Progress in Physical Geography 30, 2 (2006) pp. 270–279

Applied climatology: urban climate

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I Introduction

Given the large and ever-increasing number of urban inhabitants globally, and the profound effects of cities and their inhabitants on the atmosphere, both within and beyond urban limits, ever-increasing attention is being directed to the study of urban climates. The underlying rationale for these urban climate studies varies: ranging from the need to know more about the fundamental physics, biology or chemistry of urban atmospheres, and to integrate such understanding in operational weather forecasting and air quality models; interest in environmental sustainability and the desire to plan settlements and build houses that are more energy and water efficient; concerns about environmental health, whether related to air quality, heat stress; or 'homeland security' and the dispersion of toxic substances in cities.

In the last five years, a number of review papers on urban climatology have been published. These have been structured in terms of *methodology* – see, for example, a series of papers published from the Fifth International Conference on Urban Climates (ICUC5) by Kanda (2006) on scale models, Grimmond (2006) on measurements, Masson (2006) on numerical models, and Best (2006) on forecasting and numerical models, and the paper of Voogt and Oke (2003) on thermal remote sensing and Dabberdt *et al.* (2004) on measurements; *scales of analysis* (the urban canyon, neighburhood, entire city) – see, for example, McKendry (2003); Arnfield (2003a; 2003b; 2005); and the *climatic element* of interest (temperature, moisture; wind, etc) – see, for example Shepherd (2005); Richards (2005). Here, attention is directed to urban climate papers published in the refereed literature in the last two years. Coverage is not comprehensive and is heavily biased towards papers published in English. Studies that focus specifically on the composition of the urban atmosphere and air quality, rather than the physical state of the atmosphere, are not reviewed here.

II Spatial patterns of urban climate elements

The urban heat island (UHI) still remains the most intensively studied climatic feature of cities. Data, either from existing meteorological networks or from mobile monitoring systems, provide the empirical base for investigations of the spatial and temporal structure of the urban heat island. Recent papers using this approach include analyses of the UHI in

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10.1191/0309133306pp484pr

Seoul, Incheon, Daejeon, Daegu, Gwangju and Busan, South Korea (Chung *et al.*, 2004; Kim and Baik, 2004a; 2005), Buenos Aires, Argentina (Bejarán and Camilloni, 2003), New York City, USA (Gedzelman *et al.*, 2003), Lisbon, Portugal (Alcoforado and Andrade, 2006), Prague, Czech Republic (Beranova and Huth, 2005), and Debrecen, Hungary (Bottyán *et al.*, 2005). These studies serve to confirm results from previous investigations; notably that the urban heat island is stronger at night than in the day, that it decreases with increasing wind speed and cloud cover, it is least developed in summer, and temperature fields are strongly related to surface/building geometry, land use, vegetation and patterns of anthropogenic heat release (Giridharan *et al.*, 2004; Jonsson, 2004; Unger, 2004). The critical importance of the rural reference site, as well as the urban site, in defining urban-rural differences has also received continued attention (Hawkins *et al.*, 2004; Sakakibara and Owa, 2005). Increasingly, studies of the urban heat island are using higher-resolution data, which allow the diurnal course of the urban heat island to be studied in detail and the detection of episodes of short-lived thermal contrasts related to advection, the passing of fronts, thunderstorms, etc (Szymanowski, 2005).

The influence of building geometry on radiative fluxes is a principal reason for surface temperature differences between rural and urban areas. Urban climatologists continue to develop techniques to rapidly quantify building/canyon geometry; notably through new methods to quantify sky view factors (Chapman and Thornes, 2004) and the application of LIDAR (Zhou *et al.*, 2004). Field studies (for example, Blankenstein and Kuttler, 2004), have provided further evidence of the impact of street geometry and building materials on downward longwave radiation and nocturnal air temperature. In a study of ultraviolet radiation (UVR), Heisler *et al.* (2003), through measurements and modelling, document quite different effects of urban trees on UVR compared to photosynthetically active radiation fields, with implications for damage to materials, altered herbivory of insects and activity of microbes, modified growth of vegetation, and effects on human health.

In the last few years, there has been resurgence in interest in moisture and precipitation in urban settings. Virtually all human activities involve the generation of moisture as well as heat as a byproduct, especially the burning of fossil fuels and the use of water in cooling towers and ponds. Other anthropogenic activities, such as irrigation of urban vegetation, also provide important moisture sources, particularly in greener residential neighbourhoods and urban parks. Urban effects tend to be complex, both spatially and temporally, with important implications for radiative exchanges, fog and visibility, and also human comfort. Richards (2005), in a novel approach that integrates hardware scale model experiments, field measurements (using mini-lysimeters), and numerical modelling, has provided important new data on dew and its significance as a water flux both to vegetated surfaces and roofs. Mayer *et al.* (2003) documented spatial and temporal variability of humidity (vapour pressure) within the urban canopy layer across different land uses, though were unable to document significant relations with human perceptions of thermal comfort.

After a hiatus in research on urban precipitation (Lowry, 1998), in the last few years there has been resurgence in studies of urban effects on precipitation, clouds and storms. This has been driven in part by new technologies; for example the application of data from the Tropical Rainfall Measuring Mission (TRMM) satellite's precipitation radar (Shepherd *et al.*, 2002; Shepherd and Burian, 2003) and Doppler radar (Russo *et al.*, 2005). Such technologies allow precipitation, which can be highly variable spatially, to be more easily quantified, though ground-based rain gauges still remain the absolute reference. Recent studies (see the review in

Shepherd, 2005) serve to confirm previous understanding that urbanization has an effect on precipitation through increases in hygroscopic nuclei, turbulence via surface roughness, convection because of changes in the urban heat budget, convergent windflow over the urban area which may lead to rain-producing clouds, and the addition of water vapour from combustion from anthropogenic sources. Although Jin *et al.* (2005) were not able to relate urban increases in precipitation to aerosol concentrations. Inoue and Kimura (2004), in Tokyo, document an increase in low-level clouds around the metropolitan area on clear summer days. At larger scales, Ohashi and Kida (2004) consider urban effects on local circulations and the transport of moisture. The implications of urban effects on both rainfall and runoff for urban water management, both in terms of drainage design (Burian *et al.*, 2004) and water conservation (Mitchell *et al.*, 2003), remain a focus of many urban hydroclimatological studies, with implications both for storm-water engineering and water reuse and conservation.

III Energetics and dynamics of urban climates

Clear evidence of increasing attention to the fundamental heat, mass and momentum exchanges that generate urban climates is provided by the increasing number of field studies of the surface energy balance (see, for example, Christen and Vogt, 2004; Moriwaki and Kanda, 2004; Grimmond *et al.*, 2004; Offerle *et al.*, 2005a; 2005b; 2006a; 2006b; Spronken-Smith *et al.*, 2006). Most of these studies use eddy-covariance instrumentation, mounted on tall-towers, with data representative of the local (neighbourhood) scale. However, studies of specific urban materials/urban facets also have been undertaken (Weber and Kuttler, 2004; 2005). What is emerging is a consistent understanding of the nature of the urban surface energy balance: high storage heat uptake in the day, particularly in the morning; positive turbulent heat fluxes to the atmosphere at night; and sensible heat fluxes that exceed latent heat fluxes (although it is important to note that latent heat fluxes are not insignificant, particularly in residential settings). Attention has also been directed to the quantification of the anthropogenic heat flux, and important new information on the magnitude and variability of the flux for cities in the USA has been published by Sailor and Lu (2004) and Fan and Sailor (2005), for example.

Urban surface structures, such as buildings, significantly influence local weather and air quality. The problem is complicated because it entails complex terrain, turbulence and interactions between various energy transfer processes. Recently, a significant number of field-based, wind tunnel and numerical modelling studies of urban wind flow (Martilli *et al.*, 2003; Emeis, 2004) and atmospheric turbulence (Davies *et al.*, 2004; Kastner-Klein and Rotach, 2004; Feigenwinter and Vogt, 2005) have been conducted. These studies can be broadly categorized into those concerned with flow within (Cui *et al.*, 2004; Calhoun *et al.*, 2004; Kim and Baik, 2004b; Wang *et al.*, 2004; Zhang *et al.*, 2004) and above the urban canopy (canyon) layer (Coceal and Belcher, 2005), and those concerned with exchange processes between (Barlow *et al.*, 2004; Dupont *et al.*, 2004; Harman *et al.*, 2004b; Lien and Yee, 2004). Kastner-Klein *et al.* (2004) present an overview of experimental and wind tunnel studies of the influence of street architecture on the wind and turbulence patterns in street canyons and discuss the effects on local air quality. Small-scale features of the street architecture are shown to play an important role; for example, roof configuration affects the vortex within the canyon. Focusing on the influence of canyon geometry on scalar fluxes, Barlow *et al.* (2004), experimentally, and Harman *et al.* (2004a), with a numerical model, provide insight into the effects of urban flow on vertical fluxes for a range of urban canyon geometries. Variations in scalar flux, by more than a factor of two, for urban street canyons with different geometries lead the authors to conclude that the physical mechanisms responsible should be incorporated into energy balance models for urban areas.

In addition, there has been a very large number of studies on larger-scale dynamics and structure of the urban atmosphere. Building on the excellent work of COST-710 (Fisher *et al.*, 1998; Seibert *et al.*, 2000), investigators continue to compare information on boundary layer structure provided by different instruments (SODAR, RASS and ceiliometers) (Emeis *et al.*, 2004; Pino *et al.*, 2004), the dynamics of urban boundary layers (Nair *et al.*, 2004), and numerical simulations of urban boundary layer growth (Miao and Jiang, 2004; Tong *et al.*, 2005).

An increasingly common trait of urban observational programmes is that they are collaborative, multi-institutional, multinational and interdisciplinary initiatives; see, for example, BUBBLE (Basel UrBan Boundary Layer Experiment; Rotach *et al.*, 2005), ESCOMPTE (Durrand and Cros, 2005; Mestayer *et al.*, 2005) and Joint Urban 2003 (Allwine *et al.*, 2004). To varying degrees, these studies combine multiple methods: near-surface and remote sensing observations with numerical and physical modelling. The scale of the studies and the resources involved mean processes and effects are investigated across multiple spatial and temporal scales. In addition, many of these studies represent collaborations between those interested in both the physics and chemistry of the atmosphere, which allows critical boundary conditions to be specified (see, DAPPLE as one particularly good example; Arnold *et al.*, 2004).

IV Modelling of urban climates and effects

The nature and objectives of urban climate models cover a wide range. In terms of those models which simulate the surface energy balance (SEB), there have been significant advances recently (summarized in the reviews of Best, 2006, and Masson, 2006). The coupling of SEB models to atmospheric models makes it possible to simulate and eventually forecast city climates, in particular the UHI and city induced circulations in the boundary layer. The simplest of these models are empirical ones, such as NARP-LUMPS (Grimmond and Oke, 2002; Offerle *et al.*, 2003), which are driven by routinely collected meteorological data (solar radiation, temperature, wind speed) combined with basic measures of surface cover/morphology (height of the buildings, and fractions of the surface built and vegetated), to simulate each SEB flux. Slightly more complex, and more common, approaches involve the adaptation of existing Soil Vegetation Atmosphere Transfer Schemes (SVAT) or Land Surface Schemes (LSS). In these, dynamical effects of the urban surface (high-density obstacles) on mean airflow are incorporated either by altering the roughness length, using an appropriate urban scheme, or adding a drag force directly in the equations of motions of the atmospheric model up to the height of the buildings (see, for example, Dupont *et al.*, 2004; Otte *et al.*, 2004; Dandou *et al.*, 2005). The radiative trapping by urban canyons also is dealt with either by using a bulk approach, reducing the average albedo (Best *et al.*, 2006) or by parameterizing the attenuation of solar radiation with depth into the canopy (Dupont *et al.*, 2004). Drawing on better estimates of the anthropogenic heat flux, and the effect of building materials and urban geometry on storage heat, these effects also have been included (see examples in Best, 2005; Dandou *et al.*, 2005). More complex urban canopy models incorporate the three-dimensional shape of buildings, solve separate energy budgets for roofs, roads and walls, and parameterize radiative interactions between roads and walls. Such models can be subdivided into single-layer models, where there is direct interaction only with one atmospheric layer above the uppermost roof layer (see, for example, Masson, 2000; Masson *et al.*, 2002; Harman *et al.*, 2004a; 2004b; Lemonsu *et al.*, 2004; Kusaka and Kimura, 2004), and multilayer models, which distribute the impact of the urban area within the boundary layer close to the surface (Martilli *et al.*, 2002; Kondo *et al.*, 2005). The most appropriate model to use depends on the application at hand and computational resources.

Understanding urban canopy flow has relevance for issues of air pollution (and abatement strategies), energy usage in cities, pedestrian comfort and security concerns. Engineering-type computational fluid dynamics (CFD) models are designed to compute small-scale fluid flows and have been used in urban climate studies to simulate urban flow and dispersion, understand fluid dynamical processes, and provide practical solutions to some problems of dispersion and urban air pollution (Baik and Kim, 2002; Baik *et al.*, 2003; Kim and Baik, 2003). CFD models have been used to compute flow within and around complex building shapes (Calhoun *et al.*, 2004; Cheng and Hu, 2005; Lien and Yee, 2005; Lien *et al.*, 2005) and within urban canyons (Jeong and Andrews, 2002; Cui *et al.*, 2004). These schemes may use large-scale meteorological models to define upper boundary conditions. The development and use of CFD models is a very active area of inquiry. The models are becoming more sophisticated in terms of numerical methods, mesh structures and turbulence modelling approaches (Direct Numerical Simulation, DNS; Large Eddy Simulation, LES; and Reynolds Averaged Navier-Stokes Simulation, RANS) (see, as recent examples, Lien and Yee, 2004; Liu *et al.*, 2004; Hamlyn and Britter, 2005).

V Final comments

As highlighted in this brief progress report, the study of urban climates is attracting significant attention. Worthy of specific note are the increasing number of urban climate studies being conducted in tropical latitudes. This work has significantly advanced the recognition of spatial differences both within and between cities as a result of differences in urban fabric (materials, morphology), emissions and prevailing meteorological and climatic conditions. Interesting summaries of urban climate research in specific countries around the world are published in the newsletters of the International Association of Urban Climate (www.urban-climate.org).

Increasingly the focus of urban climate research is on understanding the fundamental processes that generate urban climates, not just the resultant effects. The scales of inquiry and methodologies used are rich and varied: scale models and wind tunnels, statistical and numerical models, remote sensing, lidar, sodar, radar and profilers, and surface-based flux measurement using eddy covariance and scintillometry. As noted by Oke (2006), one of the greatest challenges for urban climatology is to foster more exchange between those working in different subfields and methodologies. There is evidence, however, that large campaign-style studies focused on specific cities, which involve researchers from many different perspectives in the collection of data, and provide open access to data to be used by others, are encouraging such interaction, resulting in important advances in field measurements, numerical models and fundamental understanding of the energetics and dynamics of urban climates.

While the stated rationale for much urban climate research is human health and well-being or energy and water consumption, urban climatologists often note the lack of communication of new knowledge and its implications to end-users, such as planners, architects and engineers (see, for example, the comments of Mills, 2006). Recently, however, increasing attention is being directed to bridge this gap. In terms of building and urban design, for example, Mills (2006) provides a useful summary of tools (materials, building shape/orientation, outdoor landscaping, street dimensions and orientation, zoning, transport policy) that impacts indoor comfort, outdoor comfort and health, and energy use and air quality. Emmanuel (2003; 2005), with a focus on the tropics, directs special attention to building and city design to mitigate heat stress through radiant cooling, ventilation and evaporative cooling. Other studies have focused on building geometry and shading (Bourbia and Awbi, 2004a; 2004b; Compagnon, 2004; Shashua-Bar and Hoffman, 2004; Shashua-Bar *et al.*, 2004) and urban greenspace, at scales from parks to individual rooftops (Takeuchi *et al.*, 2003; Gomez *et al.*, 2004; Thorsson *et al.*, 2004).

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