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Atmospheric Science Program, Department of Geography, Indiana University, Bloomington, IN, USA

Progress in measuring and observing the urban atmosphere

C. S. B. Grimmond

With 1 Figure

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Summary

Observations of atmospheric conditions and processes in cities provide the cornerstone for advances in the understanding of urban climates and are crucial to improving the performance of urban atmospheric models. Here, recent progress in the observation and measurement of the urban atmosphere is considered in terms of: first, the research directions of those involved in conducting urban climate observations; second, advances in technology, both direct in terms of the development of new sensors and indirect in terms of computing power and capabilities in data analysis; and third, enhanced understanding of sensor placement. Increasingly, urban based observational programs are collaborative, multi-institutional, multi-national, interdisciplinary initiatives. This has important implications for the research questions addressed and the potential to investigate processes and effects across multiple spatial and temporal scales. Advances in technology have provided urban climatologists with new, improved and often more affordable instrumentation, and the ability to process and analyze data more rapidly. Greater understanding of urban atmospheric processes, and atmospheric sciences more broadly, have resulted in important insights into appropriate placement of meteorological instruments and the interpretation of results. An important issue that the urban climate community must address is how best to archive data so it is not lost. A database of current and past studies with key metadata about sites, instrumentation and data processing is proposed. Well documented and available urban data sets will enable future researchers to continue to extract valuable new insights and verify existing understanding about urban atmospheric processes. Urban field studies can be costly and time-consuming, so continuing to exploit the rich, significantly untapped, historical data sets will allow steady progress in urban atmospheric research to continue, provided funding are available for analysis of the data.

1. Introduction

Observations of atmospheric conditions and processes in cities are fundamental to advances in the understanding of urban climates. It is now nearly two hundred years since the first discussion of urban climate based on direct temperature measurements (Luke Howard's thermometer-based observations) in London in 1820. These documented that London was warmer than the surrounding countryside. However, it is important to note that from Roman times, visual observations of the urban atmosphere have suggested differences from surrounding rural areas signifying urban climate effects (see citations in Landsberg, 1981). Moreover, the first temperature network, which began between 1653–54, focused on urban areas, with stations in Florence, Vallombrosa, Cutigliano, Bologna, Parma, Milan, Paris, Innsbruck, Osnabrük and Warsaw (Camuffo, 2002). Each station had the same model of thermometer which was to be exposed in an elevated position, on a north-facing wall in order to obtain absolutely comparable data. This network, *Rete Medicea*, ended its activity in 1667, but some stations (e.g. Paris, Vallombrosa) continued to monitor temperature (Camuffo, 2002). A second international meteorological network was active from 1724 to 1735, with precise norms for instruments, operational methodology, exposure and reading times following the protocol introduced in 1660 by John Locke in London (Camuffo, 2002). Temperatures were measured indoors, in a north-facing room where fire was never or hardly ever lit.

In this paper, recent progress in measuring and observing the urban atmosphere is discussed. First, attention is directed to how urban climatology is studied and the implications of the increasing number of campaign-style, multi-group, urban-based projects on research objectives and methodologies. Second, the impact of advances in technology is considered. Of interest are direct impacts resulting from improved instrumentation and remote sensing capabilities, and indirect effects resulting from enhanced computer power on data analysis and storage. Third, the implications of greater understanding of urban boundary-layer atmospheric processes are considered, specifically in the context of instrument placement and the interpretation of observational results.

The potential scope of this paper is very broad. Thus attention is restricted to the physical meteorology of cities; observations of atmospheric composition and air quality are not considered. Moreover, only full-scale field studies are discussed; observational studies conducted using scale models are reviewed elsewhere in this volume (Kanda, 2006). The examples presented are purely illustrative; in most cases many other examples could have been chosen. Readers are directed to other papers in this volume and the recent review by Arnfield (2003) for a broader discussion of contemporary urban climate research to provide context for the discussion here, and to recent publications such as the text by Brock and Richardson (2001) on the current state and use of instruments in the atmospheric sciences more broadly.

2. The researchers

Urban climatology has a long and rich tradition of observation and measurement (see, for example, the descriptions in Oke, 1974, 1979; Landsberg, 1981; Arnfield, 2003). Much of this work has been conducted by individuals and their students or small research groups located in cities around the world undertaking their own measurements. Some of the best examples of this general approach are provided by urban heat island studies; see, for example, the studies cited in Oke (1981, 1982) and selected examples of recent investigations in Table 1. These studies have provided a wealth of empirical data on the thermal environment of cities, yielding important insight into urban atmospheric processes. But, given the limited resources that can be deployed by many of these investigators, both in terms of equipment and labor, there have been direct implications for urban climatology in terms of the types of questions that have been addressed, the range of scales considered, and the length of time, and thus range of conditions, for which data are collected.

Another important and well used source of data for urban climate investigations are the networks that have been established in cities for a variety of different management and/or regulatory purposes. If a city is large, it is likely that the national meteorological network may be suffi-

Table 1. Examples of recent urban heat island studies. These are intended to be illustrative only, many other studies have been reported

City	Authors	Time period	Number of stations
Athens, Greece	Mihalakakou et al. (2002)	1997–1998	23
Melbourne, Australia	Morris et al. (2001)	1972–1991	4
Minneapolis-St Paul, USA	Todhunter (1996)	1989	26
Salamanca, Spain	Alonso et al. (2003)	1996–1998	2 + mobile observations
Seoul, Korea	Kim and Baik (2002)	1973–1996	2
Shanghai, China	Chen et al. (2003)	1961–1997	16
Szeged, Hungary	Bottyan and Unger (2003)	Mar 1999–Feb 2000 April–October 2002	Mobile observations

ciently dense that there is climate station, or even multiple climate stations, within the urban area. For example, in Minneapolis-St Paul (USA), there is one station at the local National Weather Service (NWS) forecast office and eleven NWS cooperative network stations (Todhunter, 1996). These stations may be of different World Meteorological Organization (WMO) or national standards (WMO, 2004) or may not comply with either. This means that not all stations will measure a full range of meteorological variables; that the time resolution may be hourly at some sites and daily at others; and that exposure, and thus the nature of the measurements, may differ significantly. In addition, the maintenance and operation of the station may also differ between volunteer or "co-operator" and meteorological agency personnel, with important implications for the quality of data. Electricity/power companies, air pollution regulatory bodies, radio and television stations, and hydrological monitoring agencies also collect meteorological data in cities. Data from such networks can be, and have been, compiled to study spatial and temporal variability in urban climate patterns and processes (see examples in Table 2). Todhunter (1996), for example, in a study of the Minneapolis-St Paul urban region, compiled data from 26 co-operative stations run by the US National Weather Service, the University of Minnesota, and a television station network to study urban heat islands and other indices. Given agencies collect data for different purposes, standards for instrument placement, time of observation, and degree of maintenance (quality control/quality assessment) will differ, with important implications for the representativeness and inter-comparability of observations that must be critically evaluated. In addition, if long-term trends or changes are of interest, discontinuities in data sets must be assessed. Peterson (2003) notes that the most homogeneous long-term U.S. climate stations have an average of six discontinuities per century, and not a single station is homogeneous for its full period of record. These inhomogeneities result from changes in location (station moves that involve changes in latitude, longitude, or elevation); changes in observing practices (of particular concern are changes in the time of once-daily observing and resetting of maximum and minimum thermometers); and changes in instrumentation (Peterson, 2003). Camuffo (2002) provides a detailed historical account of the impact of changing norms for temperature measurements for data collected in Padova (Italy) between 1725 and 1998, for example.

Increasingly, urban climate research is being conducted in large-project, campaign mode by groups of scientists and agencies (see examples in Table 3). This, in part, reflects trends in science for interdisciplinary, multi-method investigations (NSF, 2000) and the increasing attention being directed to the environmental problems and issues in urban settings (Dabberdt et al., 2000, 2004; Rotach et al., 2002; Office of the Federal Coordinator for Meteorology (OFCM), 2003). Such studies allow a wide range of questions to be addressed, and benefits to be derived given the multiple people and instrumentation that could not otherwise be deployed. One of the earliest such "large" urban campaigns was the METROMEX study, conducted in St Louis in the summers (June–August) from 1971 through 1976 (Changnon, 1981a, b). The objective of METROMEX was to study "inadvertent weather and climate modification by urban-industrial effects, and in particular man-made [*sic*] changes of precipitation" (Changnon, 1981a, p 2). This study brought together researchers from universities, national laboratories, and state and federal government agencies. It also brought together "a host of instruments ... including 250 recording raingauges and hail-pads, 5 weather radars, 70 rainwater collectors, 15 pibal stations, 5 meteorological aircraft, 5 radiosonde stations, unique

Table 2. Examples of research studies that have used pre-existing climate networks within urban areas

City	References	Variables
Baltimore, Maryland, USA	Brazel et al. (2000)	Temperature
Mexico City, DF, Mexico	Jauregui and Luyando (1998)	Evaporation, Temperature
Minneapolis-St Paul, Minnesota, USA	Todhunter (1996)	Temperature
Phoenix, Arizona, USA	Brazel et al. (2000)	Temperature

Table 3. Examples of recent, large campaign-style urban climate studies

Location	Study	Characteristics	Reference for study	When
Basel, Switzerland	Basel urban boundary layer experiment (BUBBLE), SARAH	ES, AP, S1, S2, S3, S4, RS2, RS3	Rotach et al. (2005)	2001–02
Marseille, France	ESCOMPTE/CLU-UBL	AP, S1, S2, S3, S4, S5, RS1, RS2, RS3	Cros et al. (2004) Mestayer et al. (2005)	2001
Mexico City, Mexico	IMADA-AVER Boundary Layer Experiment	NP, ES, AP, RS3, S4, S5	Doran et al. (1998)	1997
Nashville, USA	Southern Oxidant Study	AP, S4, S5, RS1, RS3	Cowling et al. (1998; 2000) Meagher et al. (1998)	1995, 1999
Oklahoma City, USA	Joint Urban 2003	NP, AP, S1, S2, S4, RS1, RS3	Allwine (2004)	2003
Paris, France	Atmospheric Pollution over the Paris Area (ESQUIF) field campaign	NP, AP, S3, S4, S5, RS1, RS3	Menut et al. (2000)	1998–99
Phoenix, USA	1998 Ozone Field Study	NP, ES, AP	Fast et al. (2000) Gaffney et al. (2002)	1998
Phoenix, USA	CAP-LTER	NP, ES, S1, S2, S3, S4, S5	Brazel et al. (2000)	1998
Phoenix, USA	2001 Phoenix Sunrise Experiment	ES, AP, S1, S5, RS1, RS3	Doran et al. (2003)	2001
Salt Lake City, USA	VTMX/Urban 2000	AP, S1, S2, S4, S5, RS1, RS3	Allwine et al. (2002) Doran et al. (2002)	2000
Vancouver, Canada	Pacific ’93	ES, AP, S4, S5, RS1, RS3	Steyn et al. (1997)	1993

NP – Network Present, ES – Earlier studies in the city, AP – Air Pollution a focus
S1 – Indoor or building or canyon scale, S2 – Neighborhood or local scale, S3 – multiple neighborhoods, S4 – urban area, S5 – Region
RS1 – aircraft, RS2 – satellite, RS3 – lidar and/or sodar and/or radar

atmospheric tracers and a wide variety of standard and unusual meteorological equipment'' (Changnon, 1981a, p 2).

METROMEX had many traits that characterize more recent, large, campaign-style studies (Table 3). First, it was conducted in a city where a pre-existing instrumental network had been used previously to investigate climatological conditions. Phoenix and Mexico City were selected for large urban climate projects for similar reasons (Tables 2 and 3). More recently, the Joint Urban 2003 campaign, conducted in Oklahoma City, was selected in part because of the presence of a climatological network (Mesonet) in the vicinity (Allwine, 2004). Second, urban 'campaigns' are characterized by multiple sub-investigations with methodologies which cut across scales. Detailed investigations of processes occurring at the micro-scale (e.g. interior of building, exterior of building, urban canyon) often are conducted concurrently with local-scale (e.g. neighborhood), meso-scale (e.g. multiple neighborhoods, whole city), and regional scale observations (Table 3). The latter often rely on remotely sensed observations (aircraft, satellite, lidar, etc). For example, the integration of the CLU/UBL project of Marseille (Mestayer et al., 2005) within the ESCOMPTE project of the Marseille–Berre region (Cros et al., 2004) allowed observations of surface temperature of individual wall facets to be integrated with remote sensing of both the boundary layer and from satellites ($100\,\text{km} \times 100\,\text{km}$) (Table 3). Both studies benefited from greater information of the lower and upper boundary conditions, respectively. Similarly, the combined VTMX/Urban 2000 project integrated observations from the Salt Lake Basin (Allwine et al., 2002; Doran et al., 2002) with detailed data collected on dispersion around individual buildings (Allwine et al., 2002). What permits the wide range of scales to be studied is the fact that multiple agencies, with access to different technologies and resources, are represented in the projects. National government agencies and research laboratories, who are often the owners of the most expensive state-of-the-art instrumentation, combine resources with a wide variety of other agencies (city, regional and provincial/state government, university academics). Increasingly, notably in Europe, international co-operation is also a trait of such projects; see for example the Bubble project (Rotach et al., 2002). Such collaborations, between government university-based researchers of different national and professional affiliations, have important implications for the research and the types of questions addressed and also for the dissemination and real-world application of results (see further discussion below).

A very important feature of these ''large projects'' is the integration of different types of measurement, tower-based and remote sensing technologies, for example. New insight into the comparability and complementarities of data derived from these different types of observations has resulted (see, for example, Mestayer et al., 2005). Moreover, because field scientists and numerical modelers both are involved in these projects, discussions have been encouraged on critical differences between model ''levels'' and observation ''heights'' (Masson et al., 2002; Lemonsu et al., 2004); the variables that models need and those that are measured; the number of sites that need to be observed to be appropriately representative for model evaluation; and the complexity of the real world versus the necessary simplification of reality in modeling.

Obviously, a number of the benefits of multi-investigator projects also can be derived from smaller inter-disciplinary studies. In addition, smaller, single-investigator studies may serve as important precursors for bringing larger groups together to address in more detail features of the urban atmosphere that have been documented previously (probably the most well known of which is the Changnon (1968, 1980, 1981b) studies prior to METROMEX). It is important to recognize that large campaign style-projects are not without their limitations. They tend to be expensive and the full benefits often are not fully accrued as support does not extend for sufficient time after the field program to allow complete analysis and integration of all data. In addition, the field components of most large-project campaign style studies are of short duration (Table 3). Many key questions about the urban atmosphere can only be addressed by conducting long term measurements. Urban climatologists need to learn from other long-term studies in the Atmospheric Sciences, for example FLUXNET and its investigations of carbon dioxide fluxes (Baldocchi et al., 2001). Furthermore, most studies of urban climate tend to be focused in temperate latitudes, and there are many types of urban areas for which we have very little observational knowledge, notably in the Tropics. It is important that as the urban climate community plans new large projects these very significant and highly populated cities are seen as priorities for study.

3. Technology

Changes in technology have had a profound impact on observations of the urban atmosphere. Changes in instrumentation, specifically the development and refinement of sensors, have had a direct impact in terms of what variables can be measured, how well, under what conditions, and at what cost. Advances in computing power have had an impact on both data collection and analysis, through increases in the rates of computations, efficiency of modeling analysis and management of data, ability to merge models and data from multiple observations, maintenance and longevity of research collections, and more rapid flow of information among scientists.

3.1 Direct effects

Dataloggers, a fundamental part of all measurement programs, have developed significantly in the last decade. Orders of magnitude increases in datalogger memory have implications not only for data storage but also for the rate of data acquisition and real-time data processing. Given the wide range of dataloggers now available, there is more flexibility both in terms of the number of sensors that can be sampled by one datalogger and the possibility of having multiple sensors with their own dataloggers, which means that more sites can be studied. Obviously, developments in computer technology have impacted datalogger developments directly through specialized boards and connections, which make it possible to connect through readily available computer ports such as the serial (com) port. Additionally, advances that permit instruments to connect through USB ports or download to Personal Digital Assistants (PDAs) are affecting how measurements are made and the number of instruments that can be deployed in any study. The development of compact flash (CF) cards (and other equivalents such as secure digital-SD) is decreasing the cost of data storage and enhancing the ease of data downloads and transfers.

3.1.1 Observations of the urban surface layer

Probably the most compelling focus of climate research in built-up areas remains studies of the urban heat island (Arnfield, 2003). The most noticeable recent advances in terms of instrumentation that impact such studies relate to the advent of stand-alone sensors that can also store data. These small sensors allow networks to be established across an urban area and/or for a small areas to be intensively instrumented (similar technology also exists for relative humidity and radiation measurements). Examples of recent studies using such sensors are summarized in Table 4. Despite these advances/opportunities, it is important to note, however, that many of the fundamental issues associated with the measurement of air temperatures in urban areas have not been resolved, specifically related to the siting and exposure of sensors (see discussion in WMO, 2004). This is an issue of utmost importance for urban climatologists.

In the last decade, there have been significant advances in sonic anemometry and its application in urban settings to study wind, turbulence, and fluxes. Baldocchi (2003) provides a review

Table 4. Examples of studies that have used stand-alone temperature sensors

City	Areal coverage	Manufacturer	Reference
Lodz, Poland	Urban area	Onset Hobo	Offerle et al. (2003b)
Goteborg, Sweden	Park and surroundings	TinyTag	Upmanis et al. (1998)
Goteborg, Sweden	Urban area	TinyTag	Svensson and Eliasson (2002) Eliasson and Svensson (2003)
Marseille, France	Urban area	Rotronic	Pigeon et al. (2002)
Phoenix, USA	Urban area	Onset Hobo	Doran et al. (2003)

Table 5. Example of cities where turbulence measurements have been ongoing for periods of greater than a year

City	Reference	Comments
Baltimore, MD, USA	Grimmond et al. (2002a)	
Basel, Switzerland	Vogt et al. (2004)	
Beijing, China	Al-Jiboori et al. (2002)	325 m Tall tower
Copenhagen, Denmark	Soegaard and Moller-Jensen (2003)	
Denver, CO, USA	D. Anderson (personal communication)	
Rome, Italy	F. Miglietta (personal communication)	
Lodz, Poland	Offerle et al. (2006)	
Tokyo, Japan	Moriwaki and Kanda (2004)	
Vancouver, BC, Canada	T.R. Oke (personal communication)	Intermittent

of the history of eddy covariance in general, with an emphasis on the applications of this methodology to forested areas. Many of the problems/issues associated with tall roughness elements that he identifies are common to urban areas, and urban climatologists must be cognizant of these. In the last decade, there has been an increase in the number of companies that make sonic anemometers, reductions in their costs, improvements in their water shedding capabilities (and thus the range of conditions under which they can generate good data), a move from 1- and 2-dimensional to 3-dimensional sensors, an increase in sampling rates, and improvement in data acquisition systems. Advantages and disadvantages of particular designs of sonic anemometers relate to the configuration of the instrument head and electronics relative to the exposure that is of interest, and their sampling rate capabilities. The net effect of the advances in technology and reductions in cost is to allow continuous measurements over a wider range of conditions. This has resulted in significant increases in the number of sensors deployed both by individuals and in campaigns. For example, a study of canyon turbulence in Goteborg, Sweden, fifteen 3-d sonic anemometers have been collecting data within one canyon for more than a year (Eliasson, 2005). In the Joint Urban 2003 campaign, a study of dispersion in Oklahoma City, USA, more than 200 sonic anemometers were deployed in a month long campaign (Allwine, 2004). Increased computer capabilities have meant that the amount of data that can be collected and archived has increased substantially. Roth's (2000) review of turbulence measurements in urban areas gives some sense of the history of observations up until the late 1990s. Since that time a number of new studies have been published which provide information on turbulence characteristics of the urban atmosphere above a wider range of surface covers over more extended periods (Table 5). However, the data remain biased to dry periods as the presence of rain, snow or ice within the measurement volume or on the transducers causes measurement errors.

New technology being used to study the surface layer of the urban atmosphere includes small and large aperture scintillometer systems. Scintillometry allows spatially integrated values of momentum and turbulent heat fluxes to be measured (De Bruin, 2002). Recent studies have compared the data derived from scintillometers with results from sonic anemometry. Lagourade et al. (2002) and Irvine et al. (2002), for example, compared sensible heat fluxes measured over a path length of approximately 1.5 km in the downtown area of Marseille during the ESCOMPTE/UBL study (Mestayer et al., 2004). Kanda et al. (2002) used small aperture scintillometry in Tokyo to estimate the zero-plane displacement over a path length of 250 m. In that study, sensors were mounted at two heights above the surface. More recently, Salmond et al. (2003) deployed two levels of scintillometers over a path length of $\sim$150 m above an urban canyon and along the roofs in a downtown area of Basel as part of the Bubble project.

Advances in gas analyzers (ultra-violet and infra-red (IRGA) based) have been important in terms of studies of surface-atmosphere exchanges (see general discussions by Moncrieff et al., 1997; Aubinet et al., 2000; Baldocchi, 2003). Based on the review of Roth (2000), the first turbulence measurements that used a gas analyzer to observe humidity in an urban environment were those of Coppin (1979). Roth and Oke (1993) used both Lyman alpha and krypton hygrometer technology in their studies of turbulence over a residential area. These open path sensors allow almost coincident observations of humidity with the velocities from a sonic. In recent years, attention has focused increasingly on carbon fluxes in cities as well as water (humidity) (see, for example, Grimmond et al., 2002b; Nemitz et al., 2002; Soegaard and Moller-Jensen, 2003; Moriwaki and Kanda, 2004). In addition, closed path systems have been developed. These require the air to be drawn (sucked) from the measurement location to a detector, which causes dampening of the fluctuations (Leuning and Judd, 1996). Closed path sensors have the advantage of being able to operate during periods of rain, but the time lag involved in pumping the air to the gas analyzer has to be determined relative to the velocity observations. All these advances in technology have resulted in sensors which are operational under a wide range of conditions, which have faster response and higher precision.

3.1.2 Observations of the atmospheric boundary layer

Urban climatologists have long been engaged in studies of the urban boundary layer. These have involved traditional airsondes/tethered balloons (recent examples include Piringer and Baumann, 2001; Cleugh and Grimmond, 2001), remote sensing techniques (Banta et al., 1998; Emeis et al., 2004) (Table 6 – discussed in the next section), and instruments mounted on aircraft (for example, the Southern Oxidant Study in Nashville – Banta et al., 1998). Often the studies involve multiple techniques to investigate different aspects of the atmosphere (Castracane et al., 2001) (Table 6) or are focused on the evaluation of methods (Emeis et al., 2004). Many of the studies are integral to air quality investigations (e.g. Santacesaria et al., 1998; Table 6). Seibert et al. (2000) recently reviewed the strengths and weaknesses of the various approaches from an operational viewpoint. Given the importance of understanding boundary layer height and structure in urban settings, and the need to improve the methods of analysis of profile measurements and parameterizations (Seibert et al., 2000), more of there types of boundary layer measurements need to be made in cities both on a routine and experimental basis (Dabberdt et al., 2004).

3.1.3 Remote sensing

Since the 1970s there have been significant advances in remote sensing (RS) with many applications to the urban environment. These involve data collected from sensors mounted at the surface, and on planes and satellites, using observations from both passive and active sensors. In urban climatology, thermal bands have been used most extensively (Dousset and Gourmelon, 2003; Voogt and Oke, 2003). Voogt and Oke (2003) in their review of thermal RS in urban areas, a discussion of developments since the Roth et al. (1989) paper, list approximately 40 studies (their Table 1). These investigations employ a variety of platforms (satellite, aircraft) and sensors (e.g. Landsat TM, AVHRR, ASTER, MODIS, AGEMA, etc). Remote observation of the urban heat island remains a significant theme, continuing from Rao's (1972) early study. Thermal RS also has been used to study surface-atmosphere exchanges, for example, sensible heat flux (Voogt and Grimmond, 2000), net radiation (Chrysoulakis, 2003), evaporation (Carlson and Arthur, 2000; Arthur-Hartranft et al., 2003), and carbon fluxes (Soegaard and Moller-Jensen, 2003). Significant advances also have occurred in the range of wavelengths that are detected on a routine and experimental basis. New urban climate applications have resulted from the use of multi-sensor datasets in conjunction with new processing techniques. For example, Dousset and Gourmelon (2003) use SPOT-HRV multispectral images, and NOAA – AVHRR for Paris and Los Angeles to look at the spatial relations between surface temperatures, air quality, and surface attributes.

Voogt and Oke (2003) suggest that the difficulty of making remote sensing observations in urban areas, associated with the height of the roughness elements and the complexity of the surface, has resulted in a lag in progress relative to studies of vegetated areas. They point to the need to continue to conduct appropriately designed validation studies to assess the surface effective parameters derived from remote thermal

Table 6. Examples of urban boundary layer studies

City, Study, Period	Approaches	Authors*
Athens, Greece, Summer 1994 MEDCAPHOT-TRACE	Airborne differential absorption lidar (DIAL): Air quality profile within the urban boundary layer. Sodar: mixing height and air quality	(Kambezidis et al., 1998) (Ziomas, 1998) (Assimakopoulos and Helmis, 2003)
Essen, Germany, May 1995–Sept 1997	Sodar: urban park nocturnal low-level jet and the passage of a front, ozone maxima	(Reitebuch et al., 2000)
Florence, Italy, 1996–2000	532–1064 nm LIDAR, continuous operation PBL dynamics and vertical distribution of the aerosols	(Del Guasta, 2002)
Graz, Austria, January 1998	Sodars, tethersondes, meteorological tower: modifications to the wind field	(Piringer and Baumann, 2001)
Hamburg, Germany, 1997–2000	UV Raman Lidar: Aerosol climatology for the planetary boundary layer	(Matthias and Bosenberg, 2002)
Hong Kong, March 1999	Internal boundary layer structure under sea-breeze conditions, evaluation of a numerical model	(Liu et al., 2001)
Lyon, France, Summer 1996	Combined lidar, scanning electron microscopy, and x-ray microanalysis; pbl dynamics and 3-d aerosol distribution	(Frejafon et al., 1998)
Mexico City, 27–28 February 1991	Radiosonde and scanning backscatter lidar comparison of derived PBL heights	(Cooper and Eichinger, 1994)
Milan, Italy, February, 1993 Summer 1996	Sodar and tethersonde: wintertime convective boundary-layer structure Sodar, RASS: evaluation of nocturnal mixing height estimate methods	(Argentini et al., 1999) (Lena and Desiato, 1999)
Nashville, TN, USA, 1995 Southern Oxidants Study	Airborne differential absorption lidar (DIAL) system profiled ozone in the boundary layer	(Banta et al., 1998) (Valente et al., 1998)
Nashville, TN, USA, 1999 Southern Oxidants Study	Wind profiling radars, lidars, and aircraft, RASS, monostatic sodars and Doppler wind profilers: mixing height and clouds; evolution of boundary layer depth on days when a nocturnal inversion formed	(Angevine et al., 2003) (White et al., 2002)
Paris, France ECLAP, Winter 1995	Frequency doubled Nd-Yag backscattering lidar, monostatic sodar (both at two sites), CO_2 Doppler lidar, meteorological tower; vertical structure and diurnal evolution of the atmospheric boundary layer	(Dupont et al., 1999) (Menut et al., 1999)
Pune, India, 1986–	Bistatic argon ion laser radar, spectroradiometer, pibal; nocturnal atmospheric structures, aerosols	(Devara et al., 1995) (Raj et al., 1997) (Devara et al., 1998) (Tiwari et al., 2003)
Rome, Italy, 1994–95, 1996, 1998	Tri-axial Doppler sodar, Raman lidar, microwave radiometer and a dual polarization lidar; nocturnal urban boundary layer characteristics; diurnal evolution of the urban boundary layer solitary-type waves in the urban boundary layer Sodars, tethered balloon; interaction of a winter sea breeze with the UHI	(Casadio et al., 1996) (Castracane et al., 2001) (Rao et al., 2002) (Rao et al., 2004) (Ferretti et al., 2003)
Sacramento, CA, USA, August 1991	Tethersonde; Evaluation of CBL models	(Cleugh and Grimmond, 2001)

(*continued*)

Table 6 (*continued*)

City, Study, Period	Approaches	Authors*
Salt Lake City, UT, USA, 2000 VTMX	Radar wind profilers, sodars, radio acoustic sounding systems, Doppler lidar, aerosol lidars, and a water vapor lidar, and rawinsonde soundings in intensive observing period (IOP); processes responsible for the vertical transport and mixing of quantities such as heat, momentum, and air pollutants	(Doran et al., 2002)
Sofia, Bulgaria, Sept, Oct 1990	Lidars (aerosol and Raman), kytoon (tethered balloon) and pilot balloons; formation of stable stratification after sunset	(Kolev et al., 2000)
Thessaloniki, Greece, 1994–(1996)	Backscattering lidar; vertical structure of the Planetary Boundary Layer (PBL)	(Santacesaria et al., 1998)
Tsukuba, Japan, May 1999–May 2000	Compact micro pulse lidar; comparisons between the aerosol optical thickness, the rawinsonde data and model calculation, and mixed layer height variation with season	(Chen et al., 2001)

* In many cases there are multiple papers from one study. Those included are examples not an exhaustive list of papers from that study

sensors. Advances are being made with the advent of multi-angle sensors (Diner et al., 1999).

Remote sensing also has been extensively used to determine parameters to characterize the urban surface. Spatial data sets to characterize the fundamental physical attributes of a measurement site or to provide key parameters for urban climate models now can be derived from RS data; for example albedo (Small, 2002, 2003), emissivity (Chrysoulakis, 2003), and land cover fractions (Small, 2001; Wilson et al., 2003). In addition, other remote sensing technologies, for example airborne lidar can be used to provide detailed databases of the heights of buildings and trees (Gamba and Houshmand, 2000, 2002; Gamba et al., 2003).

Remote sensing also has been used to determine the aerosol characteristics and optical depth (King et al., 1999) within the atmosphere (Table 6). In addition, active RS has been used to study the structure of the urban atmosphere. Sodar, which emits audible pulses, became commercially available in the 1980s (Seibert, 1999). Other active RS techniques include Lidar or ceilometer, Radar, and RASS (radio acoustic sounding sytems). Each uses different techniques, wavelengths/frequencies (Figure 1 in Emeis et al., 2004) and constituents in the atmosphere to provide characteristics of the boundary layer (see Table 1 in Seibert et al., 2000). A number of reviews of these techniques have been published (e.g. Beyrich, 1997; Coulter and Kallistratova, 1999; Seibert et al., 2000; Emeis et al., 2004). In addition, comparisons of methods in urban settings have been published for: Moscow (Lokoshchenko, 2002), Hannover (Emeis et al., 2004), Marseille (Mestayer et al., 2005) (see also Table 6). Each instrument type has attributes which make different characteristics of the atmospheric boundary layer more easily observed. For example, sodar performs better at night or in daytime periods when the convective boundary layer is shallow (Emeis et al., 2004) (see also Table 6 applications). However, because of the audible pulses which generate complaints, it is often difficult to operate in residential areas at night. It is important to recognize that given the instruments are detecting different characteristics of the atmosphere, the desired characteristics being observed (e.g. mixing layer height) may not be exactly the same physical feature for the different methods (Seibert et al., 2000). In some cities, continuous measurements of boundary layer height and/or characteristics using these types of technology are now being made; for example, using Lidar in Beijing (NIES, 2004d), Nagasaki (NIES, 2004b), Sapporo (NIES, 2004c), Tsukuba (NIES, 2004a), and Florence (Del Guasta, 2002); and using sodar in Moscow (Lokoshchenko, 2002).

Precipitation, because of its spatial heterogeneity, is a difficult variable to observe and to detect urban influences upon (Lowry, 1998). Given the significant consequences of rainfall in urban areas (e.g. Petersen and Carey, 1999; Smith et al.,

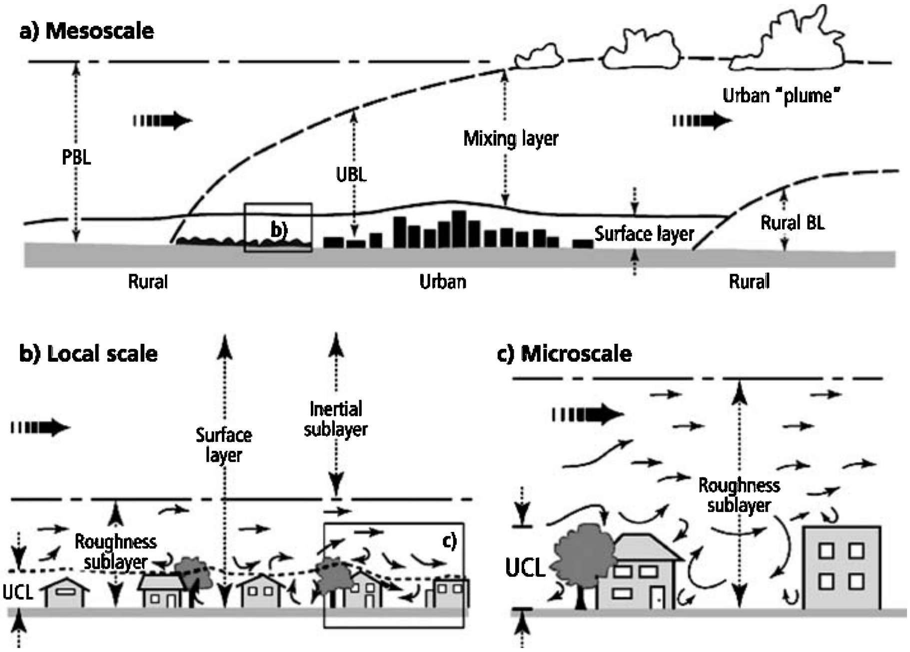

Fig. 1. Three scales used to distinguish atmospheric processes in urban area and the atmospheric layers which are typically identified at each scale. (**a**) The planetary boundary layer (PBL) and urban boundary layer (UBL) are shown for a daytime convective situation. (**b**) The urban canopy layer (UCL) is defined as being at the mean height of the roughness elements, which will include a varying mixture of buildings and trees depending on where in an urban area the local scale area or 'neighborhood' is located. The bold arrow in each of the sub-figures going towards the right indicates the mean wind direction. The smaller, arrows shown in (**b**) and (**c**) indicate the nature of the mean and turbulent flow (figure modified after Oke 1997, reprinted with kind permission of Kluwer Academic Publishers from Piringer et al., 2002, Fig. 1, p 3)

2002), some of the earlier developments in rainfall measurement focused on enabling real-time measurement (Rahimi et al., 2003). Attention focused on the rapid communication (telemetry) from traditional rain gauges. More recently, remote sensing techniques are increasingly being used. Ground-based radar of various types (Petersen and Carey, 1999), satellite based radar (Shepherd et al., 2002; Shepherd and Burian, 2003), and dual frequency microwave link (Rahimi et al., 2003) are examples of instrumentation recently deployed. Traditional raingauge networks still provide the reference for verification of these newer approaches. These techniques are often used to forecast potential flooding situations, which are exacerbated in urban areas because of the increased impervious areas. At the scale of individual buidlings it remains difficult to measure rainfall because of airflow distortion.

3.2 Indirect

Developments in computer technology and increases in computing power have had profound effects on the discipline of Atmospheric Science. Data can be collected for longer, and they can be collected, processed and transmitted to other locations more rapidly. In addition, higher resolution numerical models that incorporate urban effects, made operationally possible by more powerful computers, have driven the demand for more observational data.

Developments in communications mean data can now be transmitted from remote locations either as complete data sets or in summary form in real time. Obviously, this allows for improved quality of the data collection and reduction in data gaps, in addition to enhancing the utility of data for applied problems in situations when data are needed in real-time. These types of technological improvements have also allowed for higher level instruments, which collect vast quantities of data, to be deployed for longer time periods. Associated with the increase in the volume of data collected is an increase in the volume of data that needs to be archived. Fortunately there have been concurrent increases in data storage capabilities. However, long term archiving of data remains an issue that has not been adequately addressed and it critical to ensure that data sets are not lost and that data can be reprocessed as new methods and algorithms become available. Also, very large data sets (multi-gigabytes and larger) are not easily transported rapidly, so there is a need to ensure increased speed on data transfer ‘‘back-bones’’.

As noted above, remotely sensed data have become commonplace as the basis for the description and characterization of the nature of the urban surface, both in terms of materials and morphology. Geographic information systems (GIS) allow for the integration of such spatial data from a wide variety of sources. The combination of RS and more conventional aerial photographs have allowed the development of databases of land use change (Stefanov et al., 2001) which when used with long meteorological records have been used to study changes of urban climate (see, for example, the Brazel et al. (2000) study of Phoenix, and Baltimore). In addition, the widespread use of other geospatial technology, for example the geographical positioning systems (GPS), allows for spatial mapping of the location of surface attributes and the location of mobile sensors (Chapman et al., 2002). Digital time lapse photography of the surface also provides information on moisture and other surface properties (Offerle et al., 2003c).

One specific example of the advances that have resulted from the integration of these technologies is in the determination of sky view factors, a measure of canyon geometry related to maximum urban canopy layer air urban heat island intensity (Oke, 1981) and dewfall intensity (Richards and Oke, 2002). In the 1980s, the standard approach to quantify sky view factors involved processing photographs taken with standard SLR 35 mm cameras (Steyn, 1981; Johnson and Watson, 1984). This approach was both labor intensive and tedious. Advances have involved the application of video cameras (Steyn et al., 1986), scanning photographs (Blennow, 1995), application of GIS software (Holmer et al., 2001), use of digital cameras (Chapman et al., 2001; Grimmond et al., 2001), use of a Li-2000 (Grimmond et al., 2001), and GPS satellite reception detection (Chapman et al., 2002). The result is that now sky view factors can be measured and calculated quickly and integrated into studies of near surface temperatures (Svensson and Eliasson, 2002).

4. Instrument siting

Observation and measurement in urban climatology has been influenced by conceptual developments in boundary layer climatology (Arnfield, 2003). In particular, enhancements of our understanding of the roughness sub-layer, and the implications of surface heterogeneity and flux source areas, have had a significant influence on insight into the appropriate siting of sensors and interpretation of surface-atmosphere fluxes. While this has informed many research-level studies, unfortunately this understanding has yet to influence the location and operation of ‘‘standard’’ climate stations more generally.

Significant advances have occurred in the understanding of sensors, their fields of view/source areas, and thus the representativeness of urban climate measurements. The area influencing a measurement (the source area/field of view/footprint) is a function of the variable being observed, the method that is used in the measurement, the location of the instrument, the nature of the surface over which the observations are undertaken, and in some cases (for turbulent fluxes, for example) the meteorological conditions. With knowledge of the probable source area or footprint of the measurement it is possible to: describe the site characteristics of the measurements in detail (Grimmond and Souch, 1994; Grimmond and Oke, 1999a, b); determine if the measurements are representative of the area of interest (and/or biased) (Grimmond et al., 1998); sub-sample data by source area characteristics, and/or determine if there is sensor bias relative to the area of study (Schmid et al., 1991; Schmid, 1997).

For radiation sensors in simple environments the measurement source area is a simple function of geometry (Reifsnyder, 1967; Schmid et al., 1991). However, in urban settings this becomes complicated as the complex morphology of the surface has to be taken into account (Soux et al., 2004). To obtain representative local scale radiation measurements, for example in studies of the surface energy balance, instruments have to be located high enough above a surface to ensure that a representative number of repeatable units are included in the field of view of the instrument (Offerle et al., 2003a).

For determination of the source areas for turbulent concentrations (Schmid and Oke, 1990) and fluxes (Schmid, 1994), models have been developed which provide a probability filter that is a function of the atmospheric stability, wind speed and lateral dispersion, the roughness characteristics of the surface, and the height above the surface that the sensor is located. The source area location changes with wind direction: lying upwind of the measurement site. Schmid (2002) provides a recent review of the models that are available. Three dimensional turbulent footprint models for urban areas are still in the development stage (Kljun et al., 2002). The Schmid (1994, 1997) FSAM model, which considers only the planimetric source area, has been extensively used in urban areas to provide the probable source area location for turbulent fluxes (Grimmond et al., 1991; Grimmond and Oke, 1991, 1999a, b; Kanda et al., 2002; Moriwaki and Kanda, 2004).

The impact of roughness elements on urban wind fields is a topic that has received significant attention with implications for the siting of instruments. The distinction of three urban scales, which Oke (1984) provided formal definitions for, has undergone a number of refinements (Oke, 1997; Rotach et al., 2002; Piringer et al., 2002) based on increasing understanding of the effect of urban roughness elements perturbing flow (Fig. 1). Rotach (1999) notes that in urban areas, because of the large size of the roughness elements, the roughness sublayer (RSL) will be large and therefore the inertial surface layer (ISL) will be a shallower layer within the surface layer (Fig. 1). The height of the "blending layer" or the top of the RSL is a function of the size of the roughness elements and their spacing. Roth (2000) (his Table 2) summarizes a number of different methods for determining this. Kastner-Klein and Rotach (2004), based on wind tunnel observations, demonstrate the impact of sensor location on data collected and the scale or areal integration (see their Fig. 5). When sensors (z_S sensor height) are located close to the roughness elements (small z_S/z_H) the exact location of the sensor has a large impact on measured turbulence characteristics and mean wind. However, as the sensor is moved a greater distance above the height of the roughness elements (z_H) the results become less site specific. Thus, below about 2 z_H wind/turbulence measurements are representative of the micro-scale as the instruments are within the RSL, but above that height the instruments are within the ISL and can be considered to be representative of the local-scale (Grimmond and Oke, 1999b; Roth, 2000; Kastner-Klein and Rotach, 2004).

Spatial variability of fluxes occurs at all scales. Flux divergence will occur in both the horizontal and vertical for all fluxes. To reduce the impact of horizontal flux divergence, at the local scale, it is possible to select extensive areas that have common characteristics over which to conduct observations. However, the setting of a city, for example in complex terrain or near large water bodies, may result in meso-scale or regionally generated winds. To date these complexities have been studied primarily at the meso-scale (Doran et al., 2002; Cros et al., 2004). At the micro-scale, the complex mixture of land cover types (e.g. vegetation next to asphalt or concrete) means that there are almost always strong micro-scale advective fluxes (Spronken-Smith et al., 2000). In the vertical there can be strong radiative flux divergence, especially of long-wave radiation because of the increased presence of aerosols in the urban atmosphere. At night-time, when mixing is likely to be less, there can be large vertical differences in concentration of aerosols and atmospheric moisture, which combined with radiative cooling of intensively heated surfaces (such as roofs) as well as canyons and vegetation, may led to complex radiative patterns (Oke and Fuggle, 1972; Nunez et al., 2000).

Advances in understanding instruments and what they are measuring coupled with conceptual advances in the understanding of the urban atmosphere have greatly informed urban climate measurement. Nowhere is this more evident than in investigations of the urban heat island, although confusion still remains in some studies about the urban heat island that has actually been measured, resulting in apparently contradictory results. Oke (1976) presented a distinction between air temperature urban heat islands in the urban boundary layer and those of the urban canopy layer. Ground-based thermal remote sensing and aircraft based thermography at low enough elevation to resolve streets, roofs and walls permit definition of yet another urban heat island, namely that for the ground surface. Oke (1995) provides a framework for understanding the different urban heat islands (air versus ground; urban canopy layer versus boundary layer) that are observed by locating instruments at different positions within the atmosphere above the surface, and with sensors of different capabilities. Thermal remote sensing from satellite and high altitude aircraft raise even more issues. Voogt and Oke (1997, 1998a, b; 2003) have documented the importance of view angles and the effects of anisotropy due to differential patterns of irradiated and shaded surfaces.

5. Future considerations

Given the ever increasing number of urban inhabitants globally, and the recognition of the profound effects of cities on the atmosphere (both within and beyond urban limits), more and more attention is being direct to the observation of urban climates. Increasingly urban based observational programs are collaborative, multi-institutional, multi-national, interdisciplinary initiatives which study urban climate processes at multiple scales, integrating data from tower based instruments and remote sensing (ground, air- and space-borne) platforms. Observations have developed from descriptions of the urban atmosphere to more process oriented studies of fundamental energy, mass and momentum exchanges. Technological improvements in meteorological instruments, remote sensing and computing capacity, and new insight in terms of instrument response and sensor placement, have had profound effects on the urban climate data collected and its accuracy.

However, in many regards urban climate studies remain very much in their infancy, and much remains to be learnt about the processes occurring within the urban atmosphere and the fundamental controls on urban climates. It is clear that we need to enhance our observational capacity from both a research and routine perspective; see, for example, the papers by Dabberdt et al. (2004) focused on the United States, and Fisher et al. (2001) and Rotach et al. (2002) focused on Europe. More data need to be collected, for longer-periods of time, with more careful attention directed to the challenges of measuring in the urban environment (WMO, 2004). Moreover, data need to be collected in a broader range of cities, particularly in tropical environments, and in cities with different building materials and morphology. Specific attention needs to be directed to the influence of advection at multiple scales, which results from the complex terrain in which cities are located, the mix of land uses across a city, and the variations of land cover within a land use. In addition, data need to be collected over long periods, so temporal variability in processes and effects can be analyzed more fully.

Urban climatologists have gathered vast amounts of data. These data need to be adequately described and archived. More effort needs to be directed to developing inventories of projects that have taken place in formats/locations that are easily accessible. Relevant metadata must be included related to the objectives of the projects, the methods used, specifics of instrumentation and its installation, details of data analysis,

Table 7. Characterisitics of a site to report based on those suggested by Rotach et al. (2002), Offerle et al. (2006), and WMO (2004)

Parameter	Comments
Measurement height	
Mean building height (z_H) and tree height (z_T)	
Mean tree height	
Zero-plane displacement	Indicate method(s) used to obtain
Roughness length for momentum	Indicate method(s) used to obtain
Surface fractions (buildings, other impervious, vegetation)	Give date of coverage analysis (e.g. date of photographs or RS imagery)
Canyon aspect ratio (z_H/W)	
Urban Terrain Classification	Ellefsen (1991) or WMO (2004)
Aerial Photograph or High Resolution RS imagery	

site descriptions, and contacts for further information. In addition, it is essential that data are preserved. The METROMEX study occurred more than 25 years ago. That data set potentially provides an excellent baseline for a subsequent study to document the effects of urban change. Other groups in the Atmospheric Science/Global Change community are archiving data to facilitate comparisons and studies with broader objectives, see for example the FLUXNET community. Urban climatologists need to make this a priority.

Also, we need to be more vigilant about reporting all the appropriate data when observational programs are described in presentations and publications, so that meaningful cross-site comparisons can be conducted. In recent attempts to review and synthesize aspects of the urban climate observational literature, both Grimmond and Oke (1999b) and Roth (2000) found numerous studies that could not be used because insufficient details had been reported in publications. This is a responsibility that falls to both authors of the work and reviewers of the literature. A suggestion of the minimum information that should be included when describing a site is reported in Table 7. Given the rapid rates many cities are changing around the world, archiving land cover descriptions as well as atmospheric data is essential.

Given the increasing attention on urban environments, as a community we need to ensure that as researchers new to the urban field become engaged in urban climate research they learn from our past mistakes and do not repeat them. Critical is the appreciation of scale and the appropriate siting of instrumentation. For example, measurements of carbon dioxide concentrations taken on busy roads should not be contoured to be representative of the whole urban region. The urban climate community also needs to engage with others; for example, extensive insight into micrometeorology can be derived from the AmeriFlux and FLUXNET community (Baldocchi et al., 2001).

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Author's address: C. S. B. Grimmond (e-mail: grimmon@indiana.edu), Atmospheric Science Program, Department of Geography, Indiana University, Bloomington, IN, 47405, USA.