J7.2 VARIABILITY OF SENSIBLE HEAT FLUXES IN A SUBURBAN AREA OF OKLAHOMA CITY

C.S.B. Grimmond[1*], H.-B. Su[1,2], B. Offerle[1,3], B. Crawford[1], S.Scott[1], S. Zhong[4], and C. Clements[4]
[1]Indiana University, Bloomington, Indiana; [2]East Carolina University, Greenville, North Carolina;
[3]Göteborg University, Göteborg, Sweden; [4]University of Houston, Houston, Texas

1. INTRODUCTION[1*]

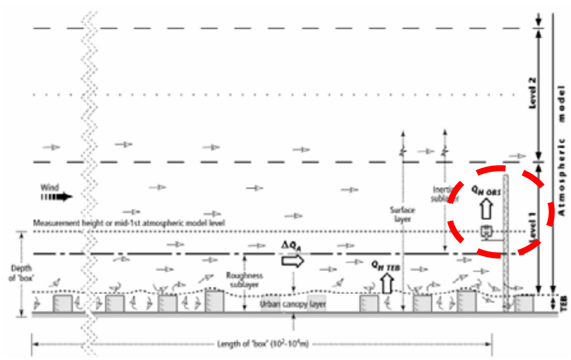
Surface energy balance (SEB) fluxes have been measured for a number of suburban areas in North American cities (Grimmond and Oke 2002). Typically net all wave radiation (Q^*) and the turbulent sensible (Q_H) and latent (Q_E) heat fluxes are directly measured, while, Q_F, the anthropogenic heat flux, ΔQ_S, the net heat storage and ΔQ_A, the net heat advection are not. Depending on location and time of year, Q_F, the heat released by human activities (e.g. combustion, metabolism, electricity) may be significant (Grimmond 1992). If the site is selected carefully, within an area of relatively uniform land cover and land use (relative to the flux source area), ΔQ_A can be minimized. If Q_F is small and ΔQ_A is minimized, ΔQ_S may be determined as a residual in the SEB (Grimmond and Oke 1999b). Alternatively, ΔQ_S can be estimated using a series of temperature measurements and assumptions about building materials (Offerle et al. 2003a; Roberts et al. 2003). Offerle et al. (2003b) demonstrated that one can obtain very good SEB closure using this approach in Ouagadougou, Burkina Faso. The results from that study with extensive fetch and minimal Q_F, indicate that the residual of the SEB was ΔQ_S.

Urban environments consist not only of extensive uniform areas where SEB measurements can be conducted and generalized, but also many patchy or heterogeneous areas. Understanding how flux measurements from these types of landscapes aggregate is important not only for interpreting the processes and observations, but also for evaluating numerical models. Many meso-scale and weather forecast models now incorporate urban areas explicitly, thus it is important that land-surface schemes are evaluated under conditions representative of all parts of a city.

The overall objective of this research was to conduct multiple site SEB flux measurements at the local-scale (neighborhood) for a suburban area in Oklahoma City (OKC). The suburban area consisted of a number of land cover/land use patches which, with appropriately located instruments, should have been extensive enough to meet the fetch requirements for local-scale turbulent heat and momentum measurements. At the larger scale, however, the suburban landscape is "patchy". Of specific interest is the representativeness of SEB measurements and larger-scale scaling.

Measurements in the roughness sublayer (RSL), which in an urban area is in the urban canopy layer or immediately above it (Figure 1), are representative of the micro-scale. To capture the local-scale integrated response of all features of the urban canopy layer, measurements need to be conducted in the inertial sublayer (ISL) (Figure 1). Based on wind tunnel measurements and other analyses, a rule of thumb is to place the instruments at a height greater than two times the mean roughness height so that they are in the ISL (Grimmond and Oke 1999a; Kastner-Klein et al. 2000; Roth 2000).

Figure 1: Relation between observations and land surface scheme lowest layers (Masson et al. 2002)



The research reported here was performed as part of the Joint Urban 2003 project, which was conducted in OKC during July 2003 (Allwine 2004). Our sites were located in the suburban area upwind of the downtown area which was the primary focus of the Joint Urban 2003 field campaign. As this preprint is the first report from the suburban area south of downtown (SASD), we provide a detailed overview of the measurements. Of particular interest here are the turbulent sensible heat fluxes for the suburban sites and their variability during a clear sky period.

The webpage for the SASD part of the Joint Urban 2003 project is located at: http://mypage.iu.edu/~grimmon/okcWeb/ .

[1]* *Corresponding author address:* Sue Grimmond, Atmospheric Sciences, Geography, SB120, Indiana University, 701 E. Kirkwood Ave, Bloomington, Indiana, 47405 USA email: grimmon@indiana.edu

2. METHODS

2.1 Meteorological conditions

The climate of Oklahoma City falls mainly under continental control characteristics of the Great Plains Region, but is sometimes influenced by warm, moist air from the Gulf of Mexico (NOAA 2003). The continental effect produces pronounced daily and seasonal temperature and precipitation changes. Summers are generally long and hot, while winters are comparatively mild and short. Summer precipitation mainly comes from showers and thunderstorms and accounts for 30% of annual totals. Also, during the summer temperatures of 37.78° C (100° F) or more occur on an average of 10 days. Average July precipitation from 1971-2000 is 63.2 mm and mean July daily temperature is 27.78° C (82.0° F) (Oklahoma-Climatological-Survey 2003b). Prevailing winds are southerly, except in January and February.

Observations were conducted from June 27 (178) to August 1 (213), 2003. Weather during the study period was exceptionally hot and dry. Based on 20 climate stations in central Oklahoma, the mean July 2003 temperature was 29.17° C, a departure of 1.39° C (warmer) from normal. The 2003 summer was the 15th warmest since 1895 (Oklahoma-Climatological-Survey 2003a). Precipitation in July 2003 was 15.7 mm, a departure of -47.5 mm making this the 7th driest summer since 1895. High pressure systems and southerly winds dominated weather patterns during the study period.

2.2 Measurement sites

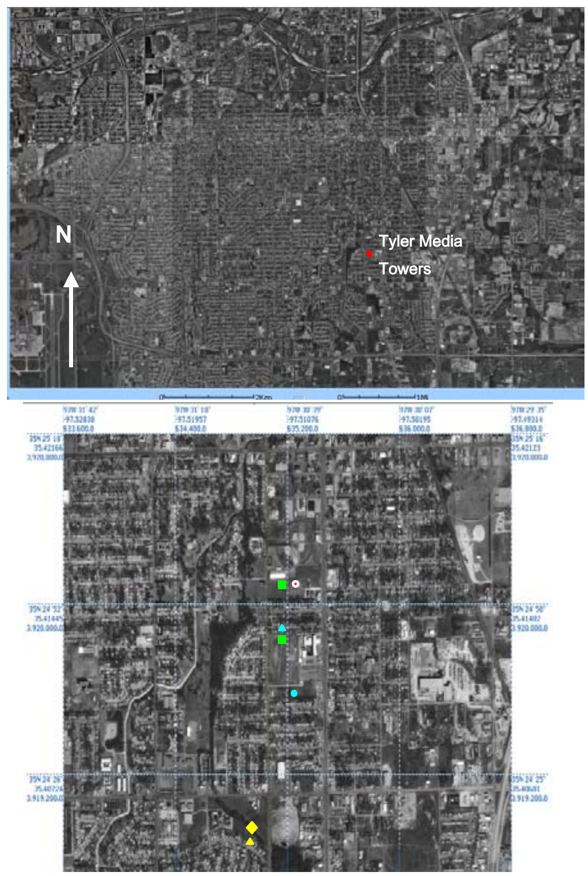
OKC is located in central Oklahoma in the south-central United States (35° 26' N, 97° 28' W). Surrounding topography is flat with an elevation of around 395 m, with no large bodies of water nearby. Population of the OKC metropolitan area is approximately 1,085,000 (McGeveran 2003). The built up downtown core has buildings that average ~130 m in height (McGeveran 2003). In contrast, the majority of buildings near our measurement sites are 1-2 storey family dwellings.

Measurements were conducted at seven sites that were representative of the micro-scale (10^1 -10^2 m) and the local- scale (10^3-10^4 m) (Table 1). The sites were located on a north-south axis (approximately), 5.5-6.5 km south of downtown OKC (Figure 2). These sites included: a grass area (GR), a brick house area (BH), a wood house area (WH), a single wooden house (WHB), a single brick house (BHB), and an aggregation of all sites (TM). The TM site was at the far north; site BHB was to the far south (Figure 2). Measurements heights are given in Table 2.

Table 1: Sites codes and names used to identify them organized by the scale the measurements should be representative of. Locations are based on GPS readings at the individual site.

Site code	Site name	Location
Local^{+} scale		
TMA	Tyler Media	35° 24.903' N 97° 30.605' W
Local scale		
BH	Brick house area	35° 24.284' N 97° 30.803' W
TMA TMB	Tyler Media (A) (B)	35° 24.903' N 97° 30.605' W
WH	Wood house area	35° 24.628' N 97° 30.603' W
Micro-scale		
GRS	Grass @ School	35° 24.772' N 97° 30.682' W
GRT	Grass @ TM	35° 24.913' N 97° 30.638' W
BHB	Brick House (building)	35° 24.260' N 97° 30.851' W
WHB	Wood House (building)	35° 24.783' N 97° 30.680 W

Figure 2: (a) Aerial photograph of the southern part of OKC. Downtown is directly N of the river and the Tyler Media tower. (b) Location of sites. Red/white dot – TM tower, Green squares GR sites, Cyan dot – WH tower, Cyan triangle WHB, Yellow diamond – BH tower, Yellow triangle - BHB (see Table 1 for letter codes). Source of imagery: Mapquest.com



2.2.1 Brick House Area Site (BH)

Instruments were mounted at two levels on a guyed, portable, telescoping 28 m aluminum tower (Aluma Tower Company, Inc, Model #TM61-WA80EB-4 S8). At 28.87 m, a sonic anemometer, krypton hygrometer, net radiometer, T/RH sensor, pyranometer, and infrared thermometer to measure surface temperature were installed (Table 2 at end). Instruments were mounted to ensure that they had minimal interference from the tower (Table 3). Fine wire thermocouples sampled temperatures at different levels on the tower. At 18.27 m a second sonic anemometer was mounted (Table 4). All data were logged on a Campbell Scientific, Inc. (CSI) CR5000 datalogger kept in an enclosure attached to the base of the tower (Table 5). The tower was located in an open field ~35 m upwind (N) of a residential subdivision of brick homes built along curving roads. Virtually all houses are 1-2 stories tall and ~5 m apart. Each house is surrounded by an irrigated, grass-covered yard, with 2-3 trees per yard. The mean tree height is ~14 m (2-2.5 x house height). Streets are paved with black asphalt and are ~7.9 m wide. The tower was located immediately north of a row of trees ~16-17 m tall along a dry stream bed. The tower was approximately 40 m from the houses.

Table 3: Mounting of instruments on towers. Tower face dimensions are given for leg center to leg center (m). The GRT tower was two tripods with a horizontal bar between them.

Site	TM-3	TM-3	BH-1	WH-1	GRS	GRT
Tower face dimensions	1.07	1.07	0.61[1] 0.36[2] 0.23[3]	0.15[1] 0.04[3]	0.34	NA
Instrument	**Distance from tower (m)**					
Sonic	1.42	1.55	0.1	0.70[4]	0.37	0.18
	1.17 TM-2	1.14 TM-4	1.1 BH-2	-	-	
KH	1.42	1.55	0.2	0.70[4]	0.27	0.08
Q*	1.5	1.5	1.66	1.0	1.25	1.092
K↓	1.01	1.01	1.16	0.5	0.49	0.53
T/RH	1.0	1.0	0.83	0.2	On tower	0.77
IRT	1.07	1.07	1.16	0.5	On tower	

[1] base width
[2] width at BH-2
[3] width at top of tower
[4] distance from top of tower

2.2.2 Wood House Area Site (WH)

WH was located northeast of BH in an open field owned by Cojac Portable Buildings Co. (Figure 2). Instruments were mounted on a guyed, portable, pneumatic 18 m mast (Hilomast, Ltd. NK-18). However, due to the weight of equipment the tower was not fully extended. Thus the instruments were mounted at 17.51 m to ensure tower stability. At this height, a sonic anemometer, krypton hygrometer, net radiometer, T/RH sensor, pyranometer, and infrared thermometer to measure surface temperatures were installed (Table 2). Thermocouple wires were also used to sample air temperatures at varying heights (Table 4). Data were collected with a CSI CR5000 datalogger and laptop computer in an enclosure at the base of the tower (Table 5). The tower was located ~25 m downwind (N) of a residential area made up of wood and brick houses. This neighborhood is arranged in rows of virtually identical one story houses running along straight E-W streets. Each house is surrounded by an irrigated yard, with several trees ~2 x house height (5.5 m) typically in the backyard. Houses were closer together than at BH (3-5 m), but streets were wider (~8.5 m) and made of gray concrete slabs. Eighteen meters south of the tower there was a dry stream bed lined with trees ~14 m high which separated the residential area from the open field where the tower was located.

Table 4: Heights (m) of fine wire thermocouples (Omega fine wire TC T-Type 0.127 mm) for each tower site. Note at the TM site there were two dataloggers, so the datalogger that the sensor was connected is indicated. The GR site instruments were moved so there are two different sets of data.

	TM	BH	WH	GRS	GRT
1	79.63 (A)	28.87	17.51	3.69	1.73
2	67.10 (A)	26.47	14.35	2.66	0.80
3	57.90 (A)	21.69	11.70	1.74	0.39
4	48.46 (A)	17.12	9.05	0.80	0.19
5	37.26 (A)	12.55	6.40	0.32	0.10
6	35.10 (B)	7.69	3.80	-	-
7	27.53 (B)	4.95	2.00	-	-
8	19.96 (B)	-	0.94	-	-
9	12.27 (B)	-	0.64	-	-
10	4.55 (B)	-	-	-	-

Table 5: Dataloggers used at each site

Site	M/M	SN	Computer
TM	CSI CR5000	1538,1521	Dell DHM Windows XP
GR	CSI CR5000	1533	Sony Vaio Laptop Windows 2000
WH	CSI CR5000	1041	Compaq Laptop Windows XP
BH	CSI CR5000	1536	Dell DHM Windows XP
WHB	CSI 21x with CSI AM25T multiplexer	3516 11451	-
BHB	CSI 21x with CSI AM25T multiplexer	8380 3515	CSI SM16M

2.2.3 Grass Area Site (GRS, GRT)

The primary grass site (GRS) was located north of WH in the athletic fields of a secondary school. A guyed 3 m tower (WT-13#14" manufactured by Universal Manufacturing Corporation, Michigan) was located at the north end of a N-S 100 m long football field. The fields were un-irrigated and grass at the site was very short and very dry. A dry, sandy, red top-layer of soil was underlain by a hard layer underneath. A sonic anemometer and krypton hygrometer were mounted at 3.69 m, a net radiometer and pyranometer at 3.09 m, and T/RH sensor at 3.19 m and an infrared thermometer at 2.66 m to measure surface temperature. Soil heat flux, temperature, and surface wetness were measured at two sites 4.5 m south of the tower, 4.4 m apart (Table 6). At GRS, atmospheric pressure, precipitation, and soil moisture were also measured. Data were collected with a CSI CR5000 datalogger and laptop computer in an enclosure at the base of the tower.

Table 6: Additional equipment located at the GRS site

Instrument	M/M (Serial number)	GRS Ht (m)	GRT Ht (m)
Rain gauge	Weathertronics 6011-B (1332)	0	
Pressure	Vaisala PTA (464322)	0	
Surface wetness	CSI 237 (x 2)	0	
Soil moist.	CSI TDR CS616		
Soil temperature	CSI TCAV thermocouples (x 2)	range -0.011 to -0.043	-0.08, -0.11, -0.08, -0.08 -0.08, -0.08, -0.07, -0.09
Soil heat flux plate	CSI HFT3 (x 2) (91226,H983367)	-0.051 -0.05	-0.08 -0.09

After day 205, the equipment was moved to another location near the TM site (GRT) (Figure 2). All variables were measured at the new site except surface wetness and surface temperature. The sonic anemometer and krypton hygrometer were mounted on a tripod at 1.75 m. Net and incoming solar radiation were measured at 1.22 m, and temperatures were sampled at 1.73, 0.80, 0.39, 0.19, and 0.10 m. Grass at this site was much longer and greener. The soil was also wetter and less compacted.

2.2.4 Tyler Media tower (TM)

Located north of GRS are two 182.9 m open lattice radio/cell phone towers owned by the Tyler Media Group. Our equipment was mounted on the western most of the two towers. Dataloggers (TMA, TMB) were located at ~80 m and at ~40 m. The equipment mounted at each level is listed in Tables 2 and 4. The instruments were installed on booms extending more than one tower width away from the tower. Fetch for this site represents an aggregation of the other sites. The houses immediately south of the TM tower are smaller than those further south (Table 8).

Table 8: Average height of buildings and trees in the vicinity of the towers (m)

Location	Houses	Trees
BH	6.5	15
WH	5.5	14
TM – immediately S	4.3	16

2.2.5 Single Brick Building (BHB)

In addition to the tower sites, individual houses were instrumented to study heat storage. A single brick house (BHB) was chosen in the fetch of the BH tower. The house is 14.5 m (E-W) by 13.23 m (N-S) and ~6 m tall. The exterior the house is predominately brick with a roof of gray tar asphalt shingles. An irrigated lawn surround the house and there were small trees (<house height) in the north yard. Surrounding houses are 6.53 m away to the east and 4.75 m to the west. The house was instrumented with infrared thermometers measuring external surface temperatures of each wall, roof facet, and the road (Table 7 at end). Fine-wire thermocouples also sampled external air temperatures at each infrared thermometer location. Indoors, thermocouples measured wall and air temperatures for each side of the house. In the lawn, soil temperature, heat flux, moisture, and surface wetness were also sampled. Variables were sampled every 10 seconds and five minute averages recorded.

2.2.6 Single Wood Building (WHB)

A wooden house (WHB) was selected immediately north of GRS and south of TM. This house was 4.28 m tall and 10.2 m (E-W) by 6.5 m (N-S). A small irrigated lawn surrounds the house and a large tree (2.5-3 times house height) provides shade on the south side. As at BHB, internal and external surface and air temperatures were recorded (Table 7). In addition, soil moisture, temperature, heat flux, and surface wetness were measured. Variables were sampled every 15 seconds and five minute averages recorded.

2.3 Processing of Data Presented

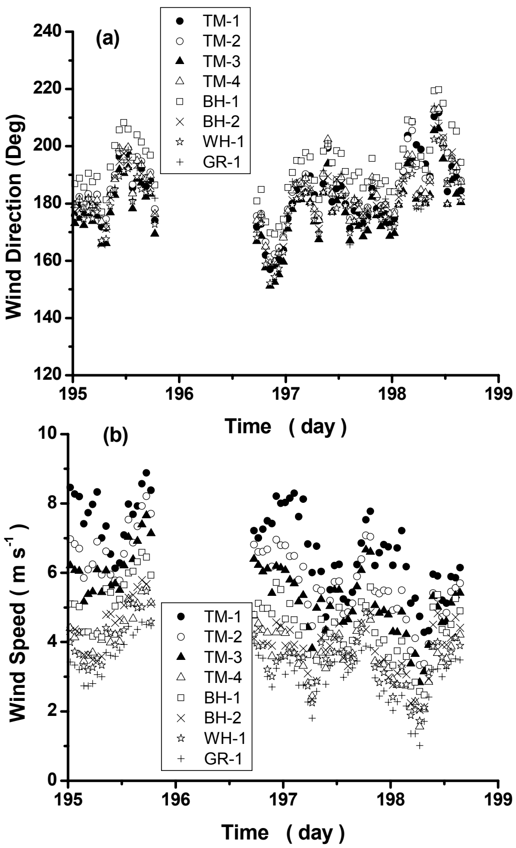
The 10 Hz data were block-averaged for 60 min periods. All data presented here are based on variables calculated for 60 min periods. All times referred to are local time (CDT); the time indicates the hour ending. The eddy-covariance fluxes were analyzed using methods similar to those described in Schmid et al. (2000), Offerle et al. (2003a), and Schmid et al. (2003).

3 RESULTS AND DISCUSSION

Here we present some preliminary results focusing on three days in a four day period (195-198 July 14-17 2003). This period is characterized by clear skies with winds consistently from the southern sector (Figure 3). It should be noted that the BH-1 sensor appears to be slightly misaligned (by 11°), but this should not affect the calculation of the eddy-covariance fluxes and other turbulent quantities.

Wind speeds show the expected increase with height. The mean wind speed (U) for TM-1 (79.6 m) was 6. 8 m s^{-1}, whereas at GR-1 [GRS] (3.7 m) it was only 3.1 m s^{-1}. The GR-1 site likely is influenced by the surrounding taller roughness elements as it was within the RSL of the suburban area; i.e. it represents a micro-scale measurement. The three sites with the most similar heights (TM-4, BH-2, WH-1, 19.4, 18.3, 17.6 m, respectively) experienced similar mean wind speeds, with an overall mean of 3.8 m s^{-1}. All three instrument levels are close to the average height of the trees but the mean roughness height is much less (Table 8).

Figure 3: (a) Wind direction and (b) wind speed observed during a clear day period. See Table 2 for heights of observations.



Friction velocity (u_*) (Figure 3) at the GR-1 site is generally much lower than at the other levels (Figure 4), indicating the strong influence of the smooth grass surface upwind. At 6 am on day 198 when U was at its minimum (Figure 3), the u_* values for all sites become more similar, but very small, indicating weak turbulent mixing and eddy-covariance flux measurements that are prone to large errors (Baldocchi et al. 2001; Su et al. 2004).

Sensible heat fluxes presented here (Figure 5) are negative at night, a notable difference from observations at other urban areas (Grimmond and Oke 2002). The study site in OKC has large amounts of vegetation present, so this result is not unexpected and consistent with observations of cool islands associated with park areas (Upmanis et al. 2001) .

The TM-1 level has the greatest loss of Q_H from the atmosphere at night and the largest daytime values. The two highest levels (TM-1,2) appear to have a dip at 1400 h which may be an apparent artifact of the two highest values observed (Figure 5a) and the small number of observations used here. Given the difference in instrumentation between TM-1 and TM-2 the consistency in daytime values is good. However, there does not seem to be the same consistency at night. The smallest flux during the daytime is from the GR-1 site.

Figure 4: Variability of friction velocity during a 4-day period between sites and levels

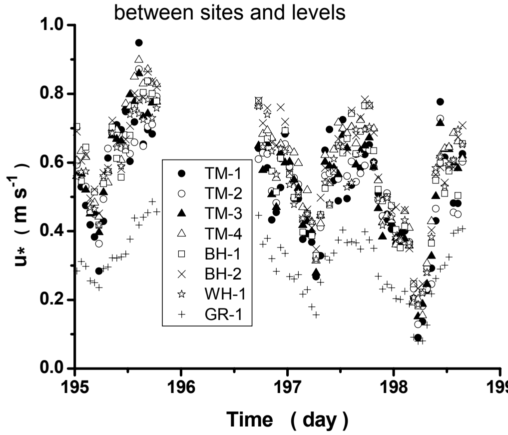
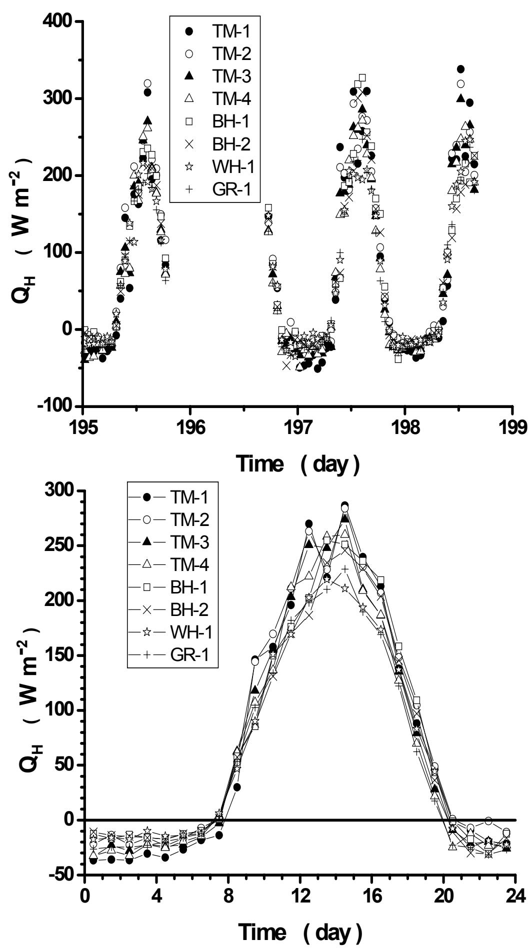


Figure 5: (a) Variability of sensible heat flux during a 4-day period between sites and levels; (b) ensemble mean of diurnal courses for the period



Comparison of hourly Q_H fluxes between sites and/or heights yielded some distinct results (Figure 6). Linear fits showed the closest or most similar relation for the two measurements with the most similar height ratios (TM-2/TM-1=0.685; BH-2/BH-1=0.633) at the same site (Figure 6a, h), with slopes of 0.94-0.95 and high R^2. As the measurement height approaches the ground on the TM or BH tower (or further away from TM-1 or BH-1), there is a general decrease in the slope and an increase in standard deviation (SD) (TM tower) of the fit (Figure 6). This could be an indication of different size and patchiness of respective source areas. The correlation coefficient (R) between the top level measurements (with TM-1 as the reference) also decreases with increasing upwind distance (GR-1 the highest, and BH-1 the lowest). This may be an indication of the relative weight (footprint) of different relatively uniform micro-scale patches of surfaces (grass, wooden house, and brick house).

Given the large amounts of vegetation in the fetch (Figure 2), the correlation between TM-1 and GR-1 is higher than would be expected if the instruments were located within an urban canyon (such as between buildings).

The results presented here are for both the daytime and nighttime. Differences are greater between levels at night (Figures 5 and 6). This is not unexpected as the source area characteristics will vary between the day time (unstable) and the nocturnal (neutral – stable). Also, the analysis presented here is based on a small number of clear days and needs to be expanded. Consideration needs to be given to the role of the differences in sonic anemometers used (Table 2) to account for any instrument differences.

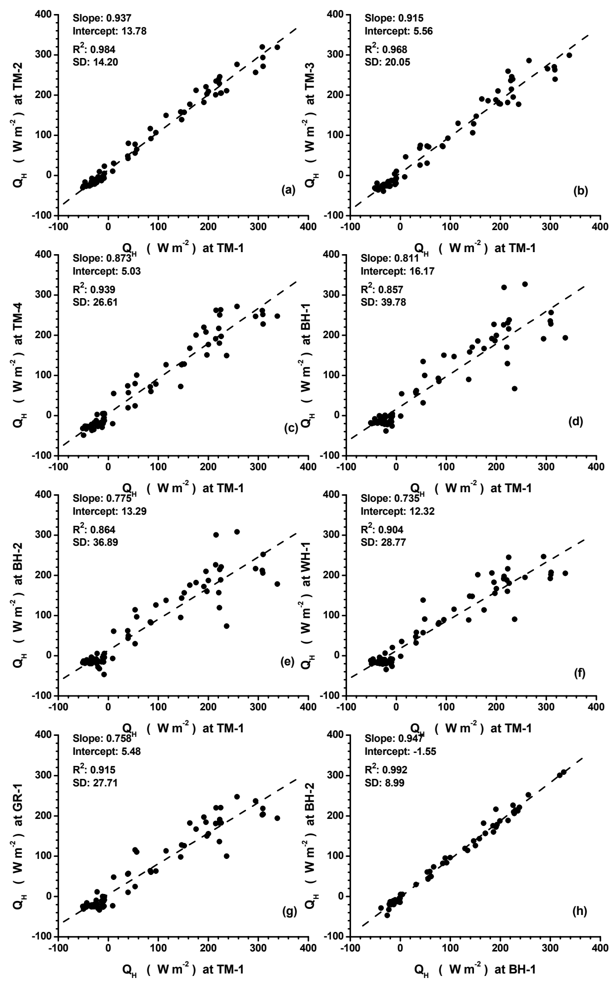
4 SUMMARY

Here we present the first results of SEB observations taken in the SASD area of the OKC Joint Urban 2003 study. A key feature is that under clear sky conditions, measured sensible heat fluxes varied significantly (over 20%) over different patches of suburban land surfaces, and also change with measurement height (footprint and source areas).

5 Acknowledgements

This research was supported by DTRA Joint Urban 2003 and NSF BCS-0095284. Equipment was provided by Indiana University (Grimmond and Schmid/Grimmond), University of Houston (Zhong) and PNL (Allwine). Sites were provided by Tyler Media, Jim and Nadine Evans, Mary Harrison, South East High School, Oklahoma School District, Cojac Portable Buildings Company, John Griffin. Jim and Nadine Evans and Mary Harrison provided electricity to run the BH, WH, and GR sites. Field assistance was provided by S.B. Kim and S.T.Kim (University of Houston). Jerry Allwine provided significant support for the installation and removal of the instruments on to the TM tower. Joe Shinn and Marty Leach (LLNL) helped secure permission to use many of these sites.

Figure 6: Comparison of Q_H fluxes between different levels. Height ratios are given in bracket. (a) TM-1 vs TM-2 (0.685) (b) TM-1 vs TM-3 (0.468) (c) TM-1 vs TM-4 (0.243) (d) TM-1 vs BH-1 (0.363) (e) TM-1 vs BH-1 (0.221) (f) TM-1 vs WH-1 (0.229) (g) TM-1 vs GR-1 (0.046) (h) BH-1 vs BH-2 (0.633). SD is the standard deviation of the comparison withTM-1 (or BH-1 h).



6 REFERENCES

Allwine, K. J. (2004). Overview Of Joint Urban 2003-An Atmospheric Dispersion Study In Oklahoma City. Joint Between The 8th Symposium On Integrated Observing And Assimilation Systems In The Atmosphere, Oceans And Land Surface And The Symposium On Planning, Nowcasting, And Forecasting In The Urban Zone, Seattle, Washington, American Meteorological Society.

Baldocchi, D., E. Falge, L. H. Gu, R. Olson, D. Hollinger, S. Running, P. Anthoni, C. Bernhofer, K. Davis, R. Evans, J. Fuentes, A. Goldstein, G. Katul, B. Law, X. H. Lee, Y. Malhi, T. Meyers, W. Munger, W. Oechel, K. T. P. U, K. Pilegaard, H. P. Schmid, R. Valentini, S. Verma, T. Vesala, K. Wilson and S. Wofsy (2001). "FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities." *Bulletin of the American Meteorological Society* **82**(11): 2415-2434.

Grimmond, C. S. B. (1992). "The Suburban Energy-Balance - Methodological Considerations and Results for a Midlatitude West-Coast City under Winter and Spring

Conditions." *International Journal of Climatology* **12**(5): 481-497.

Grimmond, C. S. B. and T. R. Oke (1999a). "Aerodynamic properties of urban areas derived, from analysis of surface form." *Journal of Applied Meteorology* **38**(9): 1262-1292.

Grimmond, C. S. B. and T. R. Oke (1999b). "Heat storage in urban areas: Local-scale observations and evaluation of a simple model." *Journal of Applied Meteorology* **38**(7): 922-940.

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)." *Journal of Applied Meteorology* **41**(7): 792-810.

Kastner-Klein, P., M. W. Rotach and E. Fedorovich (2000). Experimental study on mean flow and turbulence characteristics in an urban roughness sublayer,. Proceedings of the 14th AMS Symposium on Boundary Layer and Turbulence, Aspen, Colorado, USA., American Meteorological Society.

Masson, V., C. S. B. Grimmond and T. R. Oke (2002). "Evaluation of the Town Energy Balance (TEB) scheme with direct measurements from dry districts in two cities." *Journal of Applied Meteorology* **41**(10): 1011-1026.

McGeveran, W. A. J. (2003). *World Almanac and Book of Facts 2003*, World Almanac Education Group.1008 pp.

NOAA (2003) http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwDI~StnSrch~StnID~10009317 Accessed:10/27/03

Offerle, B., C. S. B. Grimmond, K. Fortuniak, T. R. Oke and K. Klysik (2003a). Temporal variability in heat fluxes over a Lódz. Proceeding of the 5th International Conference on Urban Climate, Lodz, Poland.

Offerle, B., P. Jonsson, I. Eliasson and C. S. B. Grimmond (2003b). Preliminary investigation of energy balance fluxes in Ouagadougou, Burkina Faso. Proceeding of the 5th International Conference on Urban Climate (ICUC5), Lodz, Poland.

Oklahoma-Climatological-Survey (2003a) http://climate.ocs.ou.edu/monthly_summary.html Accessed:10/27/03

Oklahoma-Climatological-Survey (2003b) http://climate.ocs.ou.edu/product-list.html Accessed:10/27/03

Roberts, S., T. R. Oke, J. A. Voogt, C. S. B. Grimmond and A. Lemonsu (2003). Energy storage in a European city centre. Proceeding of the 5th International Conference on Urban Climate (ICUC5), Lodz, Poland.

Roth, M. (2000). "Review of atmospheric turbulence over cities." *Quarterly Journal of the Royal Meteorological Society* **126**(564): 941-990.

Schmid, H. P., C. S. B. Grimmond, F. Cropley, B. Offerle and H. B. Su (2000). "Measurements of CO2 and energy fluxes over a mixed hardwood forest in the mid-western United States." *Agricultural and Forest Meteorology* **103**(4): 357-374.

Schmid, H. P., H. B. Su, C. S. Vogel and P. S. Curtis (2003). "Ecosystem-atmosphere exchange of carbon dioxide over a mixed hardwood forest in northern lower Michigan." *Journal of Geophysical Research-Atmospheres* **108**(D14).

Su, H. B., H. P. Schmid, C. S. B. Grimmond, C. S. Vogel and A. J. Oliphant (2004). "Spectral characteristics and correction of long-term eddy-covariance measurements over two mixed hardwood forests in non-flat terrain." *Boundary-Layer Meteorology* **110**(2): 213-253.

Upmanis, H., I. Eliasson and Y. Andersson-Skold (2001). "Case studies of the spatial variation of benzene and toluene concentrations in parks and adjacent built-up areas." *Water Air and Soil Pollution* **129**(1-4): 61-81.

Table 2: Instruments used on the towers. M/M (Manufacturer/Model) codes: CSI CSAT (CSAT), R.M. Young 81000 (RMY), CSI KH20 (KH20), REBS Q*6.7.1 (REBS), Licor Li-200SZ (200SZ), CSI CS500 (CS500), Cole-Parmer CP 39670-10 K-Type (CP-K), Ht (m) height in m with the level name indicated below.

Datalogger	TMA			TMB			BH			WH			GRS (GRT below)		
Instrument	M/M	Serial no	Ht (m)	M/M	Serial no	Ht (m)	M/M	Serial no	Ht (m)	M/M	Serial no	Ht (m)	M/M	Serial no	Ht (m)
Sonic anemometer	CSAT	214	79.63 TM-1	CSAT	491	37.26 TM-3	RMY	917	28.87 BH-1	RMY	940	17.51 WH-1	RMY	940	3.69 1.75
Sonic anemometer	RMY	939	54.56 TM-2	RMY	935	19.35 TM-4	RMY	918	18.27 BH-2	-	-	-	-	-	-
Krypton hygrometer	KH20	1184	79.63	KH20	1096	37.26	KH20	1183	28.87	KH20	1188	17.51	KH20	1188	3.69 1.75
Net radiometer	REBS	90192	80.16	REBS	90247	37.49	REBS	90247	28.0	REBS	90194	16.64	REBS	90194	3.09 1.22
Pyranometer	200SZ	11918	80.16	200SZ	11805	37.49	200SZ	11805	28.0	200SZ	16178	16.64	200SZ	16178	3.09 1.22
T/RH	CS500	s4230062	76.73	CS500	v0620001	37.26	CS500	v0620001	28.3	CS500	s3450024	16.64	CS500	s3450024	3.19 1.40
Infrared thermometer	CP-K	1C35E	80.16	CP-K	305011	37.49	CP-K	305011	28.25	CP-K	320D0	16.64	CP-K	320D0	2.66 -

Table 7: Instruments used at the BHB and WHB sites

	BHB				WHB			
	M/M (Serial No)	**Ht (m) Distance along wall (from)**	**Room, Surface material**	**Code**	**M/M (Serial No)**	**Ht (m)**	**Surface material**	**Code**
Exterior Surface (ES), Exterior Air(EA)								
N	RJ (32671)	0.495, 1.95 (E)	Brick	BH-N-ES	OIK	0.62, ,2.75 (E)	white wood	WH-N-ES
	OFT	0.536, 1.95 (E)		BH-N-EA	OFT	0.54, 2.75 (N)	wall	WH-N-EA
E	RJ (2824C)	0.545, 2.90 (N)	Brick	BH-E-ES	OIK	1.45,184 (N)	white wood	WH-E-ES
	OFT	0.59, 2.90 (N)		BH-E-EA	OFT	1.41	wall	WH-E-EA
S	RJ (2824B)	0.86, 1.95 (E)	Brick	BH-S-ES	OIK	1.24,3.07(E)	white wood	WH-S-ES
	OFT	0.98		BH-S-EA	OFT	1.3	wall	WH-S-EA
W	RJ (32672)	0.565, 2.0 (N)	Brick	BH-W-ES	OIK	0.81,2.68 (N)	white wood	WH-W-ES
	OFT	0.614		BH-W1-EA	OFT	0.7	wall	WH-W1-EA
	OT[1]	0.614		BH-W2-EA[5]		0.5		WH-W2-EA
S Roof	RJ (32670)	2.17[2]	gray tar	BH-SR-ES	OIK	0.465 [2]	gray tar	WH-SR-ES
	OT[1]	2.2[2]	shingle	BH-SR-EA	OFT	0.454[2]	shingles	WH-SR-EA
N Roof	RJ (26249)	0.582[2]	gray tar	BH-NR-ES	OIK	0.790[2]	gray tar	WH-NR-ES
	OK[1]	0.6[2]	shingle	BH-NR-EA	OFT	0.805[2]	shingles	WH-NR-EA
Road	RJ (26284)	0.96, 10.79 from	Paved	BH-R-ES	OIK	1.3	gray	WH-R-ES
	OK[1]	house	blacktop	BH-R-EA	OFT	1.19	concrete	WH-R-EA
		0.96						
Interior Surface (IS), Interior Air (IA)								
N	OK	1.4, 3.61 (E)	BR, painted white	BH-N-IS	OT	1.45, 0.995 (E)	BRC, white wall-	WH-N-IS
	OK	1.4, 3.61(E)	drywall,	BH-N-IA			papered drywall	
	OK	0.05, 3.5 (W)	Porch	BH-NP-IA				
E	OK	1.4, 2.1 (N)	BR, painted white	BH-E-IS	OT	1.24, 3.22 (S)	BR, white wall-	WH-E-IS
			drywall		OT	0.75, 3.52 (S)	papered drywall	WH-E-IA
S	OK	1.4, 0.95 (E)	BR-1, BRC-2	BH-S1-IS	OT	1.5, 1.46 (E)	BR, white wall-	WH-S-IS
	OK	1.4, 0.95 (E)	painted white	BH-S2-IS	OT	1.72, 1.25 (E)	papered drywall	WH-S-IA
	OK	1.4, 0.95 (E)	drywall	BH-S-IA				
W	OK	1.3, 1.60 (N)	K, brown wood	BH-W-IS	OT	1.07, 3.56 (N)	LR, white wall-	WH-W-IS
	OK	0.85, 1.60 (N)	paneling	BH-W-IA	OT	1.05, 3.56 (N)	papered drywall	WH-W-IA
center	OK	0.85	LR	BH-LR-IA				
Other Instruments								
	Vaisala HMP 35C (666236)	0.05	NW interior RH	BH-RH	Vaisala HMP 45C (x2840030)	1.5	Exterior[5] T/RH	WH-TRH [6]
Lawn[3,4]	CSI TCAV TC E-Type	-0.02 to -0.056	Soil temperature	BH-TSOIL	CSI TCAV TC E-Type	-0.01 -0.03	top soil layer	WH-TSOIL
Lawn[3,4]	CSI 237surface wetness	0	irrigated grass	BH-WET	CSI 237	0	irrigated grass	WH-WET
Lawn[3,4]	CSI CS616 TDR soil moisture	0- 0.15	top layer of soil	BH-MOIST	CSI CS616		top soil layer	WH-MOIST
Lawn[3,4]	CSI HFT3 (2x) (90183, 90178)	-0.06, -0.75	top layer of soil	BH-SHF	CSI HFT3 (91227)	-0.05	top soil layer	WH-SHF

[1] shielded with pvc and reflective tape [2] above roof [3] BH near NW house corner
[4] WH near SE corner of house [5] near AC unit [6] near window AC unit
RJ - Raytek CI1A J-Type IRT thermometer OIK- Omega 36SM K-Type IRT thermometer
OFT - Omega fine wire TC T-Type (0.127 mm) OK - Omega TC K-Type (24 AWG, 0.511 mm)
OT - Omega TC T-Type (24 AWG, 0.511 mm)
BR – bedroom BRC bedroom closets K – kitchen LR – living room P - Porch