Urban Energy Fluxes in Built-Up Downtown Areas and Variations across the Urban Area, for Use in Dispersion Models

Citation	Hanna, Steven, Edson Marciotto, and Rex Britter. "Urban Energy Fluxes in Built-Up Downtown Areas and Variations across the Urban Area, for Use in Dispersion Models." Journal of Applied Meteorology and Climatology 50 (2011): 1341-1353. Web. 1 Dec. 2011. © 2011 American Meteorological Society
As Published	http://dx.doi.org/10.1175/2011jamc2555.1
Publisher	American Meteorological Society
Version	Final published version
Citable link	http://hdl.handle.net/1721.1/67345
Terms of Use	Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.

Urban Energy Fluxes in Built-Up Downtown Areas and Variations across the Urban Area, for Use in Dispersion Models

STEVEN HANNA AND EDSON MARCIOTTO

Harvard School of Public Health, Boston, Massachusetts

REX BRITTER

Massachusetts Institute of Technology, Cambridge, Massachusetts

(Manuscript received 12 May 2010, in final form 9 February 2011)

ABSTRACT

Surface energy fluxes, at averaging times from 10 min to 1 h, are needed as inputs to most state-of-the-art dispersion models. The sensible heat flux is a major priority, because it is combined with the momentum flux to estimate the stability, the wind profile, and the turbulence intensities. Because of recent concerns about dispersion in built-up downtown areas of large cities, there is a need to estimate sensible heat flux in the midst of tall buildings. In this paper, the authors work with some high-quality and relevant but arguably underutilized data. The results of analysis of urban heat flux components from 10 locations in suburban and built-up downtown areas in Oklahoma City, Oklahoma, during the Joint Urban 2003 (JU2003) field experiment are presented here. At street level in the downtown area, in the midst of tall skyscrapers, the ground heat flux and the sensible heat flux are relatively large and the latent heat flux is relatively small when compared with concurrent fluxes observed in the upwind suburban areas. In confirmation of measurements in other cities, the sensible heat flux in the downtown area is observed to be slightly positive (10–20 W m^{-2}) at night, indicating nearly neutral or slightly unstable conditions. Also in agreement with observations in other cities is that the ground heat flux in the downtown area has a magnitude that is 3 or 4 times that in suburban or rural areas. These results should permit improved parameterizations of sensible heat fluxes in the urban downtown area with tall buildings.

1. Introduction and background

This study was spurred by the need to better understand diurnal variations of urban thermal energy fluxes near the surface in built-up downtown areas of large cities with tall skyscrapers of heights of 100 m and greater. Most of the previous research on urban thermal energy fluxes [see reviews by Arnfield (2003) and Masson (2006) and the model intercomparison study by Grimmond et al. (2010)] has focused on suburban areas or urban areas with buildings of no taller than a few stories and has not addressed thermal energy fluxes in the midst of downtown skyscrapers. Martilli et al. (2002) and Kondo et al. (2005) describe multilayer approaches to model energy fluxes in downtown urban areas, but these have not been fully tested in downtown areas with tall skyscrapers. The energy flux information is needed to estimate hourly averages of winds, turbulence, and stability for input to transport and dispersion models that are being increasingly used in urban areas. The atmosphere has large turbulence intensities and has nearly neutral stability in an area with many tall skyscrapers because of the large amount of mechanical mixing generated by the buildings, the contributions of anthropogenic heat sources, and the large capacity for storing solar energy that is possessed by materials that are used in streets and buildings (Hanna et al. 2007; Hanna and Zhou 2009).

Britter and Hanna (2003) review the needs of urban dispersion models in terms of meteorological inputs. The American Meteorological Society–U.S. Environmental Protection Agency (EPA) Regulatory Model Improvement Committee Model (AERMOD; Cimorelli et al. 2004, 2005) and the U.S. Department of Defense Second-Order Closure Integrated Puff (SCIPUFF; Sykes et al. 2007) dispersion models are good examples of models with state-of-the-art meteorological boundary

---

Corresponding author address: Steven Hanna, 7 Crescent Ave., Kennebunkport, ME 04046-7235.
E-mail: hannaconsult@roadrunner.com

DOI: 10.1175/2011JAMC2555.1

layer preprocessors for all types of land use, including urban areas. These are partly based on the meteorological processor developed by Hanna et al. (1985) for the Offshore and Coastal Diffusion model and by Hanna and Paine (1989) for rural terrain for the Hybrid Plume Dispersion Model (HPDM). Using extensive boundary layer observations in urban field experiments in St. Louis, Missouri, and Indianapolis, Indiana, Hanna and Chang (1992) expanded the HPDM meteorological preprocessor to account for urban terrain. Those field experiments were mainly concerned with the suburbs and the commercial/residential areas, however, with less focus on the city center with its skyscrapers.

The prime boundary layer meteorological parameters of use to dispersion models are the surface momentum flux and the sensible heat flux Q_H (positive upward). Once these fluxes are known, other key variables, such as wind speeds and turbulence intensities, can be estimated using basic boundary layer formulas, including those based on Monin–Obukhov (MO) similarity theory. Because measurements are seldom available for Q_H, it usually has to be estimated from other more routinely observed variables. Routinely available [e.g., National Weather Service (NWS)] meteorological observations are likely to include only basic variables such as wind speed at some reference height z_{ref} plus observations of weather conditions such as cloud type and sky coverage and elevation for each major cloud layer. The land-use category is available in standard files used by NWS forecast models. In some cases, the mean building height H in urban areas is known.

Most dispersion-model meteorological preprocessors use the methods originally suggested by Holtslag and VanUlden (1983) and Beljaars and Holtslag (1991) for approximating Q_H, which are based on assumptions about the energy balance formula for rural areas:

$$Q_H = Q^* - Q_E - Q_G, \tag{1}$$

where Q^* is the net radiation flux (positive downward), Q_E is the latent heat flux (positive upward), and Q_G is the ground heat flux (positive downward), all in watts per meter squared. The averaging time required for meteorological inputs to U.S. EPA dispersion-model applications is nearly always 1 h, although Eq. (1) and other boundary layer formulas are valid for smaller and larger averaging times, ranging from about 10 min to 2 or 3 h. Equation (1) applies to a thin (1–2 m) layer of air just adjacent to the ground. The fluxes Q^*, Q_H, and Q_E are usually observed at slightly different elevations within a few meters of the surface, and Q_G is observed a few centimeters below the surface of the soil.

Flux Q^* is estimated/parameterized in the above method using knowledge of the solar energy flux at the given latitude and time of day, the albedo (from the tables of values for various land-use categories), and the cloud fraction N (from NWS observations). Note that a single number for N must be determined from the information about multiple cloud layers in the routine NWS weather information. Flux Q_E is assumed to be a multiple of Q_H, usually on the basis of one of two alternate approaches: 1) tables of Bowen ratio for various land-use categories, or 2) tables of ''ground moisture availability'' for various land-use categories plus information on latest rain period. Flux Q_G is assumed to be a multiple of Q^*, again based on land use. Because Holtslag and VanUlden are from the Netherlands, many of their parameterizations were for that country's typical meteorological and land-use conditions. The meteorological preprocessors for AERMOD and SCIPUFF have made these parameterizations more general and applicable to conditions ranging from deserts or paved surfaces to wet irrigated soil. Given the Q_H estimate, the observed wind speed, and estimates of surface roughness length (again, as a function of land use), the MO similarity formulas for wind speed profiles are solved iteratively in the dispersion models' meteorological preprocessors to estimate the friction velocity u_*. The iteration method is needed because the MO length L is a function of both Q_H and u_*. The mixing depth z_i can be calculated [e.g., see Batchvarova and Gryning (1991) and Seibert et al. (2000)] along with all of the needed profiles for use by the dispersion model. Despite all of the approximations, the dispersion model predictions (and the u_* and Q_H predictions) agree fairly well with observations in rural field experiments (e.g., Hanna and Paine 1989; Cimorelli et al. 2005).

Hanna and Chang (1992) modified the above method for urban areas and tested the u_* and Q_H estimates and dispersion model concentration estimates with observations from urban field experiments. At first, they intended to include approximations for the anthropogenic heat flux Q_F but found that the 10–50 W m^{-2} values of Q_F suggested by other authors were causing the nighttime stability to shift to very unstable conditions much of the time, especially during light winds. This is not a reasonable result for a dispersion model, because it would lead to relatively large rates of dispersion at night when light winds occurred. As a consequence, Hanna and Chang (1992) rationalized that, instead, a minimum limit of $3H$ should be placed on the absolute value of the MO length L, whose magnitude is assumed to represent the approximate height to which mechanically generated turbulence dominates in the surface layer. This approach in which a minimum L is used was found to prevent extremely unstable conditions from occurring in cities at night. The AERMOD meteorological preprocessor uses a slightly different method to account for the tendency toward neutral conditions in urban areas.

Grimmond and Oke (1999, 2002) used extensive urban observations that they had collected or acquired and theoretical analyses to further modify and improve on the methods suggested by Hanna and Chang (1992). The resulting method is called the Local-Scale Urban Meteorological Parameterization Scheme (LUMPS). The research by Grimmond and Oke was related more to using the LUMPS method to provide inputs to urban climate and mesoscale meteorological models than to using it to provide inputs for dispersion models. They updated some of the parameterizations, such as the method of estimating the ratio Q_G/Q^*. They defined a layer encompassing the urban canopy layer and the ground, and accounted for the observed diurnal variations of the storage flux ΔQ_S, which does not necessarily follow the shape or timing of the diurnal variations of the net radiation flux. The quantity ΔQ_S is intended to represent the heat storage as indicated by time variation of temperatures in the air and the ground and buildings. In analyses of field experiments, however, ΔQ_S sometimes also includes "other unmeasured terms" such as Q_F and the advective flux Q_A. The Grimmond and Oke (1999, 2002) Objective Hysteresis Model provides better estimates of ΔQ_S as a function of time of day and Q^*, accounting for the release of heat from the ground in the evening after sundown and the absorption of heat by the ground after sunup. Their papers contain the results of successful comparisons of the LUMPS estimates of fluxes with observations from many cities, although the urban dataset did not include downtown areas with skyscrapers.

The above discussions and derivations of methods in meteorological preprocessors for dispersion models assume that a flux measurement is taken in an area that is horizontally homogeneous and that it is representative of the surrounding area. The underlying surface is seldom homogeneous, however, especially in urban areas. Two key related questions in the study of all boundary layers are 1) What is the upwind area that influences the measurements at a certain reference height z_{ref} on a meteorological tower? and 2) How large does an upwind area have to be to cause significant changes in the measurements at the height z_{ref}? Horst and Weil (1992), Schmid (1994), and Horst (1999) review the theory and the available observations and suggest approaches that are fairly consistent. Their derivations are based on an analogy with the rate of vertical dispersion of a passive scalar released from a surface area source. Thus, for stable conditions, the upwind area of influence extends farther than the area for unstable conditions. For example, the above references would suggest that, for a measurement height of 5 m, an approximate upwind area of influence in suburban surroundings would extend about 25 m in unstable conditions, 50 m in neutral conditions, and 100 m in stable conditions.

The technical documents and users' guides for the meteorological parameterization schemes for dispersion models seldom contain specific guidance about the spatial scales to which the boundary layer parameterizations apply. It is implied that the spatial scale is the distance over which the plume traverses and where sampling occurs and that the boundary layer should be "reasonably homogeneous" over that distance, which is at most a few kilometers in recent urban field experiments involving tracers. This implication has been interpreted liberally in practice, and the same urban boundary layer parameterizations are used, for example, for simulating dispersion across a 6-km domain during the Joint Urban 2003 (JU2003) tracer experiments in Oklahoma City, Oklahoma, even though the plume may begin in the midst of skyscrapers and eventually be transported over mixed commercial/residential neighborhoods (Allwine et al. 2004; Hanna et al. 2007).

The current paper analyzes observations of urban heat flux components from 11 sites during JU2003. These sites include several in the built-up downtown area, in the midst of skyscrapers.

2. General characteristics of the components of the urban heat budget observed in field experiments

In all of the full-scale or small-scale experiments that involve urban energy flux observations, only a subset of the significant components are observed. The most frequent situation is that Q^* is observed, often broken down into direct and diffuse solar (shortwave) energy fluxes and net longwave flux. The sensible heat flux Q_H is next in frequency of observation. In many boundary layer studies that use sonic anemometers, Q_H is observed and not Q^* because Q_H can be calculated using the fast-response observations of temperature and vertical wind speed. During the JU2003 field experiment, there were 10–20 energy flux measuring sites and over 100 sonic anemometer sites. Next in line in frequency of observation is Q_E, which can be calculated using sonic anemometer observations of vertical velocity fluctuations and fast-response hygrometers. The sonic anemometers can also measure the horizontal fluxes of latent heat, which can be important in places with areas of irrigated vegetation interspersed with dry areas consisting of streets, buildings, and parking lots.

The soil heat flux Q_G is observed at many sites. Because the diurnal soil heat flux curve damps out with increasing depth to a magnitude that is smaller by a factor of about 100 at a depth of about 0.5 m than that at the ground surface, it is customary to use a soil heat flux plate at a depth of a few centimeters. Sometimes there are two or more soil heat plates at different depths, as well as temperature measurements. This system is fairly easy to install with a shovel in areas with soil or gravel but is obviously much more difficult to install in paved areas or on buildings. Gouveia et al. (2004) measured the heat flux in a paved Oklahoma City street (during JU2003) by forcing a heat flux plate into a crack at one location and by pouring concrete around it in another location. The anthropogenic heat flux Q_F has never been measured in a comprehensive way, because there are so many components and because they vary in space and time. There have been approximate citywide estimates based on total energy usage, and there have been specific intensive studies of a few individual buildings. There are also multiple minor sources such as motor vehicles. At a given time, this component obviously varies much with space and depends on spatial averaging; Q_F is reported to have a typical average value of about 10–100 W m^{-2}. This energy is injected into the urban boundary layer at a variety of heights. Some investigators (e.g., Grimmond and Oke 2002) assume that Q_F is already included in other observed energy fluxes such as Q^* and Q_H and therefore does not need to be separately accounted for.

The so-called advective term Q_A might be more appropriately called the ''flux divergence'' term and could be calculated from knowledge of the horizontal energy flux across each face of a grid volume. This is very difficult to measure because of the need to observe an area integral of the energy flux. Of course, this term is directly available as a prediction by an NWP mesoscale meteorological model but is likely to be smoothed out because that type of model parameterizes subgrid effects and attempts to reduce convergences and divergences.

There are other energy fluxes that are sometimes included, such as the contribution from rainwater, which is usually cooler than the urban air and surface.

Last, when a vertical layer is being considered, the stored energy flux ΔQ_S is calculated as the imbalance of the other observed energy flux terms. It is not possible to directly measure this component with current observing systems. The materials that are involved in storing energy and that are warmed or cooled include air, soil, structures, vegetation, and all other objects in the layer or control volume. In some cases, such as heated or cooled buildings, there is a feedback mechanism operating, in which a tendency toward warming the building is countered by the building's heating and air conditioning system, which is attempting to maintain the internal temperature at the thermostat setting. Because there is a large diurnal swing in air temperature and soil and building skin temperature, it is obvious that the stored energy flux is not often zero; ΔQ_S typically varies from about +200 or 300 W m^{-2} on clear summer mornings to about −100 W m^{-2} on clear nights. The diurnal curve of ΔQ_S is often shifted in time (delayed by as much as a few hours) with respect to the diurnal curve of net radiation Q^* (this hysteresis effect being a direct outcome of the underlying fundamental equations).

As expected, the observed warming rate of the materials in the control volume is consistent with these ΔQ_S values. In fact, about the same fractions of ΔQ_S go into air warming and soil warming (the specific heats are about the same, and, even though the vertical thicknesses are different by a factor of approximately 1000, this difference is countered by the factor-of-approximately-1000 difference in densities).

The residual flux Q_R is defined in practice as what is left when the observed heat fluxes are subtracted from the observed net radiation flux. Note that this residual energy flux is not necessarily equal to ΔQ_S and could be very different (by hundreds of watts per meter squared). Therefore one must be careful with interpretations of Q_R. Nevertheless, Q_R and ΔQ_S are often treated the same and are interchangeable in some references and in some reported urban observations.

3. Overview of the JU2003 field experiment and its energy flux observations

Many excellent new urban meteorological databases from cities across the globe are available, and several of these are used in the model intercomparison by Grimmond et al. (2010). Observations are also available from scaled urban experiments (e.g., Pearlmutter et al. 2005). The current paper focuses on a set of energy flux observations from the Oklahoma City JU2003 field experiment. These observations are unique because there were several energy flux sites in the downtown area with nearby buildings exceeding 100 m in height.

a. *General description of JU2003*

A comprehensive description of the JU2003 field experiment is given by Allwine et al. (2004) and Allwine and Flaherty (2006). Although the JU2003 focus was on dispersion experiments using tracer gases released near street level in the built-up downtown area, there was a large network of supporting meteorological observing systems, employing hundreds of in situ and remote instruments. The JU2003 suburban/urban domain, with dimension of about 10 km, contains mostly suburban and commercial land use. The downtown inner domain, with dimensions of 1 or 2 km, contains numerous skyscrapers with heights exceeding 100 m. The downtown area was covered by many sonic anemometers near street level and by several surface heat flux observing systems operated by three organizations, in addition to having many sonic anemometers at rooftop and several attempts to measure vertical profiles using remote sounding devices and short towers. The 10-km domain also had several energy flux towers operated by different organizations, including Indiana University (IU) and the Army Research Laboratory. Grimmond et al. (2004) and Gouveia et al. (2004) describe the highlights of their own surface energy flux studies. There is not a journal article or a detailed report with a comprehensive analysis of all of the organizations' energy flux measurement results, however.

Most of the energy flux observations and associated reports from JU2003 that have been used in this paper were obtained from the data archive maintained at Dugway Proving Ground (DPG). In some cases, the heat flux data were not in the official data archive, and so we contacted the investigators directly to obtain those data or to resolve questions about units, signs of fluxes, and so on. The energy flux sites whose observations are analyzed below were six operated by IU (Grimmond et al. 2004), three operated by the Atmospheric Turbulence and Diffusion Division of the National Oceanic and Atmospheric Administration Air Resources Laboratory (ATDD; Hosker 2003), one operated by Arizona State University (ASU; Holeman et al. 2004), and one operated by the Lawrence Livermore National Laboratory (LLNL; Gouveia et al. 2004). The current authors were not directly involved in obtaining any of these observations or in producing the time-averaged values analyzed in this paper.

Figure 1 is a Google (Inc.) Earth view of the central downtown area of Oklahoma City and shows the locations of the five downtown energy flux sites (ATDD A, ATDD B, ATDD C, ASU, and LLNL). Six additional energy flux sites [a grass site (GRS), a moister grassy area (GRT), Tyler Media tower sites A and B (TMA and TMB), Wood House tower (WH), and Brick House tower (BH)] were in a suburban area about 6 km to the south (upwind) of the downtown area. Some details of the sites are given below.

b. IU suburban sites

The objective of the IU JU2003 field study was to investigate the spatial variability of energy flux components observed over slightly different surfaces in a typical suburban neighborhood of dimension 1 or 2 km (Grimmond et al. 2004; Allwine et al. 2004). The neighborhood consisted of a mixture of one- and two-story houses, lawns and trees, schools, and fields.

The 29-m BH had heat flux instruments at its top and was located in a small field about 35 m downwind of an area of brick houses with irrigated lawns and trees. The 18-m WH was located downwind of a subdivision of wood houses with irrigated lawns. The heat flux instruments at a height of 3 m at GRS were located in an unirrigated school athletic field. The instruments were moved halfway through the field experiment to the moister GRT. Sites TMA and TMB consisted of heat flux instruments mounted at the 80- and 40-m levels, respectively, on the Tyler Media tower, which was located in a field about 50 m downwind of a subdivision. The 10-Hz raw data from the IU sites were block averaged over 1 h by Grimmond et al. (2004), where the listed time indicates the end of the hour. The total period of measurement was approximately 1 month, although data are not available for all days. A further complication is that not all experiment days had data from all instruments.

Fluxes Q^* and Q_H were observed at all IU sites. Fluxes Q_E and Q_G were observed at a few sites. Two sites (GRS and GRT) measured all four heat fluxes.

Because the observing heights ranged from 3 to 80 m at the six IU sites, there was a range of upwind areas that affected the various measurements. For example, the TMA instrument at a height of 80 m would be influenced by the surface at distances out to approximately several hundred meters. In contrast, the instruments at GRS and GRT, at a height of 3 m, would be influenced by the surface only out to approximately a few tens of meters. These differences could be more carefully investigated, but we have lumped the various sites together in the current analysis. It is technically difficult, if not impossible, to match these areas between very different landscapes.

c. ATDD sites

The three ATDD sites, all at an elevation of 5 m, were in the downtown commercial and industrial area of the city. Hosker (2003) describes the ATDD heat flux observations in the following way:

> Three surface energy balance/flux tower systems were set up by ATDD to measure the heat and energy fluxes and associated turbulence over surfaces that were typical of Oklahoma City. Site A (Fred Jones parking lot) was located in a dirt and gravel parking lot area just west of the central business district (CBD). Site B (Oklahoma School for Science and Mathematics) was located in an irrigated grass area northeast of the CBD. Site C (Galleria Parking Garage) was located on the top level of a large multi-level concrete parking garage at the SW corner of the CBD. Site C was chosen to represent the built-up CBD, and was selected over other candidate sites because it had the most open fetch (i.e., it was not overly obstructed by adjacent large buildings).

FIG. 1. Downtown Oklahoma City, showing locations of ATDD, ASU, and LLNL sites (copyright Google, Inc.; the authors added the 1-km scale line and the five squares that mark the site locations).

Later, R. Hosker (2009, personal communication) gave more information on the last phrase in his quote. He indicated that there was no potential site in the downtown built-up area that could be considered truly representative, and so they chose a site that had minimal obstructions.

The ATDD data are stored on the DPG JU2003 data archive as half-hour averages. We calculated hourly averages for analysis in this paper. The measurements include Q^*, wind speed, air temperature and humidity, surface temperature, incoming solar radiation, and precipitation. Fluxes of Q_H, Q_E, and momentum were measured, as were the turbulent speed components. Data recovery rates for sites ATDD A and C were high for all parameters measured (over 95%). Data recovery rates at ATDD B were no more than 70% for most variables. We estimated the characteristics of the local land use for the downtown sites, using Google Earth to produce views of areas of approximately 400 m by 500 m around each site.

The dirt parking lot that surrounds ATDD A has dimensions of approximately 50 m in the east–west direction and 100 m in the north–south direction. ATDD A is in the middle of an area consisting of a mixture of parking lots and large flat warehouses, extending more than 200 m in all directions. There are minimal areas of lawn. Thus the entire area within 200 m of the energy flux instrument could be considered to be a dry urban surface.

The ATDD B site is located on a large (500 m × 500 m) school campus, with over 90% of the coverage being lawns and with five medium-sized buildings scattered over the tract. The instrument is in the middle of a large lawn, of size 200 m by 200 m, with a 300-m upwind fetch (to the south) over additional lawns, which were irrigated every night from about 2300 to 0700 local time (LT). The extensive use of irrigation in the area around the flux site suggests that relatively large latent heat fluxes are likely to be observed, and that was found to be true.

The ATDD C site is on the top level of a parking garage of size 100 m by 150 m, about 15 m above the surrounding street level. The top level is fairly flat, with only the usual one-story stairwell openings and with no tall buildings upwind (to the south) of the parking garage structure. There is a large surface parking area surrounding the garage, resulting in the whole parking complex covering about 200 m by 200 m. The upwind fetch (to the south) is over the parking area for about 150 m. South of the parking area is the arboretum area of size 300 m by 300 m, with lawns and trees. A 140-m-tall building is about 100 m northeast of the site. It is expected that ground heat fluxes will be relatively large and latent heat fluxes will be relatively small at the ATDD C site because of the presence of anthropogenic materials (parking lots and buildings) around the site.

The Q_G observations at site ATDD A showed unrealistically large values at night (e.g., ~400 W m^{-2}); therefore those data were not included in the analysis in this paper. Other flux measurements at site ATDD A appear to be fine. We did not include the site ATDD B flux observations in most of the current analysis, because of the very large values of Q_E (often 400–900 W m^{-2}) that are due to the irrigation. Site ATDD C has reasonable values for all energy flux components.

d. ASU site

The ASU energy flux site was located in a commercial area about 1 km to the north-northeast of the tall buildings in the CBD (see Fig. 1). The Google Earth view suggests that this site is in the middle of a dry lawn/field of dimension 100 m in the west–east direction and 50 m in the north–south direction. Within 200 m in all directions is a mixture of open areas (fields or dirt or paved) and low, flat warehouses (less than 10 m high) or manufacturing buildings. The tower was instrumented with a Kipp and Zonen, Inc., net radiometer at 9.2 m, cup anemometers at 1.5 and 8.9 m, thermistors at 1.1 and 8.3 m, an IR thermometer, an upward-facing pyranometer and downward-facing pyrgeometer at 3.5 m, and a 3D sonic anemometer (Campbell Scientific, Inc.) and a krypton hydrometer at 2.5 m. In the soil, there was a soil heat flux plate (6.5 cm below ground level) together with five thermistors (at 2, 3, 4, 5, and 8 cm below ground level) and a soil water content reflectometer (added halfway through the experiment). Data from the net radiometer, cup anemometers, thermistors, pyranometer, pyrgeometer, and soil heat flux plate are stored in the JU2003 data archive as 5-min averages. Data from the IR thermometer, sonic anemometer, krypton hydrometer, and soil water content reflectometer are stored as 1-min averages. For our analysis in this paper, all data were converted to hourly averages.

e. LLNL site

The LLNL heat flux observations are described by Gouveia et al. (2004). The data are not in the JU2003 data archive at DPG, and so the hourly averaged points plotted in this paper were estimated by eye from the figures in Gouveia et al. The LLNL site (shown in Fig. 3, described below) was in an urban street canyon, Park Avenue, which was the focus of other intensive observations described by Allwine and Flaherty (2006). Park Avenue is oriented from west to east in the midst of the group of tallest buildings in the CBD, with several 100–150-m buildings nearby. Buildings and pavement extend 200 m in all directions, leading to expectations that the latent heat flux will be relatively low and the ground heat flux magnitude will be relatively large. Flux Q^* was measured at a height of 4 m. Flux Q_G was measured by two soil heat flux plates located under concrete or pavement. One had 1.5 cm of concrete poured over it in the base constructed for one of the measurement towers, and the other was forced into a crack in the road surface at a depth of about 10 cm. There were two towers on either side of the street, and each tower held five anemometers at heights ranging from 1.5 to 15 m. There were also several infrared thermometers that measured temperatures of the exterior walls of nearby buildings, but we have not analyzed those observations.

4. Analysis of JU2003 energy fluxes

The main goal of the analysis is to use the unique observations of the energy flux components in downtown Oklahoma City to infer some fundamental relations, such as the differences in the ratios Q_H/Q^* and Q_G/Q^* between the suburban sites and the downtown sites. These results should aid in the development of improved parameterizations for use in operational meteorological preprocessors for dispersion models in these areas. We are especially interested in the Q_H observations at the five JU2003 heat flux sites in the downtown area shown in Fig. 1.

In the following figures, the flux observations are presented as diurnal variations of hourly averages. Time is expressed as LT, which in this case is central daylight time (CDT). Each hourly averaged value in the plots is itself an average over the several weeks of observations from that site. The standard deviation of variations of individual flux components over the total number of days is typically about 10–20 W m^{-2} or 10% of the averaged value, whichever is larger.

We justify our averaging of the diurnal curves over several weeks by the fact that meteorological conditions were relatively consistent during the JU2003 field experiment period. Conditions were hot and dry with infrequent clouds and rain. As is typical of Oklahoma, winds were usually out of the south with moderate speeds. Because there were a few days that did have periods of clouds, we investigated differences in the solar energy fluxes for all days. It is found that even for the days in the record with the smallest total solar energy flux (a reduction of about 30% from clear days), conditions were only partly cloudy. This is evident from the spiky characteristics of the solar energy record. There were no days that were persistently overcast.

a. *Diurnal variations of heat fluxes from individual sites*

The results for the IU suburban sites have been summarized by Grimmond et al. (2004), who noted that measured Q_H varied by about 20% or more across the six sites located over different patches of suburban land surfaces. Our analysis of the diurnal flux variations at these sites suggests that there are many similarities in the diurnal patterns and magnitudes of the IU flux observations. We found that none of the sites had diurnal flux curves that appeared to be a major departure from those at the other sites.

The GRS site is typical of the IU sites. Flux Q^* has a nighttime value of -50 W m^{-2} and a daytime value of about 450 W m^{-2}, peaking at about 1500 LT. Flux Q_H has a minimum of about -30 W m^{-2} at night and a maximum of about 180 W m^{-2} at about 1600 LT. Flux Q_G is slightly negative (about -10 W m^{-2}) at night and peaks during the day at about 30 W m^{-2} at about 1600 LT. Note that the ratio of peak Q_G to peak Q^* at midday is about 0.05–0.10, which is close to that parameterized in the Holtslag and VanUlden (1983) scheme widely used in meteorological preprocessors for dispersion models (see Hanna and Chang 1992). Flux Q_E is nearly zero at night and peaks at about 170 W m^{-2} at about 1300–1700 LT (the same time as Q_H). The Bowen ratio is about unity for the IU sites, which would be unexpected for a dry summer month, except that there is much lawn irrigation in the area, as well as some crop irrigation in upwind rural areas.

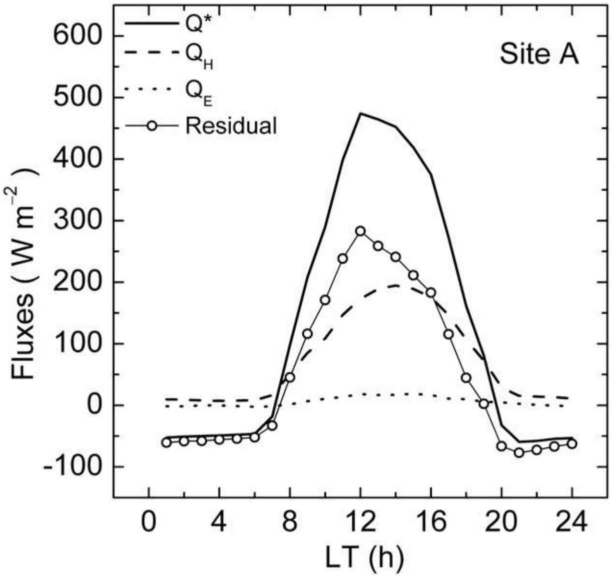

FIG. 2. Diurnal variation of energy fluxes at ATDD site A, located in a dirt parking lot on the west edge of the built-up downtown area. In this and in subsequent figures, LT is CDT.

The diurnal plots of energy fluxes for "downtown" sites ATDD A and C are shown in Figs. 2 and 3. Recall that site ATDD A is a dirt/gravel parking lot just west of the area of tall buildings, and site ATDD C is on the top level of a large parking garage, with tall buildings to the northeast. Because of the dry fetches extending 200 m or more upwind (i.e., to the south), sites ATDD A and C

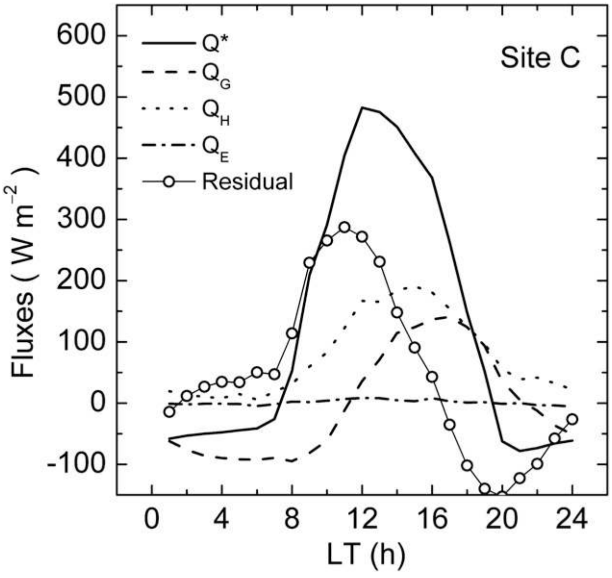

FIG. 3. Diurnal variation of energy fluxes at ATDD site C, located on the top level of a parking garage in the built-up downtown area.

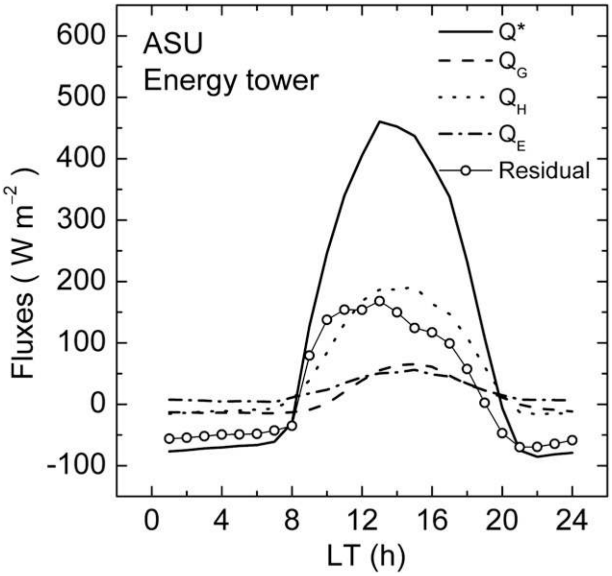

FIG. 4. Diurnal variation of energy fluxes at the ASU site, located about 1 km downwind of the built-up downtown area.

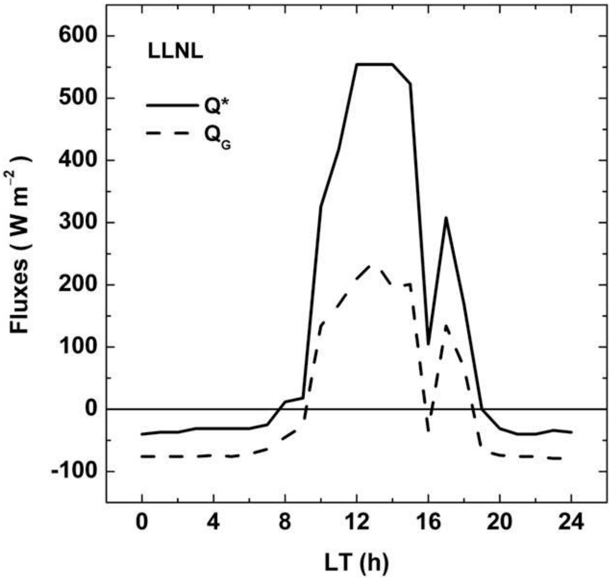

FIG. 5. Diurnal variation of energy fluxes at the LLNL site, located in the street canyon of Park Ave., in the built-up downtown area.

have relatively small Q_E, with magnitudes of less than 10 or 20 W m^{-2} (as compared with 170 W m^{-2} at the IU sites). Both sites indicate upward positive Q_H at night with a magnitude of about 10 W m^{-2} (as compared with -30 W m^{-2} at the IU suburban sites). Hanna et al. (2007) reported that most of the sonic anemometer observations at 10 additional downtown JU2003 sites during the night indicated small positive Q_H. Similar small upward Q_H values were observed at night in the borough of Manhattan, New York (Hanna and Zhou 2009). This suggests nearly neutral stabilities at night, confirming the urban boundary layer parameterizations by Hanna and Chang (1992). Site ATDD C also has a large Q_G, varying from -100 W m^{-2} at night to $+140$ W m^{-2} during the day (peaking at 1600 LT) (as compared with -10 and $+30$ W m^{-2}, respectively, at the IU sites). The nighttime value is slightly larger than Q^*, and the daytime value suggests a ratio of Q_G/Q^* of about 0.4, much larger than the rural/suburban value of 0.05–0.1.

The residual flux, also plotted in Fig. 3 for site ATDD C, is seen to be relatively large, varying from about $+300$ W m^{-2} in late morning to about -150 W m^{-2} in the evening. This may indicate the influence of heat fluxes emanating from nearby building facets, such as the south-facing side of the 140-m-tall building located about 100 m northeast of the site. This influence is expected to be much more important at the LLNL site, located in a deep street canyon with building facets only a few tens of meters away. We unfortunately do not have heat flux observations from the neighboring facets during the JU2003 field experiment.

Figure 4 contains the diurnal curves for the ASU site. In general, the Q^* and Q_H curves are similar to those at the suburban and ATDD sites. The Q_E curve at the relatively dry ASU site is between the dry ATDD downtown values and the relatively moist IU suburban sites. The midday Q_E is about 20% or 30% of Q_H. The ASU Q_G is about -10 W m^{-2} at night and about 70 W m^{-2} during the day, which is closer to the suburban IU values than to the downtown ATDD values. Because there are no tall buildings near this site, there is likely to be less influence of heat fluxes from nearby building facets. The daytime ratio Q_G/Q^* is about 0.15, which is slightly greater than the 0.1 value at the high end of the range suggested by Hanna and Paine (1989).

The Q^* and Q_G diurnal curves for the LLNL site are plotted in Fig. 5. This urban-street-canyon site has Q^* that is similar to the other sites, but its Q_G values more closely track ATDD site C, the top level of the parking garage. Flux Q_G has a minimum of about -80 W m^{-2} that persists most of the night and has a daytime maximum of 220 W m^{-2} at noon. Gouveia et al. (2004) point out that the sharp increases and/or decreases at their site at certain times of day are due to the sun coming around the edge of a building or being blocked by another building. The midday ratio Q_G/Q^* is about 0.5, slightly larger than that at ATDD site C. As mentioned under the discussion of Q_G and residual heat fluxes at site ATDD C, however, these Q_G observations do not account for heat fluxes from the sides (facets) of nearby buildings.

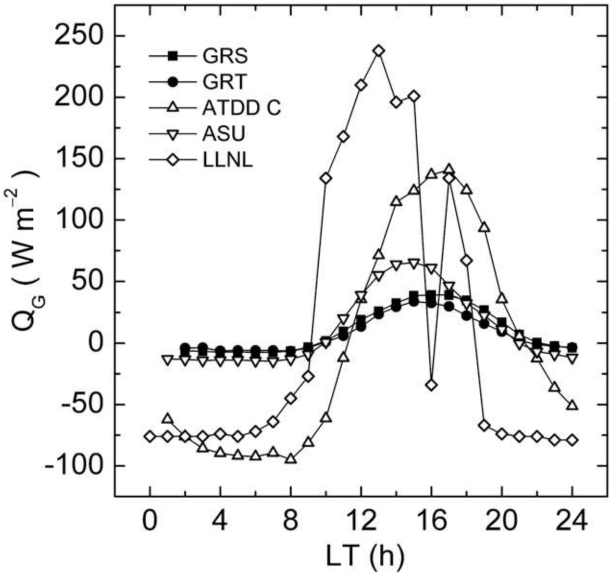

FIG. 6. Measured Q_G for all sites. Open symbols indicate sites from downtown.

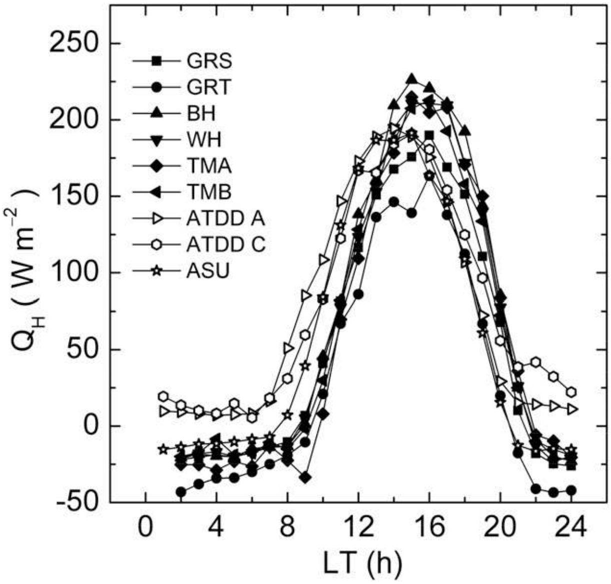

FIG. 7. As in Fig. 6, but for Q_H.

b. *Analysis of diurnal plots in which heat fluxes from several sites are shown*

In the previous set of plots, each frame contained diurnal curves of all (two–four) observed energy flux components at a single site. In the next set of plots, each frame contains diurnal curves of a single energy flux component, with one curve for each of the 10 sites. As before, ATDD site B has been excluded because of the dominance of the latent heat flux due to irrigation. Figures 6–8 each focus on a single flux component (Q_G, Q_H, and Q_E, respectively). Flux Q^* is not plotted because those diurnal curves were similar for all suburban and downtown sites. There are differences in Q^*, but they are much less than those seen in the plots for Q_G, Q_H, and Q_E.

A large suburb–downtown difference is seen for the Q_G curves in Fig. 6. The suburban IU sites (GRS and GRT) have a sinusoidal shape with nighttime minimum of about -10 W m^{-2} and daytime maximum of about 30 W m^{-2}. The downtown ASU site has 2 times as much diurnal variation (from about -30 to 70 W m^{-2}). The downtown ATDD C and LLNL sites, located in paved areas with many adjacent large buildings, have much larger minima (-100 and -80 W m^{-2}, respectively) and maxima (140 and 240 W m^{-2}, respectively). As pointed out in the discussion of Fig. 3, the influences of heat fluxes from other facets, such as nearby building sidewalls, have not been observed and therefore are not accounted for in these analyses. These terms may be partially included in the residual term, such as plotted for site ATDD C in Fig. 3. It would be useful in future field experiments to measure the heat flux components from all facets.

The Q_H curves in Fig. 7 suggest ±10%–20% differences in the magnitudes of afternoon observations from site to site in both the suburban and downtown areas, with peak values ranging from 160 to 230 W m^{-2}. Differences are seen at night, though, as discussed in section 4a and as seen in observations from other cities reported by Grimmond and Oke (1999, 2002) and from a network of sonic anemometers in downtown Oklahoma City reported by Hanna et al. (2007). The sensible heat fluxes for the paved downtown ATDD A and C sites remain positive at night, with typical values of 10–50 W m^{-2}. The ASU sensible heat fluxes at night are between the IU suburban values and the ATDD A and C values. The figure also suggests that Q_H at the three downtown sites begins increasing 1–2 h earlier in the morning than at the suburban sites.

Large differences in daytime Q_E between suburban and downtown sites are seen in Fig. 8. The suburban IU sites have daytime maxima ranging from about 160 to 290 W m^{-2} while the three downtown sites located in the midst of tall buildings and/or parking lots have much smaller maxima, ranging from about 10 to 50 W m^{-2}. As before, the value for the ASU site is between the values for the suburban sites and the two paved downtown sites (ATDD A and C). At night, the suburban sites have slightly positive Q_E while the urban sites are near zero.

5. Major results and inferences for urban meteorological preprocessors for dispersion models

The general directions of the differences in energy fluxes from the suburban to the downtown sites are

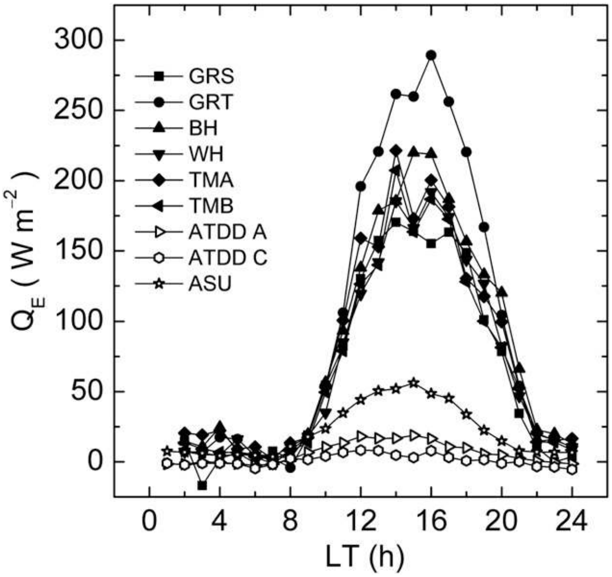

FIG. 8. As in Fig. 6, but for Q_E.

consistent with many of the trends explained by Oke (1987), Arnfield (2003), and others. That is, because of the presence of the many buildings and the anthropogenic heat contributions in the downtown area, Q_G tends to be larger in magnitude, Q_E tends to be smaller in magnitude, and Q_H tends to remain positive at night. It is useful to know that these same trends are found in this unique set of measurements in the Oklahoma City CBD with many nearby buildings with heights that exceed 100 m. Also consistent with the above basic references is that irrigation in the 50–100-m-diameter area in which the instruments are set up is found to have a large effect on Q_E.

A few conclusions about the suburban versus downtown central business district energy fluxes are of possible use in improving energy flux parameterizations for meteorological preprocessors for dispersion models:

- The Q_G/Q^* ratio is 0.05–0.1 at the IU suburban sites for most of the day and night (except at sunrise and sunset), in agreement with the 0.1 rough assumption in Holtslag and VanUlden (1983) and adopted by Hanna and Paine (1989). The ratio is larger, 0.15, during the afternoon at the ASU site 1 km downwind of the built-up downtown area. The ratio increases to about 0.4 at the ATDD C site and 0.5 at the LLNL site. This increase is in proportion to the "urban characteristics of the site," with the LLNL site being in an urban street canyon. At night, the ratio is 0.2 at ASU, 1 at ATDD C, and 2 at LLNL, again suggesting an increase as urban characteristics increase. Because the JU2003 heat flux measurements did not include the fluxes from nearby building facets (such as sidewalls), however, there is a need to investigate further the influence of these other fluxes on the interpretation of Q_G.
- The Q_H/Q^* ratio is about the same (0.3–0.4) in the suburbs and downtown during midday periods. The suburban sites have Q_H/Q^* equal to about 0.3–0.4 at night too. These ratios are similar to those found in the existing energy flux parameterizations in the dispersion model meteorological processors by Hanna and Paine (1989) and Hanna and Chang (1992). The nighttime Q_H is usually positive at 10–20 W m^{-2} in the downtown area with tall skyscrapers, however, indicating nearly neutral to slightly unstable conditions. Although the observations support a recommendation that a constant nighttime Q_H of 10 W m^{-2} be used in the downtown areas, the same problem might arise as was found by Hanna and Chang (1992)—during light winds, a Q_H of 10 W m^{-2} can cause very unstable conditions to be inferred, with large rates of dispersion. Thus the Hanna and Chang (1992) "minimum absolute value of $L = 3H$" continues to be a more robust alternative.
- The daytime Bowen ratio (Q_E/Q_H) is near 1 in the suburban area where there is irrigation but is less than 0.2 in the built-up downtown area. The smallest Q_E values are observed where there is dry pavement, buildings, or dirt for at least 100–200 m in the upwind fetch.
- A time shift (delay) in the Q_H, Q_G, and Q_E diurnal curves with respect to the Q^* curve is evident at most (but not all) sites. The magnitude of the shift ranges from 0 to 4 h, with no consistent dependency on suburban versus downtown land use. For example, there is a 2–4-h delay in Q_G and Q_H at the ATDD C site but no delay in Q_G at the LLNL site. The Holtslag and VanUlden (1983) methods assume that, in the morning, Q_H and Q_E pass from negative to positive several minutes after Q^* increases above zero. They assume that the opposite happens in the evening. Our hourly JU2003 energy flux values do not have sufficient time resolution to show this difference of a few minutes. There is a slight suggestion that Q_H begins to increase in the early morning 1–2 h earlier for the downtown sites than for the suburban sites, however.

We prepared the above general conclusions and recommendations based on the JU2003 observations. In the future, it would be useful to check the recommended flux ratios with the various urban meteorological preprocessor and/or energy flux software programs available [such as the Hanna and Chang (1992) method, the AERMOD (Cimorelli et al. 2004, 2005) method, or the LUMPS (Grimmond and Oke 1999, 2002) model].

6. Further comments

When observations from only one city are analyzed, as in this paper, there is always a question of whether the same results would be found in other cities. There unfortunately are very few energy flux observations in the built-up downtown areas (i.e., containing skyscrapers) of other large cities. As Hosker points out in his discussion of the choice of locations for the three ATDD sites in JU2003, any downtown site is inherently site specific, influenced by whatever local tall buildings are present and whatever types of irrigation may be used in the local area. We note that for the next field experiments in the series that includes JU2003—namely, the Madison Square Garden 2005 (MSG05) and Midtown 2005 (MID05) field experiments—no energy balance observations were taken, even though there were about 30 sonic anemometers set up in street canyons and on tall rooftops in Manhattan. Nevertheless, we are encouraged by the fact that the sensible heat flux observations during MSG05 and MID05 suggest less spatial and temporal variability than expected (Hanna and Zhou 2009).

More focused research is needed on measuring and understanding the missing energy flux terms in the residual flux, which is the imbalance of the energy fluxes that are observed directly. The missing terms include the heat fluxes from facets (such as building walls) other than the horizontal surface under the instrument. Another missing term is the horizontal flux divergence, sometimes referred to as the advection term. These additional terms are very difficult to measure, but for the heavily irrigated downtown site ATDD B the flux divergences must be relatively large to explain the observed Q^*, Q_G, Q_H, and Q_E fluxes.

Acknowledgments. The research by Steven Hanna and Edson Marciotto was supported by the National Science Foundation, under Award 0750878. Rex Britter was funded in part by the Singapore National Research Foundation (NRF) through the Singapore-MIT Alliance for Research and Technology (SMART) Center for Environmental Sensing and Modeling (CENSAM). We thank the many JU2003 principal investigators who responded to our questions and provided additional comments and details regarding the data.

REFERENCES

Allwine, K. J., and J. E. Flaherty, 2006: Joint Urban 2003: Study overview and instrument locations. Pacific Northwest Laboratory Rep. PNNL-15967, 92 pp. [Available online at http://www.pnl.gov/main/publications/external/technical_reports/PNNL-15967.pdf.]

——, M. J. Leach, L. W. Stockham, J. S. Shinn, R. P. Hosker, J. F. Bowers, and J. C. Pace, 2004: Overview of Joint Urban 2003—An atmospheric dispersion study in Oklahoma City. Preprints, *Symp. on Planning, Nowcasting, and Forecasting in the Urban Zone and Eighth Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface,* Seattle, WA, Amer. Meteor. Soc., J7.1. [Available online at http://ams.confex.com/ams/pdfpapers/74349.pdf.]

Arnfield, A. J., 2003: Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *Int. J. Climatol.,* **23,** 1–26.

Batchvarova, E., and S.-E. Gryning, 1991: Applied model for the growth of the daytime mixed layer. *Bound.-Layer Meteor.,* **56,** 261–274.

Beljaars, A. C. M., and A. A. M. Holtslag, 1991: Flux parameterization over land surfaces for atmospheric models. *J. Appl. Meteor.,* **30,** 327–341.

Britter, R. E., and S. R. Hanna, 2003: Flow and dispersion in urban areas. *Annu. Rev. Fluid Mech.,* **35,** 469–496.

Cimorelli, A. J., and Coauthors, 2004: AERMOD: Description of model formulation. U.S. EPA Rep. EPA-454/R-03-004, 91 pp. [Available online at http://www.epa.gov/ttn/scram/7thconf/aermod/aermod_mfd.pdf.]

——, and Coauthors, 2005: AERMOD: A dispersion model for industrial source applications. Part I: General model formulation and boundary layer characterization. *J. Appl. Meteor.,* **44,** 682–693.

Gouveia, F. J., M. J. Leach, and J. H. Shinn, 2004: Measurements of net radiation, ground heat flux and surface temperature in an urban canyon. Preprints, *Symp. on Planning, Nowcasting, and Forecasting in the Urban Zone and Eighth Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface,* Seattle, WA, Amer. Meteor. Soc., J7.4. [Available online at http://ams.confex.com/ams/pdfpapers/71499.pdf.]

Grimmond, C. S. B., and T. R. Oke, 1999: Heat storage in urban areas: Local-scale observations and evaluation of a simple model. *J. Appl. Meteor.,* **38,** 922–940.

——, and ——, 2002: Turbulent heat fluxes in urban areas: Observations and a local-scale urban meteorological parameterization scheme (LUMPS). *J. Appl. Meteor.,* **41,** 792–810.

——, H. B. Su, B. Offerle, B. Crawford, S. Scott, S. Zhong, and C. Clements, 2004: Variability of sensible heat fluxes in a suburban area of Oklahoma City. Preprints, *Symp. on Planning, Nowcasting, and Forecasting in the Urban Zone and Eighth Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface,* Seattle, WA, Amer. Meteor. Soc., Paper J7.2. [Available online at http://ams.confex.com/ams/pdfpapers/67542.pdf.]

——, and Coauthors, 2010: The International Urban Energy Balance Models Comparison Project: First results from Phase I. *J. Appl. Meteor. Climatol.,* **49,** 1268–1292.

Hanna, S. R., and R. J. Paine, 1989: Hybrid Plume Dispersion Model (HPDM) development and evaluation. *J. Appl. Meteor.,* **28,** 206–224.

——, and J. C. Chang, 1992: Boundary layer parameterizations for applied dispersion modeling over urban areas. *Bound.-Layer Meteor.,* **58,** 229–259.

——, and Y. Zhou, 2009: Space and time variations in turbulence during the Manhattan Midtown 2005 field experiment. *J. Appl. Meteor. Climatol.,* **48,** 2295–2304.

——, L. L. Schulman, R. J. Paine, J. E. Pleim, and M. Baer, 1985: Development and evaluation of the Offshore and Coastal

Diffusion Model. *J. Air Pollut. Control Assoc.,* **35,** 1039–1047.

——, J. White, and Y. Zhou, 2007: Observed winds, turbulence, and dispersion in built-up downtown areas in Oklahoma City and Manhattan. *Bound.-Layer Meteor.,* **125,** 441–468.

Holeman, J. E., M. Princevac, S. Grossman-Clarke, S. M. Lee, H. J. S. Fernando, and R. Calhoun, 2004: Joint Urban 2003 surface energy budget measurements and analysis. *Proc. 21st Int. Congress of Theoretical and Applied Mechanics,* Warsaw, Poland, 2 pp. [Available online at http://fluid.ippt.gov.pl/ictam04/text/sessions/docs/FM9/12738/FM9_12738_new.pdf.]

Holtslag, A. A. M., and A. P. VanUlden, 1983: A simple scheme for daytime estimates of the surface fluxes from routine weather data. *J. Climate Appl. Meteor.,* **22,** 517–529.

Horst, T. W., 1999: The footprint for estimation of atmospheric–surface exchange fluxes by profile techniques. *Bound.-Layer Meteor.,* **90,** 171–188.

——, and J. C. Weil, 1992: Footprint estimation for scalar flux measurements in the atmospheric surface area. *Bound.-Layer Meteor.,* **59,** 279–296.

Hosker, R. P., 2003: Initial report on ATDD observations in OKC, June–July 2003. NOAA/ARL/ATDD Rep., 8 pp. [Available from ATDD, Oak Ridge, TN 37830.]

Kondo, H., Y. Genchi, Y. Kikegawa, Y. Ohashi, H. Yoshikado, and H. Komiyama, 2005: Development of a multi-layer urban canopy model for the analysis of energy consumption in a big city: Structure of the urban canopy model and its basic performance. *Bound.-Layer Meteor.,* **116,** 395–421.

Martilli, A., A. Clapper, and M. Rotach, 2002: An urban surface energy parameterization scheme for mesoscale models. *Bound.-Layer Meteor.,* **104,** 261–304.

Masson, V., 2006: Urban surface modeling and the meso-impact of cities. *Theor. Appl. Climatol.,* **84,** 35–45.

Oke, T. R., 1987: *Boundary Layer Climates*. Routledge, 435 pp.

Pearlmutter, D., P. Berliner, and E. Shaviv, 2005: Evaluation of urban surface energy fluxes using an open-air scale model. *J. Appl. Meteor.,* **44,** 532–545.

Schmid, H. P., 1994: Source areas for scalars and scalar fluxes. *Bound.-Layer Meteor.,* **67,** 293–318.

Seibert, P., F. Beyrich, S.-E. Gryning, S. Joffe, A. Rasmussen, and P. Tercier, 2000: Review and intercomparison of operational methods for the determination of the mixing height. *Atmos. Environ.,* **34,** 1001–1027.

Sykes, R. I., S. F. Parker, D. S. Henn, and B. Chowdhury, 2007: SCIPUFF 2.3 technical documentation. Titan Corp. Tech. Rep., 336 pp. [Available from Titan Corp., P.O. Box 2229, Princeton, NJ 08543-2229.]