Progress in Urban Meteorology: A Review

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Abstract

This paper reviews the progress made in urban meteorology over the past few decades. The focus is on the impact of urban surfaces on the overlying atmosphere along the conventional meteorological frameworks. Section 1 details the difficulties in generalizing urban surfaces in a meteorological sense because of surface diversity, and considers whether conventional similarity law is applicable. Section 2 describes the characteristics of urban surfaces as the bottom boundary of the atmosphere and includes a discussion of land surface parameters and the resultant surface energy partitioning. Section 3 explains characteristics of the urban atmosphere, including temperature fields, local circulations and rainfall. Section 4 describes recent progress in numerical modeling and promising new technologies, thus revealing a possible future direction for urban meteorological studies.

1. Introduction

The characteristics of urban surfaces as the bottom boundary of the atmosphere, including land surface parameters (albedo, roughness, and wetness) and resulting surface energy partitioning, have been studied intensively in the past few decades. This is because physical processes in the urban surface layer directly influence the atmosphere above and thus understanding and modeling of these physical processes are crucial for the progress in urban meteorology. However, the generalization of meteorological features over cities is more difficult than over other land surfaces. This difficulty arises mainly from the heterogeneities of cities due to the complex three-dimensional geometry of the urban infrastructure; the multiple sources and/or sinks of momentum, heat, and moisture; and the influence of human activities on emissions. Input and compilation of knowledge from various scientific fields are needed to overcome these difficulties in describing this bottom boundary of the atmosphere. Fortunately, the range of research fields related to urban meteorology is remarkably large (e.g., climatology, geophysics, hydrology, engineering, architecture, social sciences, urban planning, and medicine; Oke 2006), and recent advances in urban meteorology can be linked to many conceptual advances in these related fields (Arnfield 2003).

This paper focuses on the impact of urban surfaces on the atmosphere using conventional mesoscale frameworks, in which the Urban Canopy Layer (UCL), composed of buildings and infrastructure, is implicitly treated as a roughness layer in the lower part of the Surface Layer (SL), and the SL is connected to the overlying Atmospheric Boundary Layer (ABL) via the Monin–Obukhov Similarity Theory (MOST). Section 2 describes the characteristics of urban surfaces as the bottom boundary of the atmosphere and considers land surface parameters and the resulting surface energy partitioning. Section 3 explains the characteristics of temperature fields, local circulations, and rainfall in the urban atmosphere. This paper
mainly reviews recent works but indirectly covers several earlier works by reviewing some excellent review papers related to these topics (Table 1).

The applicability of such conventional mesoscale frameworks is controversial. Conceptually, the problem became better defined when Raupach et al. (1980) introduced the concept of a Roughness Sub-Layer (RSL), in which layer the turbulence characteristics depend explicitly on the roughness. In the urban boundary layer, building heights and their spatial variability can be large enough to violate the distinctive separation of the RSL, SL, and ABL (Rotach 1999). Consequently, the SL may not exist over cities and thus the applicability of the MOST is questionable (Roth 2000) because the theory assumes that turbulence statistics should follow so-called universal functions that are independent of surface roughness. Although a similar controversy exists for vegetation canopies, the MOST with minor modifications to the universal functions is extensively applied to the vegetation RSL and incorporated into vegetation canopy models. Whether the MOST with minor modification as in vegetation meteorology is also acceptable in urban meteorology, or whether a completely different approach is necessary, is a topic that is still under discussion in urban meteorological research communities.

Section 4 describes recent advances in numerical simulations, remote sensing, and scale model experiments. This section contains information on future directions in urban meteorology.

2. Urban surfaces as the bottom boundary of the atmosphere

a. Land surface parameters

(1) Albedo

Complicated urban surface geometries can substantially decrease surface albedo compared to values for a horizontal surface. The decrease arises because of multiple reflections and trapping of radiation within the canyon spaces. The reduction was clearly demonstrated by Aida (1982) using arrays of 0.15-m concrete cubes (Fig. 1). Surface albedo for infinite two-dimensional street canyons (Arnfield 1982; Sievers and Zdunkowski 1985; Sakakibara 1996; Masson 2000; Kusaka et al. 2001; Martilli
et al. 2002; Sailor and Fan 2002) or three-dimensional arrays of homogeneous buildings (Ashie et al. 1999; Kanda et al. 2005a; Kondo et al. 2005) without snow cover and vegetation are theoretically predictable using the surface geometry, the albedo of the individual constituent facets, and the solar position. Measured values of albedo in urban areas range from 0.10 to 0.27, with a mean near 0.15 (see Oke 1987, 1988 and Arnfield 2003 for reviews). Arnfield (1982) reported a range in albedo from 0.08 to 0.20 over cities that include residential, commercial, and industrial areas. Urban albedo measurements derived from satellite or airborne measurements are presented in Vukovich (1983), Brest (1987), Kidder and Wu (1987), Takamura (1992), Soler and Ruiz (1994), Nakagawa and Nakayama (1995), and Sugawara (2001). Urban albedo values obtained from tower measurements are in Offerle et al. (2003), Christen and Vogt (2004), and Moriwaki and Kanda (2004). Reported values in North American cities, 0.15 ± 0.02, (Sailor and Fan 2002) are slightly higher than those in Europe and Japan, 0.12 ± 0.04, (Nakagawa and Nakayama 1995; Sugawara 2001; Offerle et al. 2003; Christen and Vogt 2004; Moriwaki and Kanda 2004).

(2) Roughness lengths

In the MOST framework, roughness lengths for momentum and heat (\(z_0\) and \(z_h\), respectively) are key parameters that define aerodynamic features of the underlying surfaces. Field and laboratory measurements of \(z_0\) over various urban-like geometries have been collated, and theoretical frameworks that determine \(z_0\) using morphometric parameters (roughness height, plane area density, frontal area index, complete surface area, and canyon aspect ratio) have been well established. A comprehensive review (Grimmond and Oke 1999b) compared several morphometric methods used to determine \(z_0\) and zero-plane displacement height \(z_d\) with those obtained from field and laboratory studies (Fig. 2). The methods of Raupach (1994), Bottema (1997), and Macdonald et al. (1998) successfully reproduced \(z_0\) and \(z_d\) across the full range of surface morphometry.

In contrast, \(z_h\) data over urban areas are relatively rare (Voogt and Grimmond 2000; Sugawara 2001; Moriwaki and Kanda 2006). \(z_h\) is generally smaller than \(z_0\) by several orders of magnitude because the bluff body effect does not act on scalar transport. Therefore, the logarithm of the ratio between roughness lengths for momentum and heat, \(\kappa B^{-1} = \ln z_0/z_h\), is conventionally used. Results from mesoscale atmospheric modeling studies suggest that the consideration of \(\kappa B^{-1}\) improves model performance over rough surfaces (e.g., Uno et al. 1995; Chen et al. 1997), but little is known about the values. Brutsaert (1982) theoretically
related $k B^{-1}$ to the roughness Reynolds number, $Re^* = u^* z_0 / \nu$, for rough bluff surfaces ($u^*$: frictional velocity, $\nu$: kinematic viscosity). Kanda et al. (2007) used data obtained from scale model experiments and three urban sites (Fig. 3) to express $k B^{-1}$ as a function of $Re^*$. This function is applicable only for non-vegetated urban settings. Field data have shown that $k B^{-1}$ decreases as the areal fraction of vegetation increases (Kanda et al. 2007).

(3) Wetness parameter

Water availability or the wetness parameter $\beta$ is used in major mesoscale modeling systems. A constant value of 0.1 has been assumed for urban and desert areas in many models. Scant observational evidence supports the use of the constant value. Instead, a posteriori reasoning shows that it yields reasonable latent heat fluxes. Grimmond and Oke (1991) measured and modeled the surface conductance for water vapor transfer in a suburban area and reported that the diurnal trend is similar to that reported for forests, but values were 75% smaller. Measured values of $\beta$ in a densely built residential area in Tokyo ranged from 0.02 to 0.3, with a mean near 0.06 (Moriwaki and Kanda 2006). $\beta$ gradually decreases with the elapsed time after precipitation (Fig. 4).

b. Energy balance

The surface energy balance of the urban surface layer can be described as follows.

$$Q^* = K \downarrow - K \uparrow + L \downarrow - L \uparrow,$$

and

$$Q^* + Q_F = Q_H + Q_E + Q_G,$$

where $K \downarrow$ and $K \uparrow$ are downward and upward shortwave radiations, $L \downarrow$ and $L \uparrow$ downward and upward long wave radiations, $Q^*$, $Q_F$, $Q_H$, $Q_E$ and $Q_G$ are net radiation, artificial heat emission, sensible heat flux, latent heat flux and heat storage, respectively.

(1) Net radiation $Q^*$

Polluted atmospheres reduce the incoming short wave radiation $K \downarrow$ in urban areas. Attenuation of $K \downarrow$ depends on the nature and amount of the pollutants (see Oke 1982, 1987, 1988 and Arnfield 2003 for reviews), but urban-induced attenuation of $K \downarrow$ is generally less

![Fig. 3. $k B^{-1}$ versus $Re^*$ (from Kanda et al. 2007). Open circles: large-scale model (L); open squares: small-scale model (S). Open triangles (VG: light industrial area, Vancouver), crosses (SU: business district, Tokyo), and filled circles (MK: dense residential area, Tokyo) correspond to urban data. Lines are from the theoretical relationship. The dotted line is from Brutsaert (1982). The solid line is from scale model data.](image-url)
than 10%, for example, in St. Louis, Toulouse, Vancouver, and Basel (Peterson and Stoffel 1980; Method and Carlson 1982; Estournel et al. 1983; Christen and Vogt 2004). Tokyo, following rapid economic growth in the 1960s, has an urban-induced attenuation value of 10 to 15% (Sekihara 1973). Some cases of extremely large urban-induced attenuations associated with poor air quality have been reported, such as a 33% decrease in Hong Kong (Stanhill and Kalma 1995) and a 22% decrease in central Mexico City (Jauregui and Luyando 1999).

Decreased $K_{\downarrow}$ in the urban area is partially offset by decreased $K_{\uparrow}$ due to a lower urban albedo, resulting in a small difference of net shortwave radiation between rural and urban areas. A similar offset relationship exists in urban areas for incoming $L_{\downarrow}$ and outgoing $L_{\uparrow}$ longwave radiation: $L_{\downarrow}$ is greater in urban areas than in rural areas because of increased emissions from gaseous and particulate pollutants, but $L_{\uparrow}$ is also greater because of warmer surface temperatures (Oke 1987, 1988). These balancing relationships between incoming and outgoing radiative components result in small differences in net radiation $Q^*$ between rural and urban areas. Offerle et al. (2003) proposed a simple scheme to estimate $Q^*$ for urban areas as a function of meteorological factors and surface properties.

(2) Heat storage $Q_G$

A large amount of heat storage $Q_G/Q^*$ is the most significant feature of the urban energy balance (Oke 1987; Grimmond and Oke 1995, 1999a). Urban thermal properties, such as large heat capacities and thermal conductivities, and the increase in the thermally active volume forced by the complex three-dimensional geometry both allow additional heat storage into buildings. Earlier studies related $Q_G$ to $Q^*$ for different surface types (Nuenz and Oke 1980; Oke et al. 1981; Oke and McCaughey 1983; Cleugh and Oke 1986; Oke and Cleugh 1987). Grimmond and Oke (1999a) proposed a simple objective hysteresis model that calculates $Q_G$ as a function of $Q^*$, $\partial Q^*/\partial t$, and the surface properties of the site. Intercomparison of measured $Q_G/Q^*$ at various urban and suburban sites (Grimmond and Oke 1995, 1999a; Christen and Vogt 2004) showed that as vegetation fraction increased, $Q_G/Q^*$ decreased. In contrast to this obvious influence of vegetation cover on $Q_G/Q^*$, a direct influence of urban surface geometry on $Q_G/Q^*$ is not evident in observed data. However, numerical work (Arnfield and Grimmond 1998) and outdoor experiment using scale models (Pearlmutter et al. 2005) suggest that surface geometry does influence $Q_G/Q^*$; radiation absorption and heat storage are higher in building arrays with deeper canyons.

Measured $Q_G$ in cities is generally determined as a residual in an energy balance of other terms that are directly observed ($Q^*$, $Q_H$, and $Q_E$). Therefore, obtained values of $Q_G$ might contain the ambiguous energy imbalance term (e.g., Lee 1998; Kanda et al. 2004a) or con-
tributions from anthropogenic heat emissions. Seasonal variations in real fields of both vegetation fraction and anthropogenic heat make it difficult to analyze the direct effects of climate conditions, such as wind velocity and solar angle, on the urban surface energy balance (Spronken-Smith 2002; Christen and Vogt 2004; Moriwaki and Kanda 2004).

Data from outdoor scale model experiments that use an array of urban-like flow obstacles are valuable because $Q_G$ is directly measured and is uncontaminated by anthropogenic heat emissions. Outdoor scale model experiments conducted continuously over a year (Kawai et al. 2007) have successfully related $Q_G/Q^*$ to wind conditions and season (Fig. 5); $Q_G/Q^*$ decreases with increasing frictional wind velocity ($u^*$) because strong winds enhance mechanically induced turbulent heat transport. $Q_G/Q^*$ in winter is slightly larger than in summer because vertical walls in urban settings can efficiently hold radiant energy in winter when the incident radiation angle to the walls is relatively high.

Large amounts of daytime $Q_G$ are balanced by a large release of nocturnal $Q_G$. Nocturnal values of $Q_G/Q^*$ in cities are generally 0.9 to 1.3 (Grimmond and Oke 1999a; Christen and Vogt 2004; Moriwaki and Kanda 2004). The nocturnal release of $Q_G$ is often larger than the radiative loss of $Q^*$, and the excess energy sustains the upward-directed sensible and/or latent heat fluxes even at night.

(3) Evapotranspiration $Q_E$

Vegetation is a major source of water vapor in urban areas. It is therefore not surprising that a relationship exists between daytime $Q_E/Q^*$ and the surface vegetation fraction (Grimmond and Oke 1999c; Christen and Vogt 2004). Strong surface controls such as summer irrigation can change $Q_E$ by a factor of 3 in a single day (Grimmond and Oke 1999c). The Bowen ratio $B = Q_H/Q_E$ depends on climate conditions and surface conditions, and thus the values differ among cities. The largest values are often measured in early spring (Christen and Vogt 2004; Moriwaki and Kanda 2004; Offerle et al. 2006) when available energy is increasing but vegetation activity is still low.

Urban evaporation $E$ has historically been assumed to be much less than evaporation from rural areas and thus has received little attention. However, recent works have shown that $E$ has a larger value than originally thought. Advection of hotter and/or drier air from areas upstream increase evaporation from isolated urban vegetation unless available water is limited. This is the oasis or leading edge effect (Oke 1987), which has been observed over several irrigated or crop fields (see Rosenberg et al. 1983, Oke 1987, and Spronken-Smith et al. 2000 for reviews). In the urban environment, Oke (1979b) found advecively enhanced evaporation over an irrigated suburban lawn. Similarly, Spronken-Smith et al. (2000) documented a leading-edge effect in urban parks. Moriwaki and Kanda (2004) showed that local $Q_E$ per unit urban vegetation is twice the available energy ($Q^* - Q_G$). Hagishima et al. (2007) demonstrated experimentally that evaporation from an isolated potted plant is twice that from one of many densely packed potted plants under the same outdoor conditions. These results suggest that evaporation per unit urban vegetation area can vary with the magnitude of isolation or the areal fraction. Thus, a simple area-weighted average that estimates regional moisture fluxes is problematic, yet that is what is generally used in numerical models.
Anthropogenic heat emission $Q_F$

In the 1960s and 1970s, the annual average values of $Q_F$ for typical cities in temperate latitudes ranged from 15 to 50 W m$^{-2}$ (Oke 1988). After 1980, spatially and temporally detailed profiles of $Q_F$ were developed for London (Harrison et al. 1984), New York (Clark et al. 1985), Vancouver (Grimmond 1992), Tokyo (Ichinose et al. 1999), and Lodz (Klysik 1996). Surprisingly, winter $Q_F$ in central Tokyo was 400 W m$^{-2}$ in the day and as much as 1590 W m$^{-2}$ in the early morning hours (Ichinose et al. 1999). These values were derived from bottom-up modeling approaches in which individual components of heat release were estimated from building-level energy statistics and then summed to produce the regional $Q_F$. Sailor and Lu (2004) proposed a simpler top-down methodology for U.S. cities, in which representative nondimensional profiles characterizing the diurnal variation of individual components of $Q_F$ were developed based on population density. Hourly peaks of $Q_F$ for large U.S. cities were up to 60 W m$^{-2}$ in summer and 75 W m$^{-2}$ in winter.

Numerical simulations showed that the direct impact of $Q_F$ on the regional temperature is up to 1.0 ($^\circ$C) even in Tokyo (e.g., Ichinose et al. 1999). Investigations of day-of-week variations in meteorological elements suggested that maximum and minimum temperatures on weekdays are statistically higher than those on weekends (Fujibe 1987, 1988a, 1988b; Gordon 1994; Simmonds and Keay 1997). Weekday versus weekend differences in temperature were at most 1.0 ($^\circ$C), indirectly showing the impact of $Q_F$.

3. Mesoscale urban atmosphere

Geographic knowledge of the urban heat island (UHI) has been described in excellent review papers (Oke 1982, 1987; Arnfield 2003). Most studies describe temperature patterns obtained from near-surface air temperature observations. Surface temperature distributions, and the identification and determination of UHI intensity, have been intensively studied. For example, more than a century of surface temperature and wind data from routine meteorological observations in Japan show clear evidence of the UHI effect: wind convergence increases during the day and nocturnal temperature fluctuations decrease as the surface inversion weakens (Fujibe 1997, 2003). These effects are beyond the scope of the present review and are not considered further. This section focuses only on the dynamics of mesoscale circulations produced and/or modified by the UHI.

a. Urban atmospheric boundary layers

Field experiments on urban boundary layers have revealed fundamental characteristics of the mesoscale UHI structure; typical nocturnal temperature profiles including elevated inversions and the crossover phenomena (Duckworth and Sandberg 1954; Bornstein 1968; Clarke 1969; Oke and East 1971), surface wind convergence in the UHI (Schreffler 1978, 1979a, 1979b), and turbulent profiles (Hildebrand and Ackerman 1984; Clarke et al. 1982; Uno et al. 1988). Oke (1974, 1979a, 1987) gives a comprehensive review of the early observational studies. Significant developments in remote sensing technology after 1990 enabled more precise monitoring of urban boundary layers (see Grimmond 2006 for review). Such monitoring emphasizes the detection of mixing layer height. Seibert et al. (2000) reviewed the various approaches that determine mixing layer height. Large field campaigns in urban areas in the past have included UBL monitoring by METROMEX in St. Louis (Changnon et al. 1981), the IMADA-AVER Boundary Layer Experiment (Doran et al. 1998), the 2001 Phoenix Sunrise Experiment (Doran et al. 2003), AFO 2000 in Hanover (Emeis et al. 2004), BUBBLE in Basel (Rotach et al. 2005), ESCOMTE in Marseille (Mestayer et al. 2005), VTMX 2000 in Salt Lake City (Fast et al. 2000, 2006) and Joint Urban 2003 in Oklahoma City (Calhoun et al. 2006). Results of these field campaigns suggest that urban areas show increased roughness and/or higher sensible heat fluxes than in rural areas. However, these results are very site-specific and complementary use of numerical and/or laboratory works are therefore indispensable for deriving canonical representations of the UBL.

Several laboratory simulations have helped to describe the local circulation and temperature fields produced by the UHI (Raman and Cermak 1974, 1975; Kimura 1975; Sethuraman and Cermak 1975; Torrance 1979; Giovannoni 1987; Noto 1996; Lu et al. 1997a, 1997b). In
these studies, basic characteristics of the nocturnal UHI, such as the mean temperature field, mixing height, and heat-island intensity, are described experimentally as functions of surface heating rates (or surface temperature perturbations), heat-island size, ambient temperature gradient, and ambient wind velocity. The Richardson number and/or Froude number are the most important similarity parameter. The major limitations of these laboratory simulations are that the Reynolds number is relatively low, surface obstacles are not resolved, and the aspect ratio of convection is limited by the model size. Nevertheless, useful simple theoretical relationships based on similarity parameters have been derived by these experiments, and the relationships successfully predicted features of the UHI over real cities.

Theoretical works designed to investigate the response of stably stratified flow to specified surface heating have revealed airflow characteristics around the UHI. Linear theories (Olfe and Lee 1971; Kimura 1976; Lin and Smith 1986; Baik 1992) and a nonlinear theory (Baik et al. 1997) have suggested upward motion downstream of the UHI, which might be partially responsible for the precipitation enhancement downstream of the UHI (see Sec. 3c).

Many numerical investigations have described the UHI. Most of the studies implicitly express the city by assigning modified land surface parameters such as albedo, moisture availability, roughness, and thermal storage (e.g., Myrup 1969; Atwater 1972; Hjelmfelt 1982; Byun and Arya 1990; Tso et al. 1990, 1991; Sailor 1995; Taha 1996, 1997, 1999; Chen et al. 1997; Sugawara et al. 2001; Liu et al. 2006). Some realistic three-dimensional numerical simulations include anthropogenic heat emissions (Kimura and Takahashi 1991; Saitoh et al. 1996; Ichinose et al. 1999; Kanda et al. 2001). Similar three-dimensional numerical simulations or data analyses have examined the interaction between UHI and local circulations in other cities: Nagoya (Kitada et al. 1998), Hong Kong (Liu et al. 2001; Tong et al. 2005), and Wroclaw (Szymanowski 2005). Ohashi and Kida (2002a, 2002b, 2004) used observations and three-dimensional numerical simulations to investigate circulations associated with two adjacent urban areas, one coastal (Osaka) and the other inland (Kyoto). These authors showed that a chain-like flow, which connected the two UHI circulations, formed between the two urban areas. This flow amplified the inland-directed transport of scalars (pollutants, heat, and moisture). Recently, the UHI and sea-breeze interaction was systematically reexamined in laboratory experiments (Cenedese and Monti 2003) and in numerical experiments that incorporated new simple urban canopy models (Lemonsu and Masson 2002; Martilli 2003; Lemonsu et al. 2006). These new studies generally supported earlier findings with some modifications.

b. Interaction with mesoscale circulations

The investigation of interactions between the UHI and mesoscale circulations is of great interest because many large cities are located near shorelines or basins. A series of studies for Tokyo area highly contributed to this topic (Yoshikado and Kondo 1989; Yoshikado 1990, 1992, 1994; Yoshikado and Tsuchida 1996). They used observations and two-dimensional numerical models to give physical insights into the interaction between the UHI and the sea breeze. The results included a few-hour delay for the inland penetration of the sea breeze and the formation of a stagnant region over the inland side of the city; the stagnant region helped to intensify sea-breeze velocities during its growth stage, and the intensity of interactions were controlled by the size of the city, the distance from the shore, and UHI intensity. Numerical experiments by Kondo (1990) showed that interactions between sea breezes and valley winds generate the so-called extended sea breeze, which is a circulation extended to 100 km from the shoreline. Kimura and Takahashi (1991) described the first realistic three-dimensional simulations of the environment around Tokyo, which incorporated detailed maps of land-use category and anthropogenic heat emissions to represent urban surfaces. Other studies followed (Kondo 1995; Saitoh et al. 1996; Ichinose et al. 1999; Kusaka et al. 2000; Kanda et al. 2001). Similar three-dimensional numerical simulations or data analyses have examined the interaction between UHI and local circulations in other cities: Nagoya (Kitada et al. 1998), Hong Kong (Liu et al. 2001; Tong et al. 2005), and Wroclaw (Szymanowski 2005). Ohashi and Kida (2002a, 2002b, 2004) used observations and three-dimensional numerical simulations to investigate circulations associated with two adjacent urban areas, one coastal (Osaka) and the other inland (Kyoto). These authors showed that a chain-like flow, which connected the two UHI circulations, formed between the two urban areas. This flow amplified the inland-directed transport of scalars (pollutants, heat, and moisture). Recently, the UHI and see-breeze interaction was systematically reexamined in laboratory experiments (Cenedese and Monti 2003) and in numerical experiments that incorporated new simple urban canopy models (Lemonsu and Masson 2002; Martilli 2003; Lemonsu et al. 2006). These new studies generally supported earlier findings with some modifications.

c. Rainfall

Early observations on the urban effect on precipitation were largely motivated by the pio-
neering observational studies at La Porte and Chicago (Changnon 1968; Holtzman and Thom 1970) that showed increases in precipitation downwind of Chicago. Huff and Changnon (1973) found evidence of warm-season rainfall increases of 9 to 17% over and downwind of major American cities. The Metropolitan Meteorological Experiment (METROMEX) was an extensive field study around St. Louis from 1971 to 1975 that investigated how major cities modified mesoscale and convective rainfall (see Changnon et al. 1981 for review). METROMEX confirmed that urban effects cause increases in convective precipitation of 5 to 25% over background values within 50–75 km downwind of a city (Braham and Dungey 1978; Huff and Vogel 1978; Changnon et al. 1981). After METROMEX many observational studies have shown that urbanization increased the frequency and/or intensity of convective precipitation, in Tokyo from 1954 to 1976 (Yonetani 1982), Phoenix from 1954 to 1985 (Ballinger and Brazel 1987), Mexico City from 1941 to 1985 (Jauregui and Romales 1996), Atlanta in 1996 (Bornstein and Lin 2000), and Atlanta from 1996 to 2000 (Dixon and Mote 2003). Numbers from the Tropical Rainfall Measuring Mission (TRMM) satellite’s precipitation data (PR) also indicated rainfall modification by major American cities during the 1998–2000 warm seasons (Shepherd et al. 2000); monthly average rainfall increased 28% in the area 30–60 km downwind of cities. Recent investigations also suggest that the UHI increases low-level clouds (Romanov 1999; Kanda et al. 2001; Inoue and Kimura 2004; Tsunematsu and Kai 2004).

Many modeling studies support observations of increased convection and precipitation associated with urbanization (Hjelmfelt 1982; Yonetani 1983; Thien et al. 2000; Baik et al. 2001; Rozoff et al. 2003). Three possible causes for urban-induced changes in precipitation are mechanical turbulence resulting from increased surface roughness, additional sensible heat flux, and increased anthropogenic nuclei. The cited numerical works investigated the influence of one or both of the former two factors.

Some observations refute the urban effect on precipitation. Kanae et al. (2004) investigated a long-term record (1890–1999) of hourly heavy precipitation in Tokyo and found no evidence of an urban effect. A U.S. Weather Research Program panel concluded that more observational and modeling research is necessary before the urban effect on precipitation can be conclusively defined (Dabberdt et al. 2000).

4. Recent technique

a. Simulation technique

(1) Simple urban canopy models

Simple urban canopy models can be classified into two categories. One category uses a resistance network analogy (Arnfield 2000; Masson 2000; Kusaka et al. 2001; Kanda et al. 2005b) and the other adds sink/source terms to the basic equations (Uno et al. 1989; Ashie et al. 1999; Vu et al. 1999, 2002; Martilli 2003; Tanimoto et al. 2004; Kondo et al. 2005). The basic concepts for these models were derived from similar vegetation models. However, vertically one-dimensional approximations used in the parameterization of momentum and energy absorptions within the vegetation canopies are no longer valid for urban canopies. Special treatment of the three-dimensional surface geometry is required instead. Urban radiation schemes typically include complicated sunlit and shade distributions with two-dimensional geometry (Arnfield 1982; Sakakibara 1996; Masson 2000; Kusaka et al. 2001; Martilli et al. 2002; Sailor and Fan 2002) or three-dimensional geometry (Ashie et al. 1999; Kanda et al. 2005b; Kondo et al. 2005). Parameterization of local transfer coefficients for momentum and scalars between surfaces (e.g., roof, street, walls) and a reference height requires more than a one-dimensional approximation. However, a compilation of experimental data suggests that such coefficients largely differ case by case and thus are difficult to arrange in a simple formulation (see Hagishima et al. 2005 for review).

Implementation of simple urban canopy models into mesoscale weather forecast systems is a realistic way to generate routine predictions without excessive computational load. Several numerical studies have included mesoscale simulations that incorporate simple urban canopy models for investigating UHI itself (Lemonsu et al. 2002, 2006; Kondo and Kikugawa 2003; Martilli 2003; Dupont et al. 2004; Kusaka and Kimura 2004a, 2004b; Otte et al. 2004; Best 2005; Kondo et al. 2005; Tokairin
et al. 2006), UHI effects on thunderstorms (Rozoff et al. 2003), and UHI effects on air pollution (Kusaka and Hayami 2006; Sarrat et al. 2006). A distinct improvement commonly observed in simulations that include a simple urban scheme is a better reproduction of the nocturnal urban temperature field because of the predicted large fraction of heat storage $Q_0/Q'$. Increased urban heat storage is a crucial process that must be considered. However, it is currently not clear what level of complexity to the representation of the urban surface is necessary for mesoscale simulations. Model intercomparison will be useful to identify the dominant physical processes and the most suitable representation for urban mesoscale simulations (e.g., Best 2006b).

(2) CFD models

An alternative approach is to simulate the urban atmosphere, which can explicitly resolve individual urban infrastructures using computational fluid dynamics (CFD) technology. Murakami et al. (1999) suggested the possibility of CFD analysis of winds at scales from human to urban. CFD methods have been used to examine flows around a single building (e.g., Murakami et al. 1990; Kogaki et al. 1997; Sada and Sato 2002). Murakami et al. (1996) reviewed the strengths and weaknesses of various modeling approaches, including Reynolds-averaged Navier–Stokes (RANS) models and Large Eddy Simulations (LES). Several numerical investigations have considered single street canyon flows (see So et al. 2005 and Li et al. 2006 for reviews).

Limitations of computational resources, however, have so far restricted CFD applications to simple cases such as turbulent flows within and above a group of buildings. Turbulent flows within and above regular obstacle arrays have been investigated by direct numerical simulations (Miyake et al. 2001; Nagano et al. 2004; Krogstad et al. 2005; Coceal et al. 2006), LES (Hanna et al. 2002; Cui et al. 2003; Kanda et al. 2004b; Kanda 2006a), and RANS (Lien and Yee 2004; Hamlyn and Britter 2005). Results from LES applications (Kanda et al. 2004b; Kanda 2006a) suggest some important physical aspects that are currently not emphasized in simpler CFD simulations: i.e., large dispersive momentum flux within the urban canopy layer due to a mean stream such as recirculation, intermittent urban canyon flow, non-persistent stream patterns, and longitudinally elongated streaks of low speed over building arrays with a scale an order of magnitude larger than individual buildings (Fig. 6a). Dispersive flux contributions should be included in sink/source term approaches (e.g., Lien and Yee 2005). Coupling of very large turbulent eddy motions and street canyon flows should be considered in the physical interpretation of turbulent flows within single street canyons.

Application of CFD technologies to real cities is a promising breakthrough in studies of urban meteorology. CFD technologies do not require the concept of roughness, the MOST, or simplified representative buildings, but instead explicitly include turbulent flows at multiple scales from individual building to the ABL, thereby representing more realistic effects of cities onto the atmosphere (Fig. 7). Such applications are currently still in the trial stage because of difficulties in the boundary conditions and limitations in computational resources (e.g., Tamura et al. 2002; Huang et al. 2005; Ashie et al. 2005, 2006; Kanda 2006c; Yamada 2006). Calculation of multi-reflective radiation processes within real urban canopies requires tremendous computational loads, and LES require unrealistic quasi-cyclic conditions for lateral boundary conditions.

b. Other promising techniques

Grimmond (2006) and Kanda (2006b) have reviewed recent progress in monitoring technologies and physical scale modeling, respectively. Promising and novel technologies that are expected to play a key role in the near future have been introduced.

Section 4a notes that an understanding of multi-scale interactions of turbulence at scales from UCL eddies to ABL eddies is crucial for directing future developments in urban surface modeling. Turbulence investigations in the lower part of the urban atmosphere from the top of the UCL to heights three to four times higher than the UCL (SL or RSL), have so far largely depended on tower-based measurements (Roth 2000), whereas one-dimensional vertical profiles of ABL turbulence from a few hundred meters from the top of the UCL to the upper ABL have been measured with various
remote sensors (Lidar, Sodar, and UHF/VHF wind profilers). The coupled use or networks of such towers and conventional remote sensors have contributed to the success of many urban field campaigns (e.g., Rotach 2005). However, horizontal deployment of such systems is quite difficult especially in the “blind region” of the lower atmosphere between the top of the tower

Fig. 6. Longitudinally elongated Low Speed Streaks (LSS) over building arrays. (a) LES result (Kanda 2006) and (b) COSMO (Comprehensive Outdoor Scale MOdel Experiments, Inagaki and Kanda 2006) result. Gray region in (a) and blue region in (b) show the instantaneous horizontal-velocity fluctuation from the horizontal mean at the height of $2z_H$. Flow is right to left.

Fig. 7. Examples of CFD application to realistic urban geometries. (a) Contour map of instantaneous surface wind in Sinjuku (from Kanda 2006c), and (b) coastal area in Tokyo (from Ashie et al. 2005).

(a) LES-CITY

(b) COSMO

(a) LES application to Sinjuku

(b) CDF application to Tokyo water front
to a few hundred meters above the tower. This layer is a key one where multi-scale interactions occur. A Coherent Doppler Lidar Velocimeter (CDLV) equipped with a three-dimensional scanner can obtain spatially and temporally detailed turbulent profiles from the UCL to the top of the ABL. Such profiles can extend in the horizontal direction as well. Dobinski et al. (2004) obtained three-dimensional flow patterns using a CDLV during the Cooperative Atmosphere Surface Exchange Study field campaign in October 1999 (CASES-99), and showed evidence of a layered turbulent structure in the near-neutral surface layer. Calhoun et al. (2006) proposed a virtual tower technique using dual CDLV during the Joint Urban 2003 Dispersion Experiment, and successfully measured wind velocity profiles from very near the ground at eight locations along a horizontal line. Frehlich et al. (2006) proposed a new CDLV algorithm and demonstrated that CDLV-derived turbulent profiles in the vertical direction are robust and accurate even under challenging conditions such as in stable boundary layers. Fujiyoshi et al. (2007) applied a new CDLV with a three-dimensional scanner in urban Sapporo and found longitudinally elongated streaks in a horizontal plane very close to the top of the UCL (Fig. 8). The streaks were similar to those simulated by LES-CITY (Kanda 2006a).

In real cities, field data acquired using towers, aircraft, and satellites yield a range of valuable information but have not yet resulted in a comprehensive understanding of the complex physical involved in the urban meteorology. As mentioned in Sec. 1, most of difficulties arise from heterogeneity and diversity in cities. Reduced-scale physical models provide an alternative and powerful method to study urban climates, free of site-specific diversities, although such models are often highly simplified. Indoor experiments that use arrays of urban-like flow obstacles or roughness elements including cubes, blocks, and cylinders have already contributed to the understanding of neutral-flow structures (see Kanda 2006b for review). Outdoor experiments are a promising way to systematically investigate relationships between surface structures and physical processes within and above the RSL under realistic synoptic conditions. Results from such models can be used to detect the physical parameters needed to construct numerical models. Pioneering outdoor experiments using large-scale obstacles (e.g., ~1 m) such as MUST (Yee et al. 2004) and Kit FOX (Hanna and Chang 2001) focused on dispersion processes and did not consider energy balance. Pearlmutter et al. (2005) evaluated urban surface energy fluxes using an open-air scale model. Comprehensive outdoor scale model experiments (COSMO) have been conducted for systematic investigations of land surface parameters (Fig. 3 from Kanda et al. 2007), energy balance (Fig. 5 from Kawai et al. 2007), multi-scale turbulent structures (Fig. 6b from Inagaki and Kanda 2006).

5. Concluding remarks

Progress in urban meteorology was reviewed mainly in relation to boundary-layer meteorology. The characteristics of urban surfaces as the bottom boundary of the atmosphere, including land surface parameters (albedo, roughness, and wetness) and resulting surface
energy partitioning, have been studied intensively in the past few decades (Sec. 2). Temperature fields, local circulations, and rainfall affected by UHI have also been investigated using conventional meteorological frameworks (Sec. 3). Recently, simple urban canopy models have been proposed and incorporated into mesoscale simulations (Sec. 4a). However, it is unclear as to what level of complexity is necessary in representing urban surfaces for the mesoscale simulations. One physical process that is indispensable to new urban land schemes is the increase in heat storage \( Q_G/Q_c \) due to urban materials. The MOST with minor modification may or may not give acceptable results. For example, a city with high-rise buildings can act as a large obstacle in the surrounding mesoscale field. Such building-barrier effects have influenced precipitation in New York City (Bornstein and Lin 2000) and prevented sea breezes in Tokyo (Ashie and Kono 2006). In these extreme cases, conventional roughness treatments fail. CFD technologies that explicitly resolve urban buildings are the most complex representation of urban surfaces. Such technologies will play an important role not only in pure application studies but also in guiding the improvement of simpler models. Coherent Doppler Lidar Velocimetry (CDLV) and outdoor scale model experiments are promising technologies for the near future. CDLV observes spatially and temporally detailed turbulent profiles from very close to the UCL and to the top of the ABL. These profiles also have considerable horizontal extent, thereby enhancing the physical understanding of multi-scale turbulent interactions from the UCL to the ABL. Outdoor scale model experiments can yield long-term records of land surface parameters, energy balance, and multi-scale turbulence, which are free of uncertainties which are commonly encountered in the filed observations over real cities. Such data sets can be used to validate numerical models.

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