Attribution 4.0

Fig. 9.2 Examples in the City of London that illustrate the relationship between buildings, energy management and outdoor spaces: (**a**) shows a canopy extension which limits the impact of fast winds that have been displaced downwards toward the ground; (**b**) shows a covering placed over the south-facing, parabolic shaped glazed façade of a building which redirected and focussed solar radiation onto adjacent streets (the façade was subsequently refurbished); (**c**) shows a set of tall buildings that channel air through a pedestrianised street and require vegetation to make the space more comfortable; (**d**) shows a configuration that has a Venturi effect on airflow as it is accelerated through a narrow gap between two very tall buildings; (**e**) shows a residential apartment block with embedded (stationary) wind turbines that rely on a common resource; and (**f**) shows a tall structure with embedded photovoltaic cells along its south-facing façade, which has subsequently become overshadowed by a neighbouring building. Each of the buildings shown here is an exemplar of energy-efficient buildings that meet carbon goals (credit: Futcher and Mills)

to meet stringent energy regulations, their combined environmental impact on their surroundings is often negative. Figure 9.2 shows images of several of these buildings that illustrate the challenges to developing on-site renewable energy, which is not a private resource, in dense urban settings; the failure to consider the impacts of redirected winds and solar radiation on climates at the ground; and the *ad hoc* architectural and landscaping responses to mitigate deleterious outdoor outcomes, some of which are predictable (such as the Venturi effect).

Over the last 5 years, the authors have run Urban Climate Walks through the City of London as an opportunity to engage with a range of urban academics, practitioners and students with interests in architecture, energy management, outdoor comfort and air quality, design and planning. The walk treats the participants as mobile ‘weather stations’ and links their sensory faculties to climate processes and observations (Mills et al. 2018). For this reason, the route is designed through a heterogenous landscape characterised by variations in:

1. Street widths, building heights and orientation
2. Traffic flows including vehicles and pedestrians
3. Building dimensions, fabrics and uses
4. Green surface cover and street plantings

The discussions that take place during the walk have convinced us that while all the experts ostensibly study the same urban environment, they do so from distinct perspectives that inhibits effective communication. For example, the well-known UHI phenomenon is frequently misunderstood in terms of type (surface or air), timing (daytime or night-time) and cause (natural energy exchanges or anthropogenic heating).

9.4 Conclusions

The urban environment is a spatially complex system with mutual dependencies such that altering a part has ramifications for other components of the system. Currently, our methods for addressing climate changes, which are often focussed on energy management, are narrowly focussed and do not address the wider environmental consequences of small-scale interventions, such as new building developments within an existing neighbourhood. We need a more comprehensive set of tools that integrate existing urban knowledge to address the challenges of creating more sustainable cities.

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