10.2 ENERGY FLUXES IN URBAN BUILT-UP DOWNTOWN AREAS, FOR INPUT TO DISPERSION MODELS

STEVEN HANNA[1*], EDSON MARCIOTTO[1], REX BRITTER[2]

[1]Harvard School of Public Health, Boston, MA; [2]MIT, Cambridge, MA

ABSTRACT

Surface energy fluxes are needed as inputs to most state-of-the-art dispersion models. The sensible heat flux is of major priority, since it is combined with the momentum flux to estimate the Monin-Obukhov length, which is a key stability indicator. Observations of urban heat flux components from 11 locations in suburban and built-up downtown areas in Oklahoma City during the Joint Urban 2003 (JU2003) field experiment are analyzed. At street level in the downtown area, 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. The latent heat flux measured at heights less than 5 m at the downtown sites is found to be strongly influenced by the local (within 50 m) surface conditions, especially the presence of irrigated lawns. The sensible heat flux in the downtown area is observed to be slightly positive at night, indicating nearly neutral or slightly unstable conditions. A delay of a few hours in the peak of the sensible heat and ground heat fluxes with respect to the net radiation flux is found at both suburban and downtown sites. Some simple parameterizations for the heat fluxes as a function of urban surface type are suggested.

1. INTRODUCTION AND BACKGROUND

This study was spurred by the need to better understand diurnal variations of urban thermal energy fluxes within urban canopies in built-up downtown areas of large cities with tall skyscrapers. Most of the previous research on urban thermal energy fluxes (e.g., the model intercomparison study by Grimmond *et al*., 2010) has focused on suburban areas or urban areas with buildings no taller than a few stories and has not addressed thermal energy fluxes in the midst of large buildings. This information is needed in order to estimate hourly averages of winds, turbulence, and stability for input to transport and dispersion models that are seeing increasing use in built-up downtown areas. The atmosphere has large turbulence intensities and has nearly-neutral stability in an area with many tall skyscrapers, due to the large amount of mechanical mixing adjacent to the buildings, the contributions of anthropogenic heat sources, and the large capacity for storing energy, particularly solar, in materials used in streets and buildings.

*Corresponding author. 7 Crescent Ave., Kennebunkport, ME 04046-7235; E-mail hannaconsult@roadrunner.com; Phone 207 967 4478

Britter and Hanna (2003) review urban dispersion models' needs for meteorological inputs, such as winds, turbulence, and stability. The US EPA's AERMOD dispersion model (Cimorelli *et al*., 2005) and the US DOD's SCIPUFF dispersion model (Sykes *et al*., 2008) are good examples of models with state-of-the-art meteorological boundary layer preprocessors for all types of land use, including urban areas. These are based on the meteorological processor developed by Hanna *et al.* (1985) for the Offshore and Coastal Diffusion (OCD) model and by Hanna and Paine (1989) for rural terrain for the Hybrid Plume Dispersion Model (HPDM). Using extensive boundary layer observations in field experiments in St. Louis and Indianapolis, Hanna and Chang (1992) expanded the HPDM meteorological preprocessor to account for urban terrain. The prime boundary layer meteorological parameters of use to dispersion models are the surface momentum flux and the sensible heat flux, Q_H (positive upwards). Once these fluxes are known, other key variables, such as wind speeds and turbulence intensities, can be estimated. Because measurements are seldom available for Q_H, it has to be estimated from other 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 also likely to be known. Most dispersion model meteorological preprocessors then use the methods originally suggested by Holtslag and VanUlden (1983) and Beljaars and Holtslag (1991) for approximating the sensible heat flux, Q_H, based on assumptions about the energy balance formula for rural areas:

$$Q_H = Q^* - Q_E - Q_G \quad (1)$$

where Q^* is the net radiation flux (positive downwards), Q_E is the latent heat flux (positive upwards), and Q_G is the ground heat flux (positive downwards) (all in W m^{-2}). The averaging time is usually one hour, although the same formulas are valid for smaller and larger averaging times, ranging from about 10 minutes to two or three hours. The variables are usually point measurements, but taken to be spatial and volume averages, where required.

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). Q_E is assumed to be a multiple of Q_H based on 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. Q_G is assumed to be a multiple of Q^*, again based on land-use. 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. Also note that equation (1) makes the assumption that the energy fluxes are in balance, which we know is not correct in general, since the air and ground temperatures warm up each morning by about 10 C and cool off by the same amount each evening. Given the Q_H estimate, the observed wind speed, and estimates of surface roughness length (again, as a function of land-use), the Monin-Obukhov (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 along with all of the needed profiles for use by the dispersion model. Despite all of the approximations and ignoring the storage heat flux, ΔQ_S, etc., 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 and 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 observations. At first, they intended to include approximations for the anthropogenic heat flux, Q_F, but found that the 10 to 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. Consequently, they argued that, instead, a limit should be placed on the MO length, L, whose magnitude is assumed to represent the approximate height to which mechanically-generated turbulence dominates in the surface layer. They set a minimum L magnitude of $3H$, which implies that mechanically-generated turbulence dominates to that height in the urban area. The AERMOD meteorological preprocessor also accounts for the tendency towards neutral conditions in urban areas.

Grimmond and Oke (2002) used extensive urban observations and theoretical analyses to further improve on the methods suggested by Hanna and Chang (1992) and the resulting method is called the Local-Scale Urban Meteorological Parameterization Scheme (LUMPS). Their research was related to use of the model in urban climate studies and as input to mesoscale meteorological models rather than use in dispersion models. They updated some of the parameterizations, such as the method of estimating the ratio Q_G/Q^*. They accounted for the observed diurnal variations of the storage flux, ΔQ_S, which does not usually follow the shape or timing of the diurnal variations of the net radiation flux. ΔQ_S is intended to represent the heat storage as indicated by time variation of temperatures in the air and the ground and buildings. But in analyses of field experiments, ΔQ_S also includes "other unmeasured terms" such as the anthropogenic heat flux, Q_F, and the advective flux, Q_A. The Grimmond and Oke (2002) Objective Hysteresis Model (OHM) provides better estimates of ΔQ_S as a function of time of day and Q^*. Their papers contain the results of successful comparisons of the LUMPS estimates of fluxes with observations from many cities.

The current paper (a reduced version of a manuscript under review at JAMC by the same authors) analyzes observations of urban heat flux components from several sites in Oklahoma City during the Joint Urban 2003 (JU2003) field experiment (Allwine and Flaherty, 2006). These sites include several in the built-up downtown area.

2. URBAN HEAT FLUX COMPONENTS

A problem with all of the full-scale or small-scale experiments involving urban energy flux observations is that all significant components of the urban energy equation are never observed. Most frequently, the net radiation flux, Q^*, is observed, often broken down into direct and diffuse solar (short wave) energy fluxes and net long wave flux. The sensible heat flux, Q_H, is next in frequency of observation. In many boundary layer studies, Q_H is observed and not Q^*, because Q_H can be calculated using observations of temperature and vertical wind speed fluctuations by sonic anemometers, which are now widely used to measure wind components, turbulence, and momentum fluxes. For example, during the JU2003 field experiment, there were 10 to 20 energy flux measuring sites, and over 100 sonic anemometer sites.

Next in line in frequency of observation is the latent heat flux, 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 areas with areas of irrigated vegetation interspersed with dry areas consisting of streets, buildings, and parking lots. Later we show examples of days during JU2003 when latent heat fluxes are observed to be 500 or 600 W m^{-2} over an irrigated area in the downtown area and are less than 50 W m^{-2} in parking lots and streets only a few blocks away.

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 about 100 times less 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 5 or 10 cm. 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 an Oklahoma City street (during JU2003) paved with standard materials 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, since there are so many components and they vary in space and time. There have been approximate city-wide estimates based on total energy usage, and 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 to 100 W m^{-2}. This energy is injected into the control volume 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, is often misunderstood, and should be called the "flux convergence" term. There can be strong advection at any location, but that does not contribute to a heat gain or loss within the grid or control volume unless the incoming flux on the upwind edge is different from the outgoing flux on the downwind edge. Q_A can be calculated given knowledge of the partial derivatives such as $\partial uT/\partial x$ and $\partial vT/\partial y$ where x is along wind direction and y is cross wind direction and u and v are the wind speed components in the x and y directions. It is nearly impossible to measure these terms since they depend on knowledge of the horizontal energy flux across each face of the control volume. For example, if the control volume is 50 m wide and 20 m high, there should be flux measurements about every 5 m on the four vertical faces of the volume (i.e., the sides of the box). Q_A is thus proportional to the difference between the integrated incoming fluxes and the integrated outgoing fluxes. 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 sub-grid effects and attempts to reduce convergences and divergences.

The stored energy flux, ΔQ_S, is never observed and is often calculated as the imbalance of the other observed energy flux terms. It is sometimes confused with the residual flux Q_R, which is also calculated as what is left when the observed heat fluxes are subtracted from the observed net radiation flux.

3. OVERVIEW OF JU2003 AND ENERGY FLUX OBSERVATIONS

We are now in an era in which many excellent new urban meteorological data bases from cities across the globe are becoming available, and several of these are being used in the model intercomparison by Grimmond *et al.* (2010). The current paper focuses on a set of energy flux observations from the Oklahoma City Joint Urban 2003 (JU2003) field experiment.

a. General description of JU2003

The JU2003 field experiment is described by Allwine and Flaherty (2006). Although the focus was on dispersion experiments using tracer gases released near street level in the downtown area, there was a large network of supporting meteorological observing systems, employing hundreds of in situ and remote instruments. The JU2003 outer domain has a diameter of about 100 km, which contains only about 10 % suburban or urban land use. The inner suburban/urban domain, with dimensions about 10 km, contains mostly suburban and commercial land-use. In JU2003, though, there was great interest in the downtown inner domain with dimensions of 1 or 2 km, containing numerous skyscrapers with heights exceeding 100 m. Going to even smaller scales, within the downtown area there is a smaller single street canyon study domain in and around Park Street, with dimensions of about 100 m. The downtown area was covered by many sonic anemometers near street level, and several surface heat flux monitors, in addition to many sonic anemometers at rooftop and several attempts to measure vertical profiles using remote sounding devices and short towers. The 10 km inner domain also had several energy flux towers operating, set up and maintained by several different organizations. For example, Grimmond *et al.* (2004) and Gouveia *et al*. (2004) published brief conference papers describing the highlights of their own surface energy flux studies. The energy flux sites whose observations are analyzed below were operated by Indiana University (IU, Grimmond *et al.* 2004), by the Atmospheric Turbulence and Dispersion Division (ATDD, Hosker 2003), by Arizona State University (ASU, Holeman *et al.,* 2004), and Lawrence Livermore National Laboratory (LLNL, Gouveia *et al.* 2004). **Figure 1** shows the central downtown box, including five sites (ATDD A, ATDD B, ATDD C, ASU, and LLNL). More details of the sites are given below.

b. Indiana University (IU) 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 and Flaherty 2006). The neighborhood is located about 6 km to the south (upwind) of the built-up downtown area and consisted of a mixture of one and two story houses, lawns and trees, schools and athletic fields. The IU instrument sites are labeled BH, WH, GRS, GRT, and TMA/B.

The 29 m Brick House (BH) tower 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 Wood House (WH) tower was located downwind of a subdivision of wood houses with irrigated lawns. The heat flux instruments at the grass site (GRS) were on a 3 m tower in an unirrigated school athletic field. The instruments were moved halfway through the field experiment to a moister grassy area (denoted by GRT) near the Tyler Media tower. Site TMA/B was the 80 m Tyler Media tower with instruments "A" at the 80 m and "B" at the 40 m levels. The tower was located in a field about 50 m downwind of a subdivision. The 10 Hz raw data were block-averaged over one hour by Grimmond *et al.* (2004), where the listed time indicates the hour ending. The total period of measurement was about one month although data are not available for all days. A further complication is that not all experiment days had data from all instruments. The net radiation flux, Q^*, and the sensible heat flux, Q_H were observed at all IU sites. The latent heat flux, Q_E, and ground heat flux, Q_G, were observed at a few sites. Two sites (GRS and GRT) measured all four heat fluxes.

c. Atmospheric Turbulence and Diffusion Division (ATDD) sites

The three ATDD sites were planned to represent 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 OKC 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)."

The ATDD data are available on the DPG JU2003 website as half-hour averaged data, and we calculated hourly averages for analysis in this paper. The measurements include net radiation flux, Q^*, wind speed, air temperature and humidity, surface temperature, incoming solar radiation, and precipitation. Turbulent fluxes of momentum and sensible and latent heat (Q_H and Q_E) were measured, as well as the mean (u, v, and w) and turbulent (σ_u, σ_v, and σ_w) wind speed components. Data recovery rates for sites A and C were high for all parameters measured (over 95%). Site B (grass site) was more problematic due to occasional power outages and the effects of an automated sprinkler system. The sprinkler irrigation system operated every night from about 11 pm to 7 am (R. Hosker, private communication, 2009). Also, data recovery rates at Site B were no more than 70% for most variables.

We attempted to determine the upwind fetches of the local land use for the downtown sites (ATDD A, B, and C; ASU and LLNL Park St). Google Earth as employed to produce views of areas about 400 m by 500 m around each. The following comments apply to the three ATDD sites:

ATDD A (stated to be "dirt parking lot", and about 1 km west of downtown tallest buildings) - The dirt parking lot itself has a dimension of about 50 m E-W and 100 m N-S. The site is in the middle of an area consisting of a mixture of dirt and paved lots, and large flat warehouses or manufacturing buildings, extending more than 200 m in all directions. There are minimal areas of lawn.

ATDD B (stated to be "irrigated lawn", and about 1.5 km to NNE of downtown tallest buildings) - This appears to be a large (500 m by 500 m) campus, with over 90 % coverage with lawns and with five medium sized-buildings scattered over the tract. The instrument is in the middle of one of the lawns, of size 200 m by 200 m, with a 300 m upwind fetch (to the S) over lawns, which were highly irrigated.

ATDD C (in middle of top level of 100 m by 150 m by 20 m tall parking garage, in the downtown tall building area) - In addition to the parking garage, there is a large surface parking area surrounding the garage, so the whole parking area covers about 200 m by 200 m. The upwind fetch (to the S) is over the parking area for about 150 m. South of the parking area is the 300 m by 300 m arboretum area, with lawns and trees. Tall buildings are to the W, N, and E of the site.

The observed latent heat flux, Q_E, was very large for Site B, probably due to the irrigation applied to the grass during the night. As a result, the ground and grass were saturated, causing a very high observed Q_E, averaging about 400 W m^{-2} during the day, with maximum values of about 900

W m^{-2}. This is almost as large as the solar heat flux outside of the earth's atmosphere. This magnitude of Q_E has been observed over other saturated vegetative surfaces, especially with dry air passing over the saturated surface. Site C (on the top level of the parking garage) has reasonable values for all energy flux components.

d. Arizona State University (ASU) site

The ASU Energy Flux site was located about 1 km to the north-north-east of the tall buildings in the Central Business District (CBD) (see **Figure 1**). The Google Earth view suggests that this site is in the middle of a lawn area of dimension 100 m (W-E) and 50 m (N-S). Within 200 m in all directions is a mixture of open areas (lawn or dirt or paved) and low flat warehouses/manufacturing buildings. The tower was instrumented with a Kipp and Zonen Net Radiometer at 9.2 m agl, cup anemometers at 1.5 and 8.9 m agl, thermistors at 1.1 and 8.3 m agl, an IR thermometer, an upward facing pyranometer and downward facing pyrgeometer at 3.5 m agl, a 3D Sonic anemometer (Campbell Sci.) and a Krypton Hydrometer at 2.5 m agl. In the soil, there was a soil heat flux plate (6.5 cm below ground level) together with six thermistors (at 2, 3, 4, 5, and 8 cm below ground level), and a soil water content reflectometer (added half way 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 minute averages. Data from the IR thermometer, sonic anemometer, Krypton Hydrometer and soil water content reflectometer are stored as one minute averages. All data were converted to hourly averages, with the listed hour indicating "hour ending".

e. Lawrence Livermore National Laboratory (LLNL) site

The LLNL heat flux observations are described by Gouveia *et al.* (2004) in a conference paper. The data are not in the JU2003 data archive, so the points plotted in this paper were estimated by eye from the figures in the paper. The LLNL site, shown in **Figure 1**, was in an urban street canyon, Park Avenue, which was the focus of other intensive observations. Park Avenue is oriented from west to east in the middle of the group of tallest buildings in the CBD, with several 100 to 150 m buildings nearby. Buildings and pavement are within 200 m in all directions.

The net radiation flux, Q^*, was measured at a height of 4 m. The ground heat 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 thermocouples that measured temperatures of the exterior walls of nearby buildings, but we have not analyzed those observations.

As expected, the diurnal time series of net radiation and ground heat flux were strongly influenced by the sequence of shading of the sensors due to the general street orientation and to a few individual taller buildings.

4. ANALYSIS OF JU2003 ENERGY FLUXES

The main goal of the analysis is to investigate differences in the energy flux components observed in the suburban and built-up downtown areas, with the hope of eventually developing parameterizations for use in operational meteorological preprocessors for dispersion models. We are especially interested in the heat flux observations from the few JU2003 heat flux sites in the downtown area. The following subsections discuss the results for individual sites and for groups of sites.

a. Diurnal variations of heat fluxes from individual sites

Hourly averages were calculated for all available energy flux terms in order to study the diurnal cycle. A value listed at a given hour represents the hourly average for the period ending at that hour. We justify our averaging of the diurnal curves over several days by the fact that meteorological conditions were relatively consistent over the JU2003 field experiment period. Conditions were hot and dry with infrequent clouds and rain. As typical of Oklahoma, during experiment days, winds were 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, using the ASU solar energy data, which were available as five minute averages. 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 with a persistent overcast.

The diurnal plots of flux observations for the IU suburban sites showed similarities in all flux components. Grimmond *et al.* (2004) conclude that "measured Q_H varied significantly (over 20 %) over different patches of suburban land surfaces". Q^* has a nighttime value of –40 to –50 W m^{-2} and a daytime value of about 450 to 580 W m^{-2}, peaking at about 14 or 15 LT. Q_H is slightly negative (about –20 W m^{-2}) at night and peaks during the day at about 20 to 50 W m^{-2} at about 16 LT. The delay in the Q_G peak is due to the several hours needed for

Q_G to penetrate to depths of 10 or 20 cm. Note that the ratio of peak Q_G to peak Q^* at mid-day is about 0.05 to 0.10, which is close to that parameterized in the Holtslag and VanUlden (1985) scheme widely used in meteorological preprocessors for dispersion models (see Hanna and Chang, 1992). The latent heat flux, Q_E, in the IU plots is nearly zero at night and peaks at about 170 to 280 W m^{-2} at about 16 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. Plus there are many trees in the area.

The diurnal plots of energy fluxes for "downtown" ATDD sites A and C are shown in **Figures 2** and **3**. Recall that site A is a dirt/gravel parking lot and site C is the top level of a large parking garage. Because of the dry fetches extending 200 m or more upwind, sites A and C have small latent heat fluxes, Q_E, with magnitudes less than 10 or 20 W m^{-2}. Both sites indicate upward positive Q_H at night with magnitude of about 10 W m^{-2}. Hanna *et al.* (2007) reported many sonic anemometer observations of small positive Q_H at downtown sites during the night during JU2003. Similar small upward Q_H values were observed in Manhattan (Hanna and Zhou, 2009). Site C also has a large ground heat flux, Q_G, varying from –100 W m^{-2} at night to +140 W m^{-2} during the day (peaking at 16 LT). Note in **Figure 3** that Q_R (i.e., ΔQ_S) has a similar shape to that observed at the IU sites, passing from positive to negative at 16 LT.

ATDD site B is an irrigated lawn in the midst of an urban area and its data are not plotted here. As mentioned earlier, Q_E is very large at site B (mid-day maximum of 450 W m^{-2}), while Q^* and Q_H are similar to what is observed at sites A and C. The large Q_E at site B leads to negative Q_R (ΔQ_S) during the daytime, which would imply local cooling. However, the temperature is observed to increase during the morning and early afternoon in a usual manner, meaning that flux convergence must be important in maintaining the daytime temperatures at that site.

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 downtown sites, but the Q_E curve is closer to the downtown alues (about 50 W m^{-2} during the day). This site, downwind of the downtown area, is drier than the IU sites. The ASU site does not have as small Q_E as ATDD sites A and C, but Q_E is still 20 or 30 % of Q_H. The ASU Q_G is about –10 W m^{-2} at night and about 50 W m^{-2} during the day, which is closer to the suburban IU values.

Finally, the Q^* and Q_G curves for the LLNL site are plotted in **Figure 5**. This urban street canyon site has Q^* similar to the other sites, but its Q_G values more closely track ATDD site C, the top level of the parking garage. Q_G has a minimum of about –80 W m^{-2} that persists most of the night, and reaches 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.

b. Analysis of diurnal plots where heat fluxes from several sites are shown.

This subsection presents figures containing diurnal variations of observed heat fluxes at several sites.

A large site-to-site difference is seen for the Q_G curves in **Figure 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, in a lawn area, has twice as much diurnal variation (from about -30 W m^{-2} to 70 W m^{-2}). The downtown ATDD C and LLNL sites, located in paved areas, have much larger minima (-100 and -80 W m^{-2}, respectively) and maxima (140 and 240 W m^{-2}).

The sensible heat flux, Q_H, curves in **Figure 7** suggest little difference in afternoon observations from site-to-site, with peak values ranging from 160 to 230 W m^{-2}. Differences are seen at night, though, as anticipated from observations from other cities reported by Grimmond et al. (1999, 2002) and from other sonic anemometer 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 to 50 W m^{-2}. The ASU sensible heat fluxes at night are between the IU suburban values and the ATDD A and C values.

Large differences in daytime latent heat fluxes, Q_E, between suburban and downtown sites are seen in **Figure 8**. The suburban IU sites have maxima ranging from about 160 to 290 W m^{-2}, while the three downtown sites 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 slight positive Q_E while the urban sites are near zero.

5. MAJOR RESULTS AND INFERENCES FOR URBAN METEOROLOGICAL PREPROCESSORS FOR DISPERSION MODELS

A few conclusions about the suburban versus downtown energy fluxes are of interest:

- The Q_G/Q^* ratio is 0.05 to 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 in the downtown urban area: In the daytime, it is 0.15 at ASU, 0.25 at ATDD C and 0.4 at LLNL sites. This increase is in proportion to the "urban characteristics of the site", with LLNL 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.

- The Q_H/Q^* ratio is about the same (0.3 to 0.4) in suburb and downtown during mid-day periods. The suburban sites have Q_H/Q^* equal to about 0.3 to 0.4 at night too. However, the nighttime Q_H is usually positive at 10 to 20 W m^{-2} downtown, indicating nearly neutral to slightly unstable conditions.
- 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 200 m in the upwind fetch.
- The 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 hours, with no clear dependency on suburban vs downtown land use. For example, there is a 2 to 4 hour delay in Q_G and Q_H at the ATDD C site, but no delay in Q_G at the LLNL site.

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REFERENCES

Allwine, K.J. and J.E. Flaherty, 2006: Joint Urban 2003: Study Overview and Instrument Locations. PNNL-15967, Pacific Northwest Laboratory, Richland, WA.

Beljaars, A.C.M and A.A.M. Holtslag, 1991: Flux parameterization over land surfaces for atmospheric models. *J. Appl. Meteorol.*, **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., S.G. Perry, A. Venkatram, J.C. Weil, R.J. Paine, R.J. Wilson, R.F. Lee, W.D. Peters, and R.W. Brode, 2005b: AERMOD: A dispersion model for industrial source applications. Part I. General model formulation and boundary layer characterization. *J. Appl. Meteorol.,* **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. Paper J7.4, 4 pages, Proceedings of the 84th AMS Annual Meeting, Seattle, Available at www.ametsoc.org.

Grimmond, C.S.B. and 33 coauthors, 2010: The international urban energy balance models comparison project: First results from Phase I. To appear in *J. Appl. Meteorol. and Clim.*

Grimmond, C.S.B. and T.R. Oke, 2002: Turbulent heat fluxes in urban areas: observations and a local-scale urban meteorological parameterization scheme (LUMPS). *J. Appl. Meteor.*, **41**, 792-810.

Grimmond C.S.B., Su H.B., Offerle B. Crawford B., Scott S., Zhong S., Clements C., 2004: Variability of sensible heat fluxes in a suburban area of Oklahoma city. Paper J.2, 7 pages, Proceedings of the 84th AMS Annual Meeting, Seattle, USA. www.ametsoc.org.

Hanna, S.R. and J.C. Chang, 1992: Boundary layer parameterizations for applied dispersion modeling over urban areas. *Bound.-Lay. Meteorol.*, **58**, 229-259.

Hanna, S.R., E. Marciotto and R. Britter, 2010: Urban energy fluxes in built-up downtown areas and variations across the urban area for use in dispersion models. Under review at *J. Appl. Meteorol. and Climatol.*

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

Hanna, S.R., 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 Poll. Control Assoc.*, **35**, 1039-1047.

Hanna, S.R., J. White and Y. Zhou, 2007: Observed winds, turbulence, and dispersion in built-up downtown areas in Oklahoma City and Manhattan. Bound.-Lay. Meteorol., 125, 441-468.

Hanna, S.R. and Y. Zhou, 2009: Space and time variations in turbulence during tha Manhattan Midtown 2005 field experiment. *J. Appl. Meteorol. and Clim.*, **48**, 2295-2304.

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. Proceedings, ICTAM, Warsaw, 2 pages.

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

Hosker, R.P. 2003: Initial report on ATDD observations in OKC, June – July 2003. ATDD Report. NOAA/ARL/ATDD, Oak Ridge, TN.

Sykes, R.I., S.F. Parker, D.S. Henn, and B. Chowdhury, 2008: SCIPUFF 2.4 Technical Documentation, DRAFT Technical Report for Contract No. DTRA01-03-D-0013, L-3 Titan Corporation, Princeton, NJ.

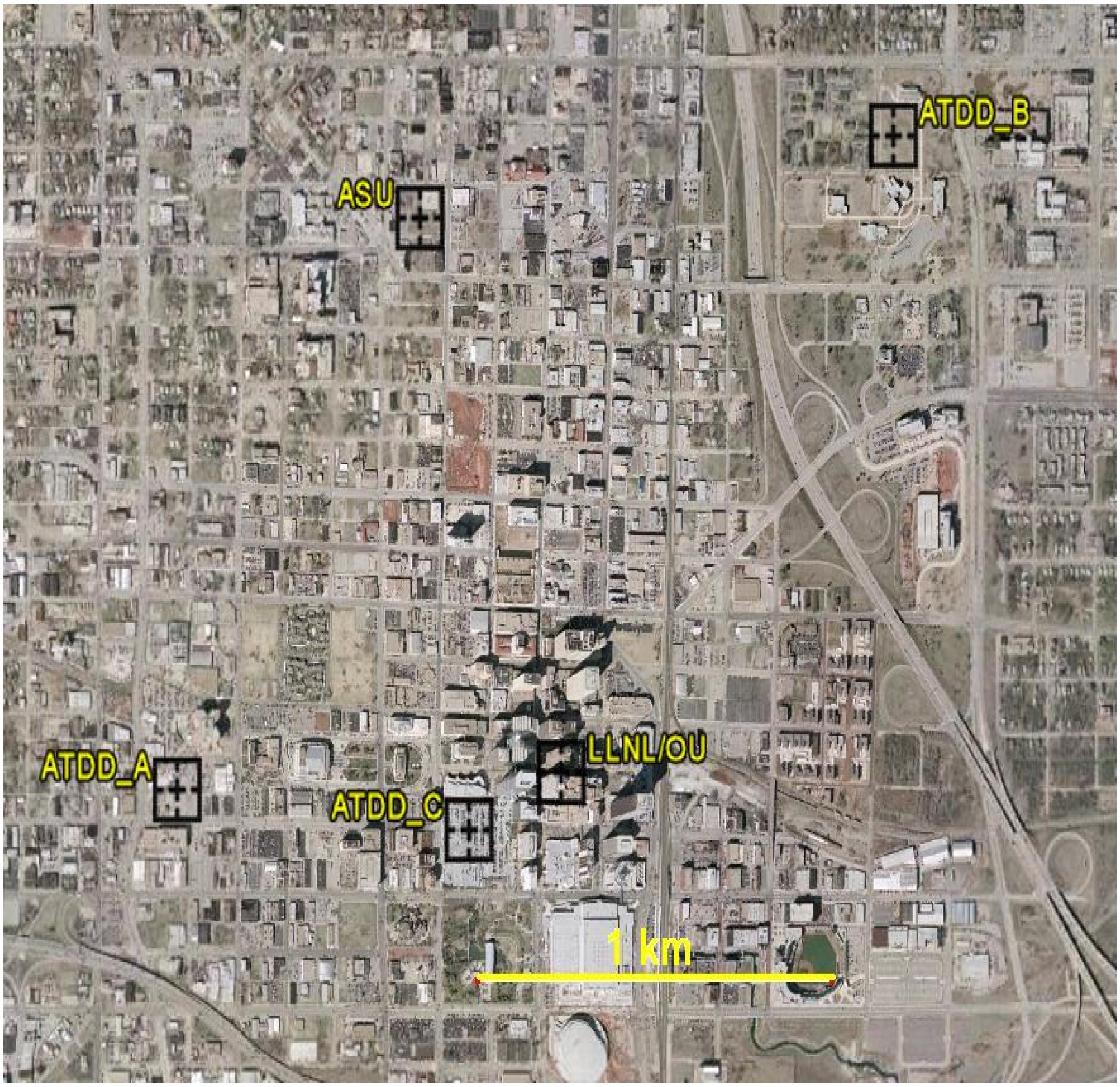

Figure 1. Downtown Oklahoma City, showing locations of ATDD, ASU, and LLNL sites (from GoogleEarth).

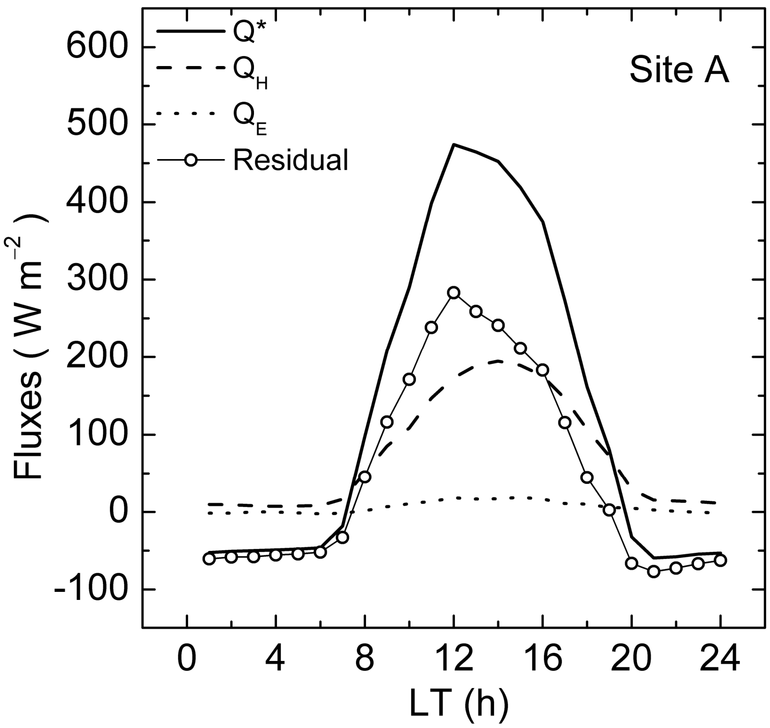

Figure 2. Diurnal variation of energy fluxes at ATDD site A, located in a dirt parking lot on the west edge of the built-up downtown area.

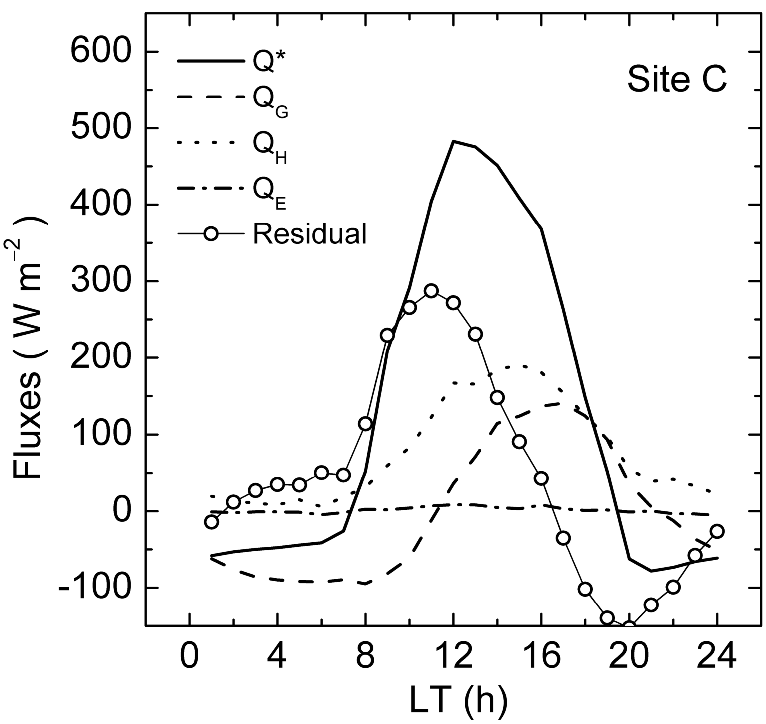

Figure 3. Diurnal variation of energy fluxes at ATDD site C, located on the top level of a parking garage in the built-up downtown area.

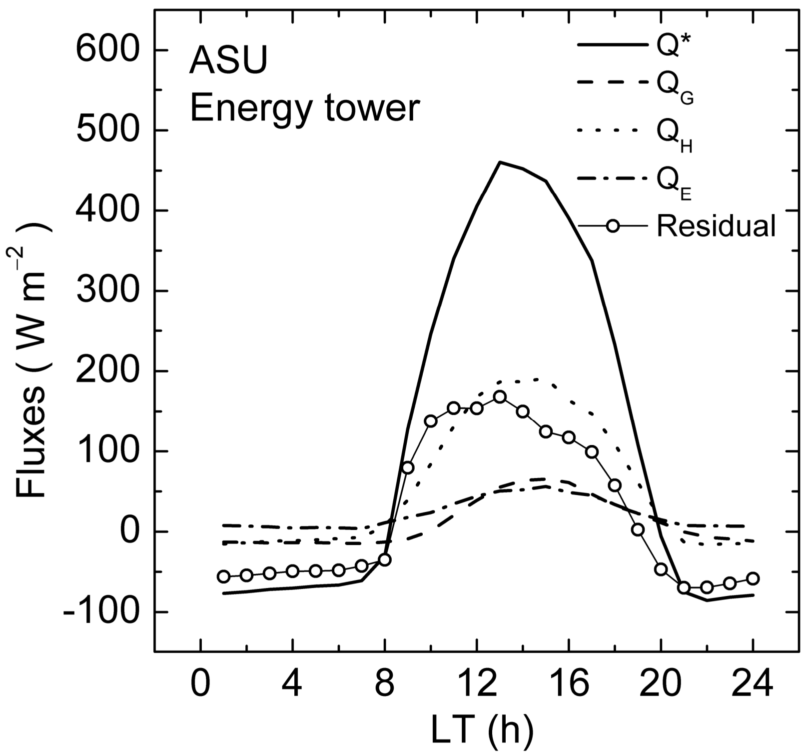

Figure 4. Diurnal variation of energy fluxes at ASU site, located about 1 km downwind of the built-up downtown area.

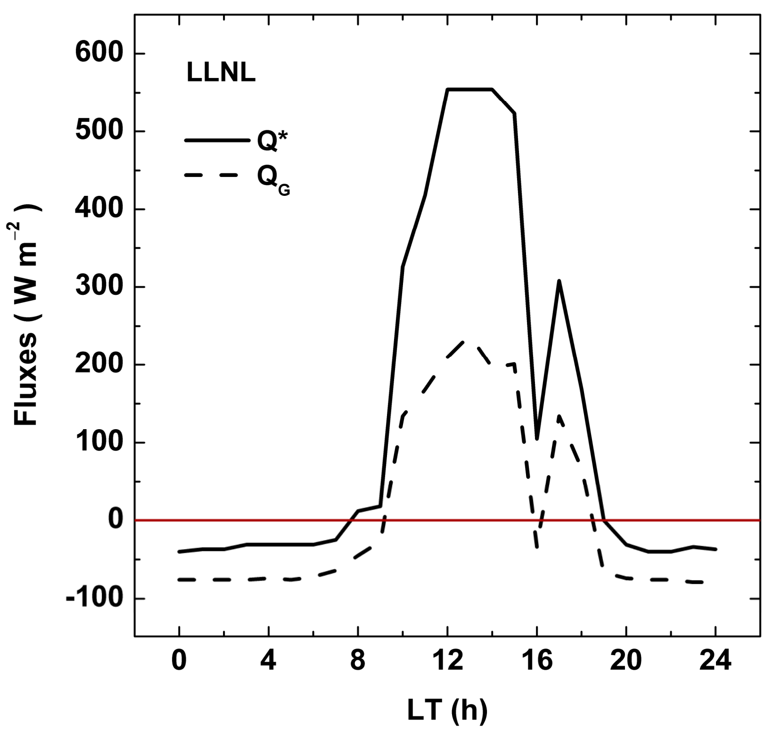

Figure 5. Diurnal variation of net radiation flux Q* and ground heat flux Q_G at LLNL site, located in the street canyon of Park Avenue, in the built-up downtown area.

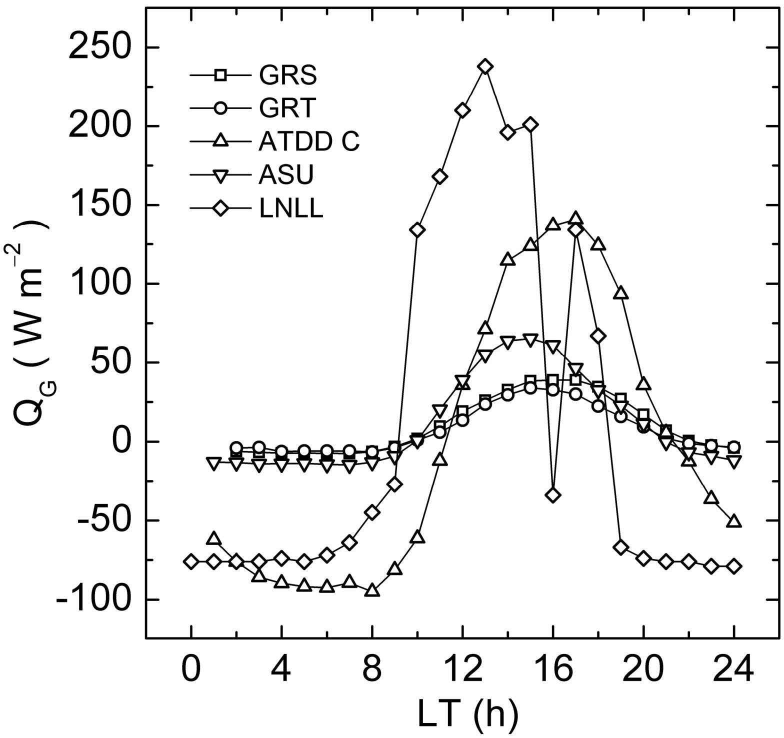

Figure 6. All sites measured ground heat flux Q_G. GRS and GRT are in the suburbs and ATDD C, ASU and LLNL are in the downtown area.

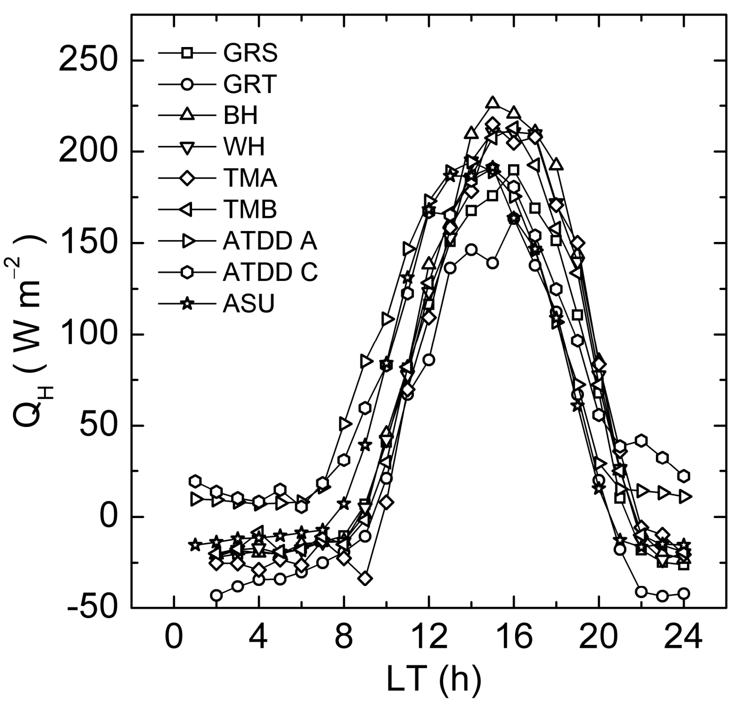

Figure 7. All sites measured sensible heat flux Q_H. The first 6 are IU suburban sites. ATDD A, ATDD C and ASU are downtown sites.

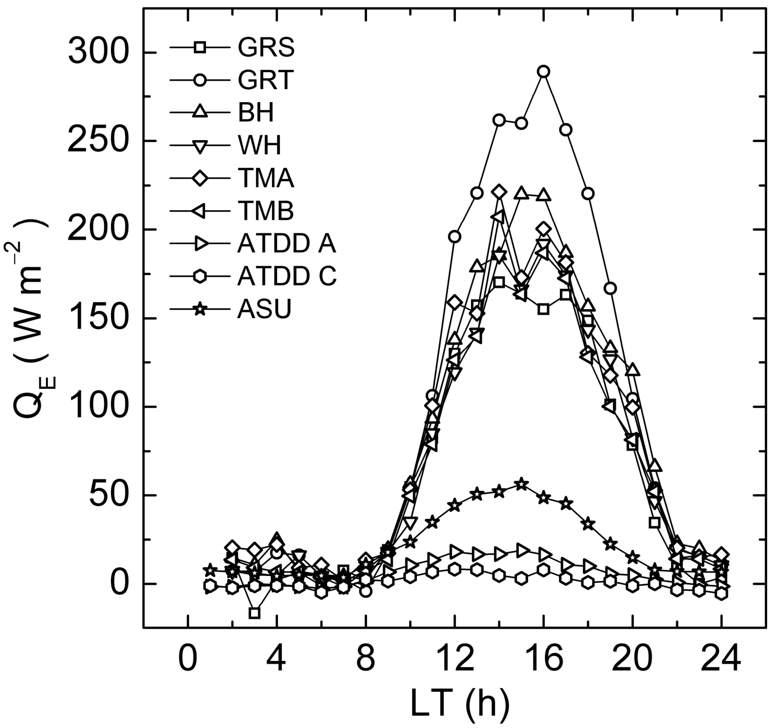

Figure 8. All sites measured latent heat flux Q_E. The first 6 are IU suburban sites. ATDD A, ATDD C and ASU are downtown sites.