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REVIEW

TWO DECADES OF URBAN CLIMATE RESEARCH: A REVIEW OF TURBULENCE, EXCHANGES OF ENERGY AND WATER, AND THE URBAN HEAT ISLAND

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ABSTRACT

Progress in urban climatology over the two decades since the first publication of the *International Journal of Climatology* is reviewed. It is emphasized that urban climatology during this period has benefited from conceptual advances made in microclimatology and boundary-layer climatology in general. The role of scale, heterogeneity, dynamic source areas for turbulent fluxes and the complexity introduced by the roughness sublayer over the tall, rigid roughness elements of cities is described. The diversity of urban heat islands, depending on the medium sensed and the sensing technique, is explained. The review focuses on two areas within urban climatology. First, it assesses advances in the study of selected urban climatic processes relating to urban atmospheric turbulence (including surface roughness) and exchange processes for energy and water, at scales of consideration ranging from individual facets of the urban environment, through streets and city blocks to neighbourhoods. Second, it explores the literature on the urban temperature field. The state of knowledge about urban heat islands around 1980 is described and work since then is assessed in terms of similarities to and contrasts with that situation. Finally, the main advances are summarized and recommendations for urban climate work in the future are made. Copyright © 2003 Royal Meteorological Society.

KEY WORDS: urban climate; urban energy budget; urban water budget; urban heat island; urban atmospheric turbulence; urban roughness; spatial heterogeneity

1. INTRODUCTION

In the year 2000, 45% of the world's population lived in urban areas, with a much higher fraction (75%) in the more developed countries (Population Reference Bureau, 2001a). By 2007, it is projected that half of Earth's population will be city dwellers if trends continue, and most of this additional urbanization will take place in developing countries (Population Reference Bureau, 2001a), most of which are in the tropical world (Population Reference Bureau, 2001b; United Nations, 2001). Given the large and increasing fraction of the population exposed to the atmospheric environments of cities, it is understandable that the growth in urban climatology reported by Oke (1979b) has continued and accelerated.

This creates a problem for a reviewer, however, as the literature of the field has expanded enormously. Accordingly, this review will limit consideration in three ways. First, it will cover the period since about 1980, spanning the lifetime of the *International Journal of Climatology*. Second, it will restrict consideration to a limited set of topics that have been the focus of significant advance in themselves and which have also

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driven progress in other areas of urban climate research. Third, it will be confined to scientific literature published in the English language.

The topical focus of this review is twofold. First, it will assess advances in the study of selected urban climatic processes relating to urban atmospheric turbulence (including surface roughness) and exchange processes for energy and water. Specifically, this will be done for characteristic scales of consideration from about 10^1 to 10^4 m, corresponding to individual facets of the urban environment, through streets and city blocks to neighbourhoods. Understanding these processes is critical to the explanation of the climatic characteristics of urban landscapes at this 'human scale', and our deepening knowledge in these areas has furthered and driven advances in other areas of urban climatology. Second, this review will describe and evaluate what has been learned about the temperature fields of cities, including the *urban heat island* (UHI), which is often regarded as the most well documented example of anthropogenic climate modification.

Adoption of this particular perspective will mean that many other areas of urban climatology must be neglected. Table I provides references to sources of information on other urban climate topics that have appeared shortly before or during the review period. Furthermore, this review will largely ignore *applications* of urban climatology, despite their significance and far-reaching scope: Table II provides some representative and illustrative examples from these areas.

2. CONCEPTUAL ADVANCES AND URBAN CLIMATOLOGY

The period addressed by this review has seen the initiation or consolidation of several conceptual advances relevant to urban climatology. Some of these are specific to the urban atmospheric environment, while others are of more general applicability within boundary-layer climatology but they address issues crucial to the understanding of the city atmosphere. This section will review some of these advances in general terms; many of these will arise again in subsequent treatments of particular empirical studies.

2.1. Scale, spatial heterogeneity and urban climate

The concept of scale is fundamental to understanding the ways in which elements of the urban 'surface' interact with adjacent atmospheric layers. An individual building, for example, consists of walls and roof facets, each with a differing time-varying exposure to solar radiation, net longwave radiation exchange and ventilation (e.g. Arnfield, 1984, 2000b; Paterson and Apelt, 1989; Verseghy and Munro, 1989a, 1989b). Horizontal ground-level surfaces are a patchwork of elements, such as irrigated gardens and lawns (Oke, 1979a; Suckling, 1980), non-irrigated greenspace, and paved areas (Doll *et al.*, 1985; Asaeda *et al.*, 1996; Anandakumar, 1999) with contrasting radiative, thermal, aerodynamic and moisture properties, frequently including trees (Oke, 1989; Grimmond *et al.*, 1996; Kjelgren and Montague, 1998). These different surface elements possess diverse energy budgets that generate contrasts in surface characteristics (e.g. 'skin' temperature), and lead to mutual interactions by radiative exchange and small-scale advection. These fundamental morphological units may be aggregated hierarchically. Building walls and the elements lying between buildings, for example, define the *urban canyon* (UC). UCs and the roofs of adjacent buildings define city blocks, which in turn scale up to neighbourhoods, land-use zones and, ultimately, the entire city. At each scale, units will possess distinctive energy balances that, in general, represent more than the area-weighted average of the budgets of individual elements but also incorporate the distinctive interactions among their constituent units. Moreover, each unit interacts with adjacent ones in the same scale category by advection (Ching *et al.*, 1983). As spatial scale increases, spatial variability is likely to be reduced; that is, there is probably less difference among two land-use zones in a city than between the north- and south-facing walls of an individual building within one of them (Schmid and Oke, 1992). Urban climatology is required to come to terms with this heterogeneity and complexity, either explicitly, in terms of detailed mapping of urban morphology (Ellefsen, 1990–91; Grimmond and Souch, 1994; Cionco and Ellefsen, 1998), or in interpreting observations at aggregate scales.

Linkages among scales are explicit, for example, in parameterizations of the storage heat flux using the objective hysteresis model (OHM) of Grimmond *et al.* (1991), which aggregates the heat storage responses

Table I. Reviews, bibliographies and summaries on urban climatology published during the review period

Reference	Topic
Oke (1979b)	Review of urban climatology, 1973–76
Changnon (1980)	The La Porte precipitation anomaly
Oke (1980)	Bibliography of urban climate literature, 1977–80
Landsberg (1981a)	Multiple topics in urban climatology
Changnon (1981)	A review and summary of the METROMEX project
Landsburg (1981b)	Multiple topics in urban climatology
Oke (1982)	Urban energy balance
Douglas (1983)	Urban physical environment in general with one chapter on urban climate
Lockerby (1983)	Bibliography on the climate of cities
Lee (1984)	Multiple topics in urban climatology
Oke (1986)	Urban climatology with special emphasis on tropical areas
Oke (1988b)	Urban energy balance
Smithson (1989)	Progress report (includes ‘urban climates’)
Oke (1989)	Trees in cities
Smithson (1990a)	Progress report (includes ‘urban climates’)
Smithson (1990b)	Progress report (includes ‘urban climates’)
Yoshino (1990–91)	Emphasis on Japanese urban climate work
Oke *et al*. (1990–91)	TRUCE (Tropical Urban Climate Experiment)
Brazel *et al*. (1991)	Includes section on urban climatology
Changnon (1992)	Inadvertent climate change in urban areas and lessons for global climate work
Steyn (1992)	Integrated studies of air pollution meteorology
Cermak *et al*. (1995)	Wind climates in cities
Goldreich (1995)	Review of Israeli urban climate work
Arnfield (1998a)	Review of urban climate work published in 1996
Arnfield (1998b)	Review of urban climate work published in 1997
Sturman (1998)	Urban climate processes, mitigation of urban climate effects and implications for urban design
Lowry (1998)	Urban effects on precipitation amount including a critique of experimental design
Arnfield (2000a)	Review of urban climate work published in 1998
Roth (2000)	Atmospheric turbulence in urban environments
Arnfield (2001a)	Review of urban climate work (‘urban canyon studies’ and ‘urban climates outside the mid-latitudes’) published in 1999
Arnfield (2001b)	Review of urban climate work published in 2000

of diverse surface types to net radiation forcing according to the spatial extent of each. Likewise, UC energy budget models (Terjung and O’Rourke, 1980a,b; Mills, 1993; Arnfield, 2000b) generate canyon system energy budgets by combining the budgets of the constituent facets, which incorporate mutual interactions.

Fundamental to the issue of scale is the distinction between the *urban canopy layer* (UCL) and the *urban boundary layer* (UBL). This distinction, originally applied to UHIs by Oke (1976), has been a guiding principle in urban climate research of all types. In the UCL (roughly from ground to roof level), processes of airflow and energy exchange are controlled by microscale, site-specific characteristics and processes. The UBL, above roof level, in contrast, is that part of the planetary boundary layer whose characteristics are affected by the presence of the urban surface (or its land-use zones) below and is a local- to meso-scale phenomenon controlled by processes operating at larger spatial and temporal scales. The distinction goes beyond mere scale, therefore: it reflects different assemblages of *processes*.

The patchy and heterogeneous nature of the urban surface has significant implications in the interpretation of measured energy budgets and in the design of tower-based flux studies. Few ideas have had such a profound impact on urban climatology during the review period than the realization that turbulence characteristics (including fluxes) measured at height over a complex urban landscape may not be in equilibrium with the surface below, but may instead reflect the characteristics of the surface upwind, the size and location of which will depend on wind speed and direction, roughness and atmospheric stability (Schmid and Oke, 1990; Schmid, 1994). The source-area model of Schmid and Oke (1990) has found applicability in the suburban energy balance measurements of Oke *et al.* (1989), Schmid *et al.* (1991) and Grimmond (1992).

2.2. The roughness sublayer

Several experimental studies (e.g. Thom *et al.*, 1975, Garratt, 1978, 1980) in agricultural and forest meteorology have demonstrated that, in the air layers *immediately* above horizontally uniform surface types with tall roughness elements, conventional flux–profile relationships and Monin–Obukhov similarity theory are likely to be invalid. In this layer, termed the *roughness sublayer* (Raupach, 1979), flow consists of the interacting wakes and plumes (of heat, humidity and pollutants) introduced by individual roughness elements. At some height above the canopy, the blending effect of turbulent mixing will erase the significance of individual roughness elements and create a layer (the *inertial sublayer*, *surface layer* or *constant-flux layer*, Tennekes, 1973; Roth, 2000) in which turbulent fluxes are constant with height, permitting measurement of landscape-scale energy balance fluxes and Reynolds stress. The roughness and overlying surface layer constitute the lowest portion of the UBL defined in the previous section (Roth *et al.*, 1989b). The nature of the urban surface, with its rigid buildings of different heights and physical characteristics, separated by trees, canyons and open spaces, makes it particularly susceptible to the development of a roughness sublayer of significant depth, perhaps several times the average building height (Raupach *et al.*, 1980, 1991; Roth, 2000).

Within the roughness sublayer, characteristics depend on a horizontal distance scale determined by inter-element spacing, rather than height and vertical temperature gradient, as in the surface layer. Flow and turbulent fields are different from those in the inertial sublayer (Högström *et al.*, 1982; Rotach, 1993a,b; Roth, 1993; Roth and Oke, 1993; Oikawa and Meng, 1995). Strong vertical shear, large turbulence intensities, wake diffusion, form drag, diversity and spatial separation of sources and sinks of momentum and scalars, and local advection stemming from extreme heterogeneity are the norm within this layer (Roth, 2000). Roth *et al.* (1989b) provide evidence that measurements of fluxes and turbulent spectra made close to the interface between the surface and roughness layers are in good agreement with those from smoother surfaces, and make recommendations regarding implications for measurements of eddy fluxes from towers over suburban terrain. Profiles of turbulence statistics across a roughness sublayer are presented by Rotach (1995), and the case for explicit recognition of the roughness sublayer in operational models for pollution dispersion has been made by Rotach (1999) and de Haan *et al.* (2001) and can be expected in urban climate simulation models for the same reasons.

2.3. The diversity of UHIs

The UHI remains a compelling focus of climate research in built-up areas. However, a characteristic feature of work during the period of this review is the emergence of the idea that there are many UHIs, displaying different characteristics and controlled by different assemblages of energy exchange processes. Oke's (1976) original distinction between the UHI in the UBL and that in the UCL has been discussed briefly in Section 2.1. Though these possess different scale manifestations and are thought to result from different processes (Table 2 in Oke (1982)), both have historically found expression in an *air* temperature excess over that in the rural environs.

Ground-based thermal remote sensing (and aircraft-based thermography at a low enough elevation to resolve streets, roofs and walls) permits definition of yet another UHI, namely that for the ground surface.

Table II. Examples of research publications in applications of urban climatology

Urban climate application	Examples of research
Meteorological and climatic characteristics at the individual building scale	Hall *et al.* (1999); Hoyano *et al.* (1999); Murakami and Mochida (1989): Smith *et al.* (2001)
Urban air pollution dispersion	Grant and Wong (1999); Hanna and Chang (1992); Kotake and Sano (1981); Taha (1997)
Urban design and planning	de Schiller and Evans (1996); Oke (1984, 1988a); Scherer *et al.* (1999)
Biometeorology and human comfort in towns	Burt *et al.* (1982); de Assis and Frota (1999); Pearlmutter *et al.* (1999)
Road climatology in towns	Shao and Lister (1995); Shao *et al.* (1994)
Energy conservation issues	Bretz *et al.* (1998); Rosenfeld *et al.* (1995); Sailor (1998); Simpson and McPherson (1998)
Historic and cultural preservation	Camuffo *et al.* (1999)
Global warming research	Epperson *et al.* (1995); Hansen *et al.* (2001); Jones *et al.* (1989); Kukla *et al.* (1986)

Though surface temperatures show some similar spatial and temporal patterns to those for air temperatures, this correspondence is not exact. In particular, under calm, clear, nocturnal conditions, they generally display a much stronger dependence on microscale site characteristics, especially sky view factor reduction brought about by street geometry, than do simultaneously evaluated air temperatures (Bärring *et al*., 1985; Eliasson, 1990–91, 1996a). These results suggest that street temperature possesses a simpler causality than air temperature, which is coupled to the thermal state of the adjacent surfaces but is also subject to advective influences (Bärring *et al*., 1985; Stoll and Brazel, 1992). It is perhaps this simplicity that has permitted successful hardware and numerical simulation modelling of the street surface UHI under calm, night-time conditions, when solar shading is absent and turbulent interactions between street and air and advective fluxes are minimal (Oke, 1981; Arnfield, 1990b; Johnson *et al*., 1991; Oke *et al*., 1991; Swaid, 1993a).

Thermal remote sensing from satellite and high-altitude aircraft platforms (Carlson *et al*., 1981; Vukovich, 1983; Kidder and Wu, 1987; Roth *et al*., 1989a; Lee, 1993; Nichol, 1996) raises additional issues. While some studies have reported similarities between spatial patterns of air temperature and remotely sensed surface temperature (Henry *et al*., 1989; Nichol 1994), most suggest significant differences, including the time of day and season of maximum UHI development and the relationship between land use and UHI intensity (Roth *et al*., 1989a). In particular, remotely sensed UHIs are usually stronger and exhibit greatest spatial variability by day, the opposite to air temperature UHIs. Roth *et al*. (1989a) suggest that these differences have their origins in the nature of the urban surface 'seen' by a satellite sensor, especially one at a high elevation angle, giving a bird's eye or plan view of the city. In this case, roofs, treetops, roads and open horizontal areas are oversampled and vertical surfaces and areas below tree crowns are neglected. These sensors sample poorly the true 'active surface' within the city, and those types of facets that are well represented in the thermal image tend to have quite different physical properties and radiative and turbulent environments from those that are undersampled. This issue is addressed by Voogt and Oke (1997, 1998a,b), who use radiative thermometry to define a 'complete urban surface temperature'. They show that this temperature can exhibit significant deviations from airborne estimates of surface temperature at nadir and off-nadir viewing angles and that the urban surface exhibits a strong 'effective anisotropy' due to differential patterns of irradiated and shaded surfaces within a sensor field of view. Shoshany *et al.* (1994) present an image processing technique to eliminate roof top signals from thermal imagery to approximate ground-level surface temperatures more closely, although this method still provides no information on wall facets for nadir viewing directions.

In summary, developments over the past two decades have underlined that UHIs are more diverse than originally suspected. We may define a variety of such features based on the medium sensed (air, surface, even subsurface) and the sensing system employed. Each will possess its own climatology and will be subject to varying causal influences, but it is essential that the nature of the measurements used to define the heat island be presented in reporting results in a manner that is interpretable to the urban climate community. Likewise, great care must be exercised in comparing UHIs if the medium sensed and the methods employed in sensing it differ.

3. SELECTED SMALL-SCALE URBAN CLIMATE PROCESSES: ATMOSPHERIC TURBULENCE AND EXCHANGES OF ENERGY AND WATER

3.1. Urban roughness parameters

The aerodynamic roughness of cities, as expressed in the roughness length z_0 and zero-plane displacement z_d, exceeds that of essentially all other types of landscape element. These parameters are essential in understanding the processes occurring within urban air layers (surface drag, shearing stress, wind profile forms and turbulence characteristics), as well as such urban climatic phenomena as wind shear over cities, induced vertical motions, the depth of the UBL and pollutant dispersion above urban canopies.

Rooney (2001) provides an example of the experimental determination of these parameters for Birmingham, UK. Grimmond *et al.* (1998) review anemometry-based methods for evaluating these parameters for four suburban areas in North American cities. The particular problems associated with measurements in the urban environment create difficulties for many conventional methods, and no conclusion could be reached on the best one. Techniques have been proposed to estimate these critical parameters from measures of the geometric form of building arrays (e.g. Bottema, 1997; Duijm, 1999). A comprehensive review (Grimmond and Oke, 1999a) finds that most morphometric methods yield plausible values of z_0 and z_d but that most 'observed' values are of insufficient quality to decide truly between competing techniques. Statistical agreement between those empirical values judged best and morphometric estimates is not impressive.

The implications of these two studies are sobering. Though more high-quality estimates of z_0 and z_d would seem to be desirable, uncertainties and errors in the current methods of obtaining such data are not encouraging. Given the centrality of these parameters in modelling pollution dispersion and UBL climates, however, Grimmond and Oke (1999a) suggest practices for choosing the most plausible values.

3.2. Turbulence in the urban atmosphere

Just prior to the beginning of this review period, Oke (1979b) remarked that 'evidence of the structure of turbulence over cities is limited'. The availability of turbulence measurements in urban environments has improved dramatically since that time, however. During the 1980s, results were reported by Melling and List (1980), Högström *et al.* (1982), Steyn (1982), Hildebrand and Ackerman (1984), Ching (1985), Fujitani (1986), Yersel and Goble (1986), Uno *et al.* (1988) and Roth *et al.* (1989b). In the following decade, attention was directed more to turbulence processes in and close to the UCL, although this focus was not universal (Rotach, 1993a,b, 1995, 1999; Roth, 1993; Roth and Oke, 1993, 1995; Kalogiros and Helmis, 1995; Oikawa and Meng, 1995; Yadav *et al.*, 1996; Xu *et al.*, 1997; Feigenwinter *et al.*, 1999). Zhang *et al.* (2001) compare turbulence spectra for suburban and urban areas with those for rural surfaces. A comprehensive and perceptive review of turbulence in the urban atmosphere is provided by Roth (2000). Some implications of this work, generally not considered to be conventionally 'climate', do have profound implications for climate-oriented work. For example, Roth and Oke (1995) suggest that inequalities in transfer efficiencies for heat, mass and momentum may invalidate turbulent flux evaluations over urban surfaces using conventional profile methods.

3.3. Storage and anthropogenic heat fluxes in the urban energy balance

No understanding of urban energy balance can avoid wrestling with the implications of scale (Section 2.1) and the issue of the precise definition of the 'surface' to which the balance refers. These are interrelated matters: while it is generally uncontested what constitutes the ‘surface’ to which the energy balance of a building wall, suburban lawn or warehouse roof applies, this becomes increasingly uncertain as we scale up through individual landscape units, like UCs, to land-use zones and even whole cities. The energy balance for a simple plane facet may be written as

$$Q^* = Q_{\mathrm{H}} + Q_{\mathrm{E}} + Q_{\mathrm{G}} \tag{1}$$

where Q^* is net radiation, Q_{H} and Q_{E} are the turbulent fluxes of sensible and latent heat respectively, and Q_{G} is the (primarily) conductive heat flux into or out of the material that constitutes the surface. Behaviour of Q_{G} for simple facets has been described by Doll *et al.* (1985) and Anandakumar (1999) and can normally be evaluated using heat flux plates or by measuring time rates of temperature change if the heat capacity of the substrate is known.

Oke (1988b) suggests that, at larger scales, for *total* urban landscapes, a useful approach is to evaluate the equivalent energy fluxes through the top of an imaginary volume, extending from a depth in the substrate below which energy exchanges are negligible at the time scale of consideration to a level roughly at roof level, at the upper margins of the UCL. The energy budget for this volume can be written as

$$Q^* + Q_{\mathrm{F}} = Q_{\mathrm{H}} + Q_{\mathrm{E}} + \Delta Q_{\mathrm{S}} + \Delta Q_{\mathrm{A}} \tag{2}$$

where Q_{F} represents anthropogenic energy releases within the volume, ΔQ_{A} is net advection through the sides of the volume, and ΔQ_{S} is the storage heat flux and represents all energy storage mechanisms within the volume, in air, trees, building fabric, soil, etc. In practice, by virtue of the sizes of heat capacities for air and solid fabric, ΔQ_{S} can normally be equated to the aggregate Q_{G} for all air–solid interfaces within the volume.

It is generally believed that ΔQ_{S} is large (as a fraction of Q^*) for urban landscapes, but direct measurement of this term by aggregating heat flux plate determinations for a representative sample of urban facets is not feasible. Accordingly, methods have been sought to parameterize the storage heat flux for use in total energy balance studies of urban landscapes. Nunez and Oke (1980) and Oke *et al.* (1981) propose simple regression relationships between ΔQ_{S} and Q^* for different surface types, weighted by the area occupied by each. This scheme was used in evaluating suburban energy balances by Oke and McCaughey (1983) and Cleugh and Oke (1986). Oke and Cleugh (1987) note that heat storage displays a hysteresis loop when plotted against net radiation and that a better parameterization would involve both Q^* and the time derivative of Q^*. The OHM of Grimmond *et al.* (1991) makes use of this concept and employs urban land cover data to scale up individual hysteresis relationships for different surface types to the total suburban landscape, an approach that is validated by Roth and Oke (1994) and Grimmond and Oke (1999b). Arnfield and Grimmond (1998) use a numerical simulation approach to attempt to identify the main sources of hysteresis for canyons, one of the surface types defined in the OHM, and conclude that substrate thermal admittance and canyon geometry are of most importance.

The OHM was used by Taha (1999) in a mesoscale meteorological model of urban energy balance. It is also incorporated in neighbourhood-scale energy budget evaluations by Schmid *et al.* (1991), Oke *et al.* (1992) and Grimmond (1992), using a highly detailed database of three-dimensional surface types for the locale, which is sampled dynamically to provide appropriate coefficient weights for the turbulent flux source area (Section 2.1).

The state of knowledge on anthropogenic heat flux Q_{F} is well summarized by Oke (1988b). Table 3 in that source lists what was known of this flux density at that time, primarily shown for whole cities. Incorporation of anthropogenic heat flux in simulation models of urban climate is relatively straightforward, involving the addition of a (usually constant) term in the surface energy budget equation. Swaid and Hoffman (1990–91) and Swaid (1993b) assess the role of Q_{F} (55 and 11 W m^{-2} in these two studies) on air temperature in a simulation of UC forms, while Kimura and Takahashi (1991) incorporate a large-scale anthropogenic heat flux in a simulation of temperature fields in Tokyo. Steinecke (1999) found a city-averaged Q_{F} of about 35 W m^{-2} for Reykjavik, and Ichinose *et al.* (1999) provide highly detailed, spatially and temporally differentiated estimates of this term for Tokyo, suggesting an average of about 30 W m^{-2} for residential areas in the summer, while typical values for the central city reach 400 W m^{-2} by day and an astounding 1590 W m^{-2} in winter.

Evaluations of Q_F at local scales, for incorporation into energy balances for suburban terrain, are given by Grimmond and Oke (1991) and Schmid *et al.* (1991). They compute this term as $Q_F = Q_{FV} + Q_{FH} + Q_{FM}$, where the individual components are the heat released by vehicles, stationary sources such as house furnaces and metabolism, requiring inputs such as vehicle numbers by road type, length of road in the contributing area, number of electricity and gas consumers by class (house, school, etc.) and the number of people and animals. Use of this technique by Grimmond (1992) gave a total Q_F of 7–14 W m^{-2}, with stationary sources dominating and the metabolic contribution being negligible.

It should be noted that, in some cases, Q_F is included *implicitly*. For example, the Terjung and Louie (1974), Mills (1993) and Arnfield (2000b) energy budget simulation models incorporate constant internal building temperatures, which reflect the investment of anthropogenic energy in heating and cooling living spaces. Though not appearing as an explicit item in the urban surface energy budget, such schemes influence external climate via conductive heat fluxes through building walls and roofs. They do not, of course, incorporate energy releases to the external environment, like motor vehicle waste heat, flue gases or air-conditioner heat output.

3.4. *Urban radiation balance*

At the beginning of the review period (Oke, 1979b, 1982), additional attenuation by urban boundary-layer pollutants was believed to reduce solar irradiance $K\downarrow$ at the top of the UCL by 0–10% in general (but up to 20% in some cases: see Table 1 in Oke (1988b)). More recent experiments have, for the most part, substantiated these general conclusions for full-spectrum irradiances. Peterson and Stoffel (1980) found 3% urban depletion for central St Louis, with larger amounts in the winter than in the summer, and smaller reductions at suburban sites. A similar-sized urban effect was reported for Toulouse by Estournel *et al.* (1983) and for Vancouver by Hay (1984). Somewhat larger attenuations are given for St Louis (7%: Method and Carlson, 1982) and Hangzhou (9%: Wang and Liu, 1982).

However, some more recent investigations have found extremely large excess attenuations in cities with significant industrial aerosol or photochemical smog. Stanhill and Kalma (1995) detected a 33% decrease in $K\downarrow$ in Hong Kong over a 35 year period that cannot be ascribed to a change in cloud-cover frequency and to which they attribute the virtually absent urban warming of that city. Central Mexico City, notorious for its poor air quality, shows an average 22% smaller $K\downarrow$, with larger depletion during periods of weak winds and high relative humidity (Jáuregui and Luyando, 1999). The temporal variability of absorption by urban aerosols is emphasized by Hänel *et al.* (1990) for Frankfurt. Cerveny (1989) uses a radiative transfer model to show that 'shadowing' of neighbourhoods distant from a pollutant cloud may produce large percentage attenuations at low solar elevations, but that this effect tends to be lost in daily totals because of the small irradiances at those times.

Recent years have brought an increase in interest in urban effects on the spectrum of solar radiation, frequently because of the potential biological implications of such changes. Lorente *et al.* (1994) measured spectral distributions for different turbidity conditions in Barcelona. Huge changes in the beam ultraviolet (UV) portion of the spectrum are noted (>25%), with compensating increases in diffuse UV. Jacovides *et al.* (1998) and Repapis *et al.* (1998) found similar results for Athens, Greece, and note that UV-B is more strongly attenuated than the longer wavelength UV-A. Photosynthetically active radiation is also significantly depleted under very polluted atmospheric conditions: Jacovides *et al.* (1997) found reductions in the global irradiance of this quantity of more than 18% in some circumstances.

Incoming longwave radiation $L\downarrow$ is generally believed to be increased by urban areas, either due to the increased warmth of the urban atmosphere (UHI) or enhanced atmospheric emissivity brought about by the presence of particulate and gaseous pollutants (Oke, 1979b, 1982). Suckling (1981) found consistently larger $L\downarrow$ in Brandon, Manitoba, compared with the rural environs (average 10% increase, maximum 20%). Slightly smaller percentage changes found by Estournel *et al.* (1983) for Toulouse were shown to be largely a result of increased urban atmospheric temperatures rather than pollution. In contrast, Tapper (1984) attributes the inability of estimation equations to reproduce measured $L\downarrow$ to a neglect of the emissivity excess induced by pollutants.

Radiative processes *within* the UCL have been a major focus of activity during the past two decades. Buildings and other roughness elements in towns intercept the direct solar and reduce diffuse solar and sky-derived longwave flux densities, yet may also enhance irradiance by reflection of solar or emission of longwave radiation. Measurements of these effects or their consequences are presented by Adebayo (1990), for Ibadan, and Mills (1997), for a scale model of an idealized urban canopy. Models for computing radiation loads on the facets of arbitrary building groups include those of Arnfield (1984) and Verseghy and Munro (1989a,b).

Computation of the radiation exchanges among the inclined and obstructed facets of UCs, and between them and external radiation sources, is a relatively straightforward geometrical exercise requiring computation of skyline obstructions (e.g. Frank *et al.*, 1981a,b; Arnfield, 1982a, 1984) and view factor relationships among the facets of the canyon form (Steyn, 1980; Johnson and Watson, 1984, 1985; Steyn and Lyons, 1985; Steyn *et al.*, 1986; Watson and Johnson, 1987; Chapman *et al.*, 2001; Grimmond *et al.*, 2001). Perhaps as a result, a number of canyon radiation simulation models exist. The UC radiation model of Arnfield (1976) seeks to provide a general method of computing solar and longwave irradiances on canyon facets, using view factor geometry and a scheme for representing multiple reflections, based both on canyon geometry and distributions of surface materials. This model was employed to evaluate canyon albedo, emissivity and radiation budgets for different land-use zones within Columbus, Ohio, by Arnfield (1982b) and to assess the role of canyon geometry on solar radiation access to UCs by Arnfield (1990a). This model successfully simulated the urban surface top albedos obtained in scale model experiments by Aida (1982) (Arnfield, 1988) and was validated for nocturnal longwave fluxes by Voogt and Oke (1991). Aida and Gotoh (1982) and Kondo *et al.* (2001) offer methods for simulating canyon top albedos, as a function of aspects of UC geometry. Terjung and Louie (1973, 1974), Brühl and Zdunkowski (1983) and Zdunkowski and Brühl (1983) employ the principles of radiation geometry to evaluate the solar and/or longwave radiation balances of canyon facets. Sievers and Zdunkowski (1985) employ the Brühl and Zdunkowski (1983) scheme to simulate the albedo of street canyons, again using the Aida (1982) scale model measurements as validation.

Urban albedo measurements from satellite platforms are presented by Brest (1987), Kidder and Wu (1987), Soler and Ruiz (1994) and Vukovich (1983). The large spatial variability in albedo found by Kidder and Wu (1987) for urban–rural areas with a snowcover is consistent with the simulation results of Arnfield (1982b).

Although each of the radiation streams (incoming and outgoing solar and longwave radiation) is modified by urbanization, there appears to be little reason in most circumstances to challenge the notion, first offered by Oke (1974), that Q^* is unlikely to vary by a large amount between urban and rural areas. Decreased $K\downarrow$ within a city is partially compensated for by the generally lower albedos characteristic of built landscapes (Arnfield, 1982b). Increased $L\downarrow$ due to enhanced urban atmospheric emissivity and the UBL UHI will tend to be offset by the effect of the surface temperature UHI on longwave emittance. Arnfield (1982b) simulated rural–central city Q^* differences and concluded that typical pollution and heat island effects on the incoming longwave and solar fluxes are such that the difference could be positive or negative but, in the absence of a snowcover, will tend to be small. This generalization has been shown to be valid to a few percent by the measurements of Oke and McCaughey (1983), Kerschgens and Hacker (1985) and Cleugh and Oke (1986), and Q^* has also been shown to be conservative within particular land-use classes (e.g. Schmid *et al.*, 1991). There are some interesting exceptions to this generalization, however: Grimmond *et al.* (1996) measured 19% more Q^* for a Los Angeles suburb with 30% tree and shrub cover than for a nearby neighbourhood with 10% cover.

3.5. *Urban facet energy balance*

Virtually all observational and modelled estimates of the components of the energy balance of urban surfaces have postdated the year 1970 and so the preponderance of our knowledge on this most fundamental area of urban climatology has been accumulated during the review period.

This discussion will start with the energy balances of fairly distinct, plane facets, based on Equation (1), and will move to larger spatial scales in subsequent sections, including both observational and modelling approaches.

Asaeda and Ca (1993) develop and validate a numerical model to investigate the role of heat and moisture transport within both exposed soil and soil covered by asphalt and concrete. 'Waterproofing' of the soil by the impervious layer reduces the evaporative sink, leading to high surface temperatures and an upward-directed $Q_{\rm H}$, even at night. Increasing the depth of the layer increases $Q_{\rm G}$ during the day and produces more withdrawal of heat at night. Anandakumar (1999) measured $Q_{\rm G} > Q_{\rm H}$ on an annual basis for a dry asphalt surface, with both fluxes exhibiting an out-of-phase relationship with Q^*. Irrigated lawn vegetation was found by Oke (1979a) to exhibit very high $Q_{\rm E}$, in excess of Q^*, supported by microscale advection from contiguous dry impermeable surfaces, such as driveways, roads and building facets. In contrast, Suckling (1980) found $Q_{\rm E} \approx 0.65Q^*$ for a suburban lawn, similar to moist rural surfaces, for an environment in which advection was less likely. Contrasts in the energy balances of rooftop lawns and a conventional tar–gravel roof were found by Jones and Suckling (1983) to suppress surface heating greatly. Kjelgren and Montague (1998) used a two-layer canopy model to evaluate the role of the ground surface type (asphalt or turfgrass) in controlling $Q_{\rm E}$ for trees. No simple conclusion was reached, as the higher surface temperatures of the asphalt both increase the longwave flux to the canopy, hence increasing transpiration, and lead to higher leaf temperatures, which caused stomatal closure.

At slightly larger scales, urban park energy budgets have attracted the attention of Spronken-Smith and Oke (1999). Nocturnal cooling of a scale model park was shown to depend on the interaction of sky view factor, controlling net longwave radiation, and thermal admittance, which determines $Q_{\rm G}$. Latent heat losses play little role at night, but they may have been instrumental in establishing the relative coolness of the park at sunset. The role of advection in maintaining high $Q_{\rm E}$ from an irrigated park, with a downward-directed sensible heat flux, was demonstrated by Spronken-Smith *et al.* (2000).

3.6. UC energy balance

Within the UCL, energy budgets are governed by microscale processes mediated by the site conditions of the immediate surroundings. These conditions, consisting of the specifics of surface three-dimensional geometry, substrate materials and wetness, wind exposure, shading and the like, are subject to myriad variations within real cities. As a means of distilling what is common to many urban landscapes from what is unique to the particular architectural, cultural, and geographical milieu, much urban climate work has adopted the construct of the UC. The UC consists of the space between adjacent buildings, comprising the solid surfaces on the faces of those buildings and the street, the enclosed air volume, the open 'top' at roof level and the 'ends' of the canyon at street intersections, through which mass and energy fluxes may occur horizontally. The canyon *aspect ratio* (AR), the ratio of wall height to building separation, has been suggested by many as a major control on flow within the UC, on turbulent intensities, on radiative environments and, hence, on the total energy budget.

The literature of urban climatology yields very few empirical energy budget studies in an explicit *canyon* framework. Nunez and Oke's (1977) pioneering investigation of a north–south UC (AR = 0.86) in Vancouver, Canada, showed that the timing and magnitude of the energy exchanges on the different facets differed considerably, in response to patterns of radiation receipt and loss, but that the energy balance for the system as a whole was relatively smooth and symmetric. By day, canyon top net radiation is mainly dissipated in the sensible heat flux to the UBL above, with $Q_{\rm H} \approx 0.64Q^*$ at noon and the majority of the remainder going to the substrate heat flux. A latent heat flux from the canyon floor and down-canyon advection were other secondary components of the budget. By night, $Q_{\rm G}$ and the net longwave irradiance balanced each other.

In contrast, the Yoshida *et al.* (1990–91) experimental canyon (Kyoto, Japan) was dry, oriented east–west, with an AR = 0.94. By day, $Q_{\rm H} \approx 0.35Q^*$ at the UC top, with the remainder being stored within the urban fabric. No measurements or estimates of horizontal fluxes within the canyon were made. These authors point out that the canyon top acted as a weaker heat source than the adjacent roof areas, which they attribute to the extensive shading of canyon surfaces and the low wind speeds there. By night, the energy budget of the canyon as a whole was similar to that of Nunez and Oke (1977).

Arnfield and Mills (1994b) studied a markedly asymmetric dry, east–west UC (AR = 1.52). Diurnal Q^* patterns resembled those in the previous two studies, but $Q_{\rm H}$ measurements showed notable contrasts. By day, both the turbulent and circulation-driven components of this flux were small in absolute magnitude, subject to irregular fluctuations and uncorrelated with Q^*. By night, the turbulent flux was weakly upward-directed. Several hypotheses were offered to account for these characteristics, including the lack of a clearly defined vortex circulation, the advection of warm air over the canyon top from adjacent roofs and the shading/shelter argument advanced by Yoshida *et al.* (1990–91). Indirect lines of evidence are offered that Q_G may account for the bulk of the energy budget residual by night, suggesting a similar balance to that for the Vancouver and Kyoto canyons By day, however, analysis suggests a remaining residual of up to 200 W m^{-2}, which, it is argued, is dissipated by down-canyon advection and, to a lesser extent, by bulk flow through the canyon top, even with perpendicular winds.

These results suggest the intriguing possibility that the daytime partitioning of net radiant energy within dry canyons may perhaps be a function of the AR of the canyon, with sensible heat production through the canyon top decreasing as aspect ratio increases. Unfortunately, these three studies do not represent a well-structured experimental investigation of this hypothesis because the AR was not the only difference between these studies — weather conditions, canyon orientation, canyon asymmetry and other factors were not held constant, and so may have interfered in any possible relationship between AR and canyon system Q_H.

Numerical simulation using an appropriately validated canyon energy budget model is a far more effective method of assessing the dependence of UC energy budget quantities on synoptic conditions and canyon characteristics. That, and perhaps the assumed geometrical simplicity of the UC form, have made simulation the methodology of choice in most UC energy budget investigations.

A major limitation in modelling the energy balances of the facets within UCs is the lack of well-founded theory for the turbulent fluxes within the canyon air space, as is available for the horizontal, uniform surfaces more characteristic of rural sites. Nunez and Oke (1980) provide a model of the daytime UC energy budget, but the procedure is theoretically rigorous only in its calculations of the absorbed solar radiation. Computation of Q^*, Q_G and, hence, Q_H (as a residual) is highly parameterized, based on the empirical data of Nunez and Oke (1977). Such a procedure is context specific and cannot be expected to yield good estimates of energy budgets for canyons and conditions much different from the one used to create the parameterizations.

The URBAN3 model of Terjung and Louie (1974) has been used extensively in investigating the climatic environments of cities, as these depend on city surface structure and weather conditions, and has contributed significantly to the causal explanation of near-surface city climates. URBAN3 is not strictly a *canyon* model, as it simulates energy budgets for the total urban surface system, including roofs. Its validation consisted of a comparison with surface temperature data for Los Angeles city surfaces during clear, relatively calm conditions, an evaluation that is probably not as rigorous as validating with flux data. The radiation fluxes are handled theoretically, using radiation geometry and view factor concepts, and the turbulent fluxes employ an 'exchange coefficient' approach (e.g. Cole and Sturrock, 1977), based on wind speed. Terjung and O'Rourke (1980a) conclude that two primary causal factors in the UHI, sensible heat flux and outgoing longwave radiation, show considerable spatial variability within a model city of typical North American structure and cast doubt on the validity of the energetic lower boundary conditions in many mesoscale models. Terjung and O'Rourke (1980b) show that many aspects of urban facet energy budgets in city zones of differing physical structure exhibit counterintuitive characteristics. This versatile model was used by Terjung and O'Rourke (1981a) to analyse energy budgets as they vary with city structure and was combined with a plant canopy model (Terjung and O'Rourke, 1980c) to elucidate the photosynthetic and evaporative role of street-level vegetation by Terjung and O'Rourke (1981b) and O'Rourke and Terjung (1981a, b). The model was driven with characteristic weather conditions for several synoptic weather types by Todhunter (1989) and Todhunter and Terjung (1990) to reveal the dependence of the magnitude and direction of energy budget components on synoptic-scale controls. Todhunter (1990) investigated the role of canyon orientation and asymmetry on canyon energy budget, emphasizing the role of the diurnal pattern of solar irradiation on the total energy budget.

Another UC energy budget model that was described early in the review period is that of Sievers and Zdunkowski (1986). This combines their generalized stream-function–vorticity method wind model with the radiation models of Brühl and Zdunkowski (1983) and Zdunkowski and Brühl (1983) to simulate the temperature distribution over the cross-section of a canyon under mid-latitude summer conditions, with and without a central vegetated strip on the canyon floor. The resulting distributions of temperature show some promising correspondences with observed temperature patterns (e.g. Nakamura and Oke, 1988), although the authors admit to the somewhat arbitrary nature of many of the input parameters, which were chosen to demonstrate the capabilities of the model. The scheme is a two-dimensional one and does not incorporate advection effects.

Given the complexity of the UC system, several workers have sought to restrict consideration to conditions under which simplifications in the energy balance can be introduced without undue loss of realism. In particular, under nocturnal conditions, with calm winds, solar radiation and the turbulent fluxes of heat and water vapour may be neglected, leading to a simplified energy budget in which substrate heat loss is dissipated in the net longwave irradiance. Such a budget has some empirical justification (e.g. Nunez and Oke, 1977). Simulations of night-time surface cooling under these simplified conditions have been the objective of modelling exercises by Arnfield (1990b), Oke *et al.* (1991), Johnson *et al.* (1991) and Swaid (1993a), all of which have demonstrated the importance of both canyon geometry and materials in giving rise to the urban surface temperature excess over the rural environs.

The STTC model of Swaid and Hoffman (1989) employs the concept of the UC to adjust background meteorological station temperature data for use in building energy-use models. It was extended by Swaid and Hoffman (1990–91) and Swaid (1993b) to incorporate the effects of anthropogenic heat sources and artificial shading of city streets for temperature control purposes. The model is subject to a number of physical assumptions and constraints (Elnahas and Williamson, 1997), however, which limit its general applicability to a particular canyon and meteorological situation. Elnahas and Williamson (1997) have proposed means of avoiding these limitations, but this has been achieved by employing a number of parameterizations (e.g. exchange coefficients, an evapotranspiration model, wind velocity multipliers) that may limit the model's generality.

The scheme of Mills (1993) combines the wind model of Nicholson (1975), the Arnfield (1976, 1982b) canyon radiation budget model and a novel procedure for evaluating temperature change in the air as it circulates within the UC. The model was found to predict satisfactorily the canyon facet surface temperatures and net radiation (Mills and Arnfield, 1993), and to characterize the *form* of the canyon top sensible heat flux to the UBL. However, the mechanism responsible for this heat exchange (the vortex circulation) was not apparent in the data set used to validate the scheme (Arnfield and Mills, 1994a, b); the observations also suggested the importance of down-canyon advective fluxes and bulk flow through the canyon top, neither of which is present in the Mills model.

Arnfield and Grimmond (1998) employ the same radiation scheme as Mills (1993), but a simplified within-canyon wind model (application of a constant 'shelter factor' to above-canyon winds) to investigate the phase relationships between canyon system substrate heat flux and net radiation. The model reproduced the canyon system energy budget of Nunez and Oke (1977) reasonably well, but it showed some error for the individual facet balances.

Virtually identical schemes for handling the radiation budget and substrate heat flow, but with different approaches to turbulent exchange within the canyon air space, have been presented by Herbert *et al.* (1997, 1998), Arnfield *et al.* (1998) and Arnfield (2000b). The work reported in 1997 and 1998 uses a computational fluid dynamical approach to air flow around and within the canyon with a $k-\varepsilon$ turbulence sub-model, based on Paterson and Apelt (1989), coupled with the scalar dispersion model of Johnson and Hunter (1995). This model is able to reproduce many observed aspects of UC airflow, thermal behaviour and energy exchange, but it has not yet been formally validated. Arnfield (2000b) replaces the wind and dispersion model with a parameterized scheme in which the wind at roof level is resolved into across- and down-canyon components. The former drives the canyon vortex model of Hotchkiss and Harlow (1973) and the latter defines a logarithmic profile of wind velocity for the down-canyon flow. These components of the wind are combined within the canyon and are used in an exchange coefficient parameterization to evaluate sensible heat flux. The model is computationally economical and replicates the Nunez and Oke (1977) canyon facet and system energy fluxes with excellent veracity. Sakakibara (1996) also presents a canyon model and uses it to contrast the canyon energy budget with that of an open parking lot site.

3.7. *Urban neighbourhood energy balance*

Few areas in urban climatology have undergone such a radical transformation as our understanding of energy budgets at the local scale, corresponding to distinctive neighbourhoods within a city. In particular, very little was known about the energy balance of *suburban* land uses prior to the review period, despite the fact that this type of landscape occupies the majority of the area of most cities in North America. This is particularly critical, since these suburban areas often possess large greenspace fractions, are often irrigated, and potentially deviate markedly from the view of the city as a 'desert' that frequently prevailed prior to 1980. These areas offer particular difficulties in terms of temporal and spatial sampling and the applicability of conventional boundary-layer theory. In particular, the energy balance framework adopted at this scale is that of Equation (2), with the upper surface of the volume well above the building roofs to avoid the complexity of the roughness sublayer. This enhances the danger of radiative and turbulent flux divergence over the atmospheric layer between measurement height and the roughness elements (Funk, 1960; Fuggle and Oke, 1976) and necessitates consideration of the geometry of the flux source area upwind of the measurement point (Section 2.1). Oke *et al.* (1989) suggest that the difficulties of measurement in such landscapes can be overcome with careful site selection, consideration given to the height of measurement and appropriate temporal sampling procedures.

Kalanda *et al.* (1980) made pioneering Bowen ratio–energy budget determinations of energy exchange for a suburban area in Vancouver. Q_E was always significant and Bowen ratios were mostly in the range 0.5–1.0. Abrupt day-to-day changes in energy partitioning between the two turbulent fluxes were found that were unrelated to precipitation events. It is speculated that this feature reflects irrigation practices by homeowners in response to drying cycles. Rates of latent heat loss often equalled or exceeded the 'equilibrium' rate, which Kalanda *et al.* (1980) attribute to enhanced rates of evapotranspiration from irrigated lawns, fed by the city's piped water supply and driven by microscale advection (Oke, 1979a).

Oke and McCaughey (1983) present simultaneously measured energy budgets for a suburban and rural surface for mostly clear conditions after a period of high precipitation, with moist soil. Unexpectedly, suburban evaporation rates were greater than the rural rates, averaging about 80% of Q^*. The authors suggest that microscale advection from moist gardens and lawns, especially under high radiation conditions when impermeable surfaces are dry and hot, is responsible for this phenomenon, since suburban water loss was smaller than the rural water loss under cloudier conditions when such advection is likely to be weaker. The same sites were used by Cleugh and Oke (1986), but, in this case, the disposition of energy between the turbulent fluxes was as expected. Q^* was 4% larger and Q_H was about 50% larger in the suburban area, leading to Bowen ratios of about 0.5 for the rural site and 1.3 for the city. Large day-to-day variations in flux partitioning at the suburban site were observed and are interpreted in terms of the McNaughton and Jarvis (1983) Ω parameter, which indexes the relative dependence of evaporation on radiative and advective forcing. The aerodynamic roughness in the suburban environment couples the surface closely to the mixed layer, the characteristics of which vary with synoptic conditions. Cleugh and Oke (1986) also suggest that this may be the explanation for the difference between their results and those of Oke and McCaughey (1983).

Spatial variability in energy balances over an apparently 'homogeneous' suburban area in Vancouver was found by Schmid *et al.* (1991) to be far greater than expected. Though Q^* was relatively conservative spatially (attributed to the surface albedo–surface temperature feedback), turbulent energy flux densities were found to vary by 25–40% at horizontal scales of 10^2–10^3 m, as a result of the shifting over time of the source area with wind speed and stability (Section 2.1). Storage and anthropogenic heat fluxes also exhibited significant spatial variability based on the morphology of the urban surface. Hence, *temporal* variability in measured turbulent fluxes is a manifestation of *spatial* variability in surface cover types at the microscale as they are sensed by the turbulent flux instrumentation on the measurement tower.

Grimmond (1992) describes the first spring and winter energy balance measurements for suburban terrain. For springtime, the relative sizes of the different fluxes were similar to the summer cases described above, but wintertime data showed an enhanced relative magnitude for latent heat flux, which was the largest use of the net radiation under the moist winter maritime West Coast climate. Not unexpectedly, anthropogenic heat flux played a more significant role in winter.

Summertime energy budgets for four North American cities (Tucson, Sacramento, Chicago, Los Angeles) with different morphologies and prevailing climates were compared by Grimmond and Oke (1995). Though the absolute magnitudes of the ensemble average energy fluxes varied, as expected, the diurnal trends in flux partitioning were quite similar. The results suggest that, for cities where irrigation is practised, a typical value for the Bowen ratio is 1.5 but that this is somewhat lower (0.8–1.0) for locations with frequent natural water inputs via precipitation. Typical partitioning of Q^* into Q_H, Q_E and ΔQ_S was 40%, 30% and 30%, respectively. The daytime average Bowen ratio was also found to be inversely related to the area irrigated. Grimmond *et al.* (1996) explored the role of trees in the suburban energy budget and found that, in absolute value, all fluxes, including Q_H, were increased at a site with greater tree cover, as a result of increased Q^* brought about by reduced albedo and lower radiative temperature. However, as a fraction of Q^*, Q_E and ΔQ_S were increased and Q_H was reduced.

Mexico City has been the site of three energy budget studies at a similar spatial scale to those described above for North American cities. Oke *et al.* (1992) measured Q^* and Q_H at a site within a mixed residential, commercial and industrial area, used the OHM of Grimmond *et al.* (1991) to parameterize ΔQ_S and obtained Q_E (summed with Q_F) as the residual. Derived Bowen ratios for the ensemble average energy budget were not dissimilar to those for temperate cities (around 1.1 on a daily basis), a remarkably small value for a city in which only 21% of the plan area and 8% of the three-dimensional surface is vegetated, a fact attributed to trees (excluded from the surface analysis), and use and leakage of piped water. The Q_H and ΔQ_S terms were of similar magnitude, which implies a much larger role for the latter than is typical of temperate urban areas.

The first energy balance for a dry, densely built, city-centre site (for Mexico City) is described by Oke *et al.* (1999). As expected, evaporation was small and the Bowen ratio was large (about eight). Surprisingly, during the day, the fraction of Q^* that was channelled into storage within the urban fabric was remarkably large (58% of Q^*, even larger than in Oke *et al.* (1992)), so that Q_H was smaller than expected for such a site. At night, withdrawal of this heat balanced the net longwave loss or, in some cases, exceeded it, leading to an upward-directed Q_H (implying a negative potential temperature gradient). In contrast to this study, Barradas *et al.* (1999) measured the energy balance at a vegetated suburban site in Mexico City during the dry and wet seasons. Budget terms were very similar to those expected for rural sites under conditions of soil water availability and moisture stress, with average Bowen ratios of 1.9 and near zero for the dry and wet seasons respectively.

3.8. The urban neighbourhood water balance

The urban water budget for a volume extending from about roof level to the depth in the substrate where no net exchange of water takes place during the time period relevant to the process under investigation can be written as

$$p + I + F = E + r + \Delta A + \Delta S \tag{3}$$

(Grimmond and Oke, 1991) where p is precipitation, I is the piped water supply of the city, F is the water vapour released due to anthropogenic activities, such as combustion, E is evapotranspiration, r is runoff, ΔA is the net advection of moisture for the volume and ΔS is the change in water storage during the time period. The water balance is linked to the energy balance through E, which is virtually proportional to Q_E. The terms in this equation may be expressed as masses or depths per unit time. When the former units are used, $Q_\mathrm{E} = L_\mathrm{v} E$, where L_v is the latent heat of vaporization of water.

Grimmond *et al.* (1986) employ this balance equation, with ΔA and F set to zero, to construct a model for the components of the urban water balance, intended to be driven by standard climate data and employing simple site-specific parameters. The scheme includes an evaporation model of the combination type (Priestley and Taylor, 1972) and performs calculations for suburban areas based on three distinct surface types: impervious, pervious irrigated and pervious unirrigated. This model is applied to a Vancouver suburban catchment by Grimmond and Oke (1986) for periods ranging from a day to a year. A particular focus is the role of irrigation (mainly garden sprinkling by homeowners) in the water balance. Piped water use is related to prevailing weather conditions, but in a manner that is complex and involves a feedback system that involves human perception and decision making as well as biophysical controls. In particular, following rainfall, E declines as water stores are depleted and piped water use remains low (below E) for several days, after which I increases to roughly equal E, which rebounds in response to the availability of irrigation water. The authors speculate that high rates of evaporation are maintained by microscale advection of warm, dry air from impervious to vegetated surfaces and by the entrainment of dry air into the UBL by penetrative convection enhanced by the roughness of the city surface and an unstable atmosphere.

Kalanda *et al.* (1980), Oke and McCaughey (1983), Oke *et al.* (1992) and Grimmond (1992) all report unexpectedly high evaporation rates from city sites; the Grimmond *et al.* (1986) model provides a theoretical framework within which to analyse such occurrences, as these relate to the particular characteristics of urban areas and the provision of piped water to the external environment through irrigation, street washing and the like.

A model to permit calculation of evapotranspiration from and interception by urban and suburban areas is given by Grimmond and Oke (1991). It adapts the well-established Penman–Monteith–Rutter–Shuttleworth evapotranspiration–interception model (Penman, 1948; Monteith, 1965; Rutter *et al.*, 1971: Shuttleworth, 1978), originally developed for forests, to suburban use, and employs the Schmid and Oke (1990) source area model and the OHM for ΔQ_S (Grimmond *et al.*, 1991). Anthropogenic heat flux is included and surface water availability is described using a surface resistance concept. The model provides realistic hourly and daily estimates of urban evapotranspiration and surface water state.

4. THE URBAN HEAT ISLAND

4.1. Observational studies of heat islands

The state of knowledge on the intensity, spatial and vertical structure, dynamics and determinants of the UHI at the beginning of the review period is summarized by Oke (1982). His review relates to temperature patterns derived from near-surface (approximately standard screen-level) air temperature observations. The methods used to describe UHIs during the past two decades do not differ significantly from those employed previously, and all possess the limitations outlined by Lowry (1977) for the unequivocal identification of ‘urban effects’. Examples of these methods are time trends at a single urban station (e.g. Tarleton and Katz, 1995; Montávez *et al.*, 2000; Tereshchenko and Filonov, 2001), comparative time trends at one or more urban stations and one or more rural ones (e.g. Schmidlin, 1989; Magee *et al.*, 1999; Philandras *et al.*, 1999), statistics on urban–rural differences based on pairs of stations or groups of stations (e.g. Ackerman, 1985; Nasrallah *et al.*, 1990; Moreno-Garcia, 1994), networks of fixed stations within and around a city (e.g. Hsu, 1984; Kuttler *et al.*, 1996; Morris *et al.*, 2001), transects across an urban area (e.g. Yamashita *et al.*, 1986; Westendorf *et al.*, 1989; Goh and Chang, 1999; Kumar *et al.*, 2001; Unger *et al.*, 2001) and weekday–weekend differences (Figuerola and Mazzeo, 1998).

Winkler *et al.* (1981) showed the importance of correcting for observation time and site location in correctly defining the magnitude of the UHI and Tarleton and Katz (1995) stress the importance of incorporating trends in *variability* in temperature, as well as in *means*, in explaining changes in extreme UHI temperature events.

Oke’s (1982) observation that ‘[w]hilst there is a relative abundance of research on the nature of heat islands in temperate climates, there is a dearth regarding those of equatorial, tropical, sub-polar and polar settlements’ is probably less valid today. Heat island studies reported in the past two decades include those from:

(a) equatorial wet climates — Singapore (Tso, 1996; Goh and Chang, 1999), Kuala Lumpur (Tso, 1996) and Ibadan (Adebayo, 1987);
(b) tropical wet–dry and monsoonal climates — Guadalajara (Tereshchenko and Filonov, 2001) and Mumbai (Kumar *et al.*, 2001);
(c) tropical highland climates — Mexico City (Jauregui, 1997);
(d) tropical deserts — Kuwait City (Nasrallah *et al.*, 1990), Phoenix (Hsu, 1984; Tarleton and Katz, 1995);
(e) subtropical climates — Johannesburg (Goldreich, 1992);

(f) high-latitude locations — Göteborg (Eliasson and Holmer, 1990; Eliasson, 1996b; Holmer and Eliasson, 1999), Fairbanks (Magee *et al*., 1999) and Reykjavik (Steinecke, 1999).

Mediterranean climates seem to have been particularly well served by heat island studies during the period; results have been reported for Athens, Greece (Philandras *et al*., 1999), the three Spanish cities of Barcelona (Moreno-Garcia, 1994), Madrid (Yagüe *et al*., 1991) and Granada (Montávez *et al*., 2000) and various locations in Israel (Goldreich, 1995).

The vertical structure of the UHI is explored by Tapper (1990) and Shahgedanova *et al*. (1997). The former found evidence of 'crossover' (i.e. urban temperatures *lower* than rural ones aloft) in Christchurch, New Zealand, above about 290 m (Duckworth and Sandberg, 1954; Bornstein, 1968). The latter found an unexpectedly high frequency of surface inversions for a site in Moscow during the summer, which was attributed to the open structure of the area and the lack of anthropogenic energy release in that season.

4.2. Determinants of heat island magnitude and structure

Though the UHI studies published in the last 20 years have broadened the geographic scope of the phenomenon, the generalizations offered by Oke (1982) largely remain unchanged (Table III). Much of this

Table III. Confirmation of UHI generalizations from Oke (1982) in empirical work from the review period

Empirical generalization	Reference
UHI intensity decreases with increasing wind speed	Ackerman (1985); Park (1986); Travis *et al*. (1987); Kidder and Essenwanger (1995); Eliasson (1996b); Ripley *et al*. (1996); Figuerola and Mazzeo (1998); Magee *et al*. (1999); Morris *et al*. (2001); Unger *et al*. (2001)
UHI intensity decreases with increasing cloud cover	Ackerman (1985); Travis *et al*. (1987); Kidder and Essenwanger (1995); Eliasson (1996b); Ripley *et al*. (1996); Figuerola and Mazzeo (1998); Magee *et al*. (1999); Morris *et al*. (2001); Unger *et al*. (2001)
UHI intensity is greatest during anticyclonic conditions	Unwin (1980); Unger (1996); Shahgedanova *et al*. (1997); Tumanov *et al*. (1999); Morris and Simmonds (2000)
UHI intensity is best developed in the summer or warm half of the year	Schmidlin (1989); Kłysik and Fortuniak (1999); Philandras *et al*. (1999); Morris *et al*. (2001)
UHI intensity tends to increase with increasing city size and/or population	Park (1986); Yamashita *et al*. (1986); Hogan and Ferrick (1998)
UHI intensity is greatest at night	Unwin (1980); Adebayo (1987); Schmidlin (1989); Djen (1992); Ripley *et al*. (1996); Jauregui (1997); Magee *et al*. (1999); Montávez *et al*. (2000); Tereshchenko and Filonov (2001)
UHI may disappear by day or the city may be cooler than the rural environs	Unwin (1980); Tapper (1990); Steinecke (1999)
Rates of heating and cooling are greater in the countryside than the city	Johnson (1985)

work is, hence, confirmatory in nature. This is not to suggest, however, that new insights have not been forthcoming. Nasrallah *et al.* (1990) found that the UHI for Kuwait City was poorly developed, unlike that for Phoenix, Arizona, in a similar climate, and explain this difference in terms of city form and location on the Arabian Gulf. Ripley *et al.* (1996) found maximum UHI intensities for sunny *days* in Saskatoon under clear, calm conditions. Unusual seasonal patterns of UHI development were reported by Unwin (1980), who detected the greatest urban–rural difference in spring and autumn (Birmingham, UK), and by Magee *et al.* (1999) and Kumar *et al.* (2001), who found this in winter (for Fairbanks, Alaska, and Mumbai, India, respectively). Reykjavik, Iceland, shows a tendency for negative heat island intensities (rural area warmer than urban area) in summer and only weak development at other times of the year (Steinecke, 1999). Brázdil and Budiková (1999) detected a larger rate of growth of Prague's UHI since the 1920s in winter and spring than in summer.

In tropical regions, winter–summer differences have proven to be less significant than wet–dry season contrasts. Both Adebayo (1987), for Ibadan, and Jauregui (1997), for Mexico City, found a larger heat island effect in the dry season than the wet season, a conclusion consistent with larger thermal admittance in the rural environs during times of moist soils. Indeed, Tereshchenko and Filonov (2001), for Guadalajara, Mexico, found negative heat island intensities in the rainy months.

The hardware scale model simulation of UC cooling of Oke (1981) presents the hypothesis that, for clear skies, calm air and an absence of significant anthropogenic heating, maximum UHI intensity can be related to the 'openness' of the urban structure, represented by canyon AR or sky view factor, since this controls the rate of urban cooling by limiting net longwave loss at street level. Oke was able to show that this concept was capable of describing the heat island intensities for settlements from many geographical regions with great precision. He cautioned, however, that such a relationship may not be expected to describe spatial patterns of temperature *within* a particular city, even for clear, calm conditions, because of the interfering effect of thermal admittance, anthropogenic heat release and other differences. Nevertheless, several empirical studies have shown that air temperatures and rates of temperature change with time within cities do show a relationship with measures of urban geometry; examples include Bärring *et al.* (1985), Johnson (1985), Yamashita *et al.* (1986), Westendorf *et al.* (1989), Eliasson (1990–91, 1992, 1994), Goh and Chang (1999), and Montávez *et al.* (2000).

The application of this concept in successfully simulating the dependence of UHI intensity on urban geometry and thermal admittance (as well as anthropogenic heat inputs and cloud cover) has already been discussed (Arnfield, 1990b; Oke *et al.*, 1991; Johnson *et al.*, 1991; Swaid, 1993a). The role of all of the hypothesized causes of the UCL heat island was explored intensively by Oke *et al.* (1991), who conclude that geometry and thermal admittance differences may be of approximately equal significance. The release of anthropogenic heat from within buildings is also potentially important, but it depends on the role of building insulation. A very important conclusion of this study was the role of *rural* thermal admittance in generating a heat island. Moist soils possess thermal admittance values that are not dissimilar from those for typical dense urban building materials, which may explain the small (and negative) UHI intensities found for the moist tropical locations above.

Other factors that have been demonstrated to control the form, magnitude and dynamics of the UHI include site factors (e.g. Ackerman, 1985; Goldreich, 1992; Kuttler *et al.*, 1996), interaction with urban–rural humidity differences (Holmer and Eliasson, 1999) and advection caused by the circulation generated by the rural–urban temperature gradient (Haeger-Eugensson and Holmer, 1999). Recently, Runnalls and Oke (2000) described an empirical model intended to disentangle the multiple controls on Vancouver UHI intensity, including time of the day, wind speed, cloud cover and rural thermal admittance.

4.3. Large-scale heat island observations and simulations

It is beyond the scope of this review to summarize modelling efforts at scales in which cities are represented by surface parameters that are uniform or apply to large-scale land-use zones and the plentiful remotely sensed heat island studies at similar scales. The following is a sample of such work.

(a) Scale models: Noto (1996), Poreh (1996) and Lu *et al.* (1997).

(b) Numerical models: Baik (1992), Baik and Chun (1997), Baik *et al.* (2001), Kimura and Takahashi (1991), Richiardone and Brusasca (1989) and Tapper *et al.* (1981).
(c) Remotely sensed heat islands: Balling and Brazel (1988), Gallo *et al.* (1993a,b), Hafner and Kidder (1999) (also includes modelling), Kim (1992), Roth *et al.* (1989a) and Vukovich (1983).

5. CONCLUDING REMARKS

This review has attempted to characterize significant advances in, and the current status of, two areas within the broader field of urban climatology for the period of two decades since the establishment of the *International Journal of Climatology*. The first of these is a selected set of small-scale climatic processes encompassing atmospheric turbulence and exchanges of energy and water. The second is the UHI. The major findings and recommendations of this exercise may be summarized as follows.

1. Urban climatology has benefited profoundly from conceptual developments in boundary-layer climatology, broadly defined. In particular, recent enhancements in our understanding of the roughness sublayer and of the implications of heterogeneity and flux source areas has found extensive application in both the interpretation of urban energy balances and their measurement.
2. Simulation experiments in particular, and other methodological approaches in general, would benefit from studies that contribute to our database of the fundamental physical parameters which determine the distinctive climates of urban areas, or that provide estimation algorithms by which these parameters might be estimated with adequate precision from more readily observable entities. Examples would be methods of characterizing the radiative effects of urban pollutants on $K\downarrow$ and $L\downarrow$, methods of evaluating z_0 and z_d from urban form, thermal and radiative properties of building materials and other common surface types in cities, ways of assigning surface resistance values and water storage capacities for permeable urban elements and similar parameters useful in the numerical modelling and interpretation of urban climatic systems.
3. Though information on the form and dynamics of the UHI is now available for climatic zones outside the temperate regions, it would now be advantageous to extend energy balance evaluations beyond those areas, as exemplified by the pioneering field programs of Oke *et al.* (1992, 1999) for Mexico City. This is consistent with the objectives of the TRUCE initiative (Oke *et al.*, 1990–91) and can contribute to the generality of urban climatology's knowledge base.
4. In addition, energy balance measurements of the type now employed routinely for suburban locations are required for central city sites. The sampling, measurement height and other observational requirements for such programs will, however, prove difficult to meet for city centres with high-rise buildings.
5. Complete water budgets for urban areas of different types should be constructed, including all components (natural and anthropogenic). Such studies are needed to elucidate the role of evapotranspiration in urban areas, especially its interaction with boundary-layer growth, surface water availability, the piped water supply and microscale advection.
6. Additional empirical observations and methods of estimation are required for the two anthropogenic fluxes, Q_F and F. These are essentially unique to urban environments and are particularly fascinating in that they introduce phase characteristics into urban energy and water balances that are independent of the solar cycle, being determined by human perception and decision-making imperatives. Explorations of ways in which traffic counts, population data, homeowner questionnaires, utility records, *etc.* can be incorporated into climatic research at urban scales should continue to be pursued.
7. Oke (1982) stated that urban heat islands were 'well described but rather poorly understood'. Two decades later, this statement could not be made with as much confidence. Nevertheless, simple methods are still needed to estimate UHI intensity *within* urban areas, as a function of time, weather conditions and structural attributes, for practical applications such as road climatology, phenology, energy conservation, and weather forecasting.

8. Methods are required to link small-scale and mesoscale urban climate work. Such linkages are troublesome and challenging but not impossible. For example, Voogt and Grimmond (2000) explore the links between remotely sensed surface temperatures, complete surface temperatures and calculations of sensible heat flux using a bulk transfer approach and Masson (2000) employs concepts of canyon geometry to calculate urban surface energy budgets in mesoscale models.
9. Numerical simulation, a methodology perfectly suited to dealing with the complexities and non-linearities of urban climate systems, continues to grow in popularity. Validation of models, unfortunately, lags behind their creation and, when performed, is often weak, relying more on plausibility of outputs than direct comparison with process variables. This is not surprising, because the difficulty of measuring such variables is a prime reason that numerical simulation is so popular. Closer collaboration between modellers and field climatologists is encouraged to close the methodological gap.
10. Urban climatology continues to migrate methodologically from descriptive and inductive ‘black box’ approaches to process studies and process-response (simulation) modelling. This migration is a positive aspect of the field’s recent history (Terjung, 1976; Oke, 1982), because it enhances the explanatory power urban climatologists have at their disposal. This trend should continue.

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