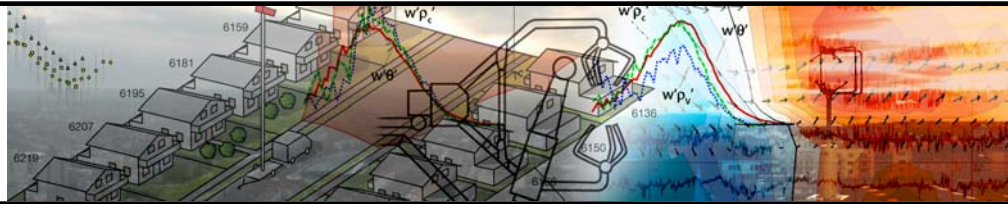




FluxLetter

THE NEWSLETTER OF FLUXNET

In this issue of the FLUXLETTER, we profile a few of the sites that are using the eddy covariance method to determine the carbon, water and energy balance in urban ecosystems across the globe. These sites document very different sources and sinks of carbon and energy than are found in natural systems. In this issue we profile sites in the UK, Poland and the U.S.



URBAN
FLUX
NETWORK

Flux measurements in urban ecosystems

Sue Grimmond and Andreas Christen

The physical functioning of a city – sometimes referred to as the ‘urban metabolism’ - requires a continuous intake of water, food, fuel, materials and power. The consumed resources are converted into waste products, some of which are injected into the urban atmosphere (i.e. waste heat, aerosols, pollutants, greenhouse gases). Many of the atmospheric wastes affect health, weather and climate at various time and space scales – hence they are important and must be incorporated in weather, air pollution and climate models, often with detailed spatial and temporal resolution.

Land-atmosphere exchange in urban ecosystems

To formulate the energy, water and carbon balance equations over an urban ecosystem, we include terms to describe the anthropogenic injections (Figure 1). For example, the energy balance (Figure 1a) contains a term to account for the injection of waste heat (anthropogenic heat flux Q_e). The urban water balance (Figure 1b) must include two additional terms - the water from irrigation / sprinkling (I) and water vapour released by fuel combustion (F). The carbon-dioxide exchange

over an urban ecosystem (Figure 1c) is often dominated by fuel combustion (C) from vehicles, industry and buildings rather than the biological processes of photosynthesis (P) and respiration (R_g).

In addition to these additional anthropogenic terms, the partitioning of energy and water can be affected dramatically by the specific construction materials, land cover and the three-dimensional form (structure). For example, it is well documented that in densely urbanized areas the heat storage in buildings and fabrics can be sufficient to maintain an upward directed sensible heat flux throughout the night. This can contribute to the genesis of the urban boundary

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Flux measurements in urban ecosystems

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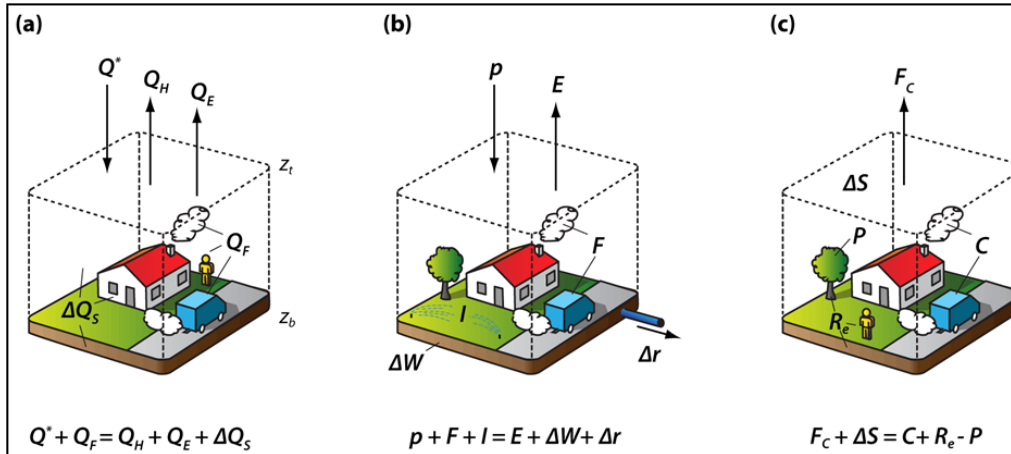


Figure 1 - Conceptual representation of the urban (a) energy balance, (b) water balance, and (c) CO₂ budget for a balancing volume that reaches from the depth where no exchange with the subsurface is found (z_b) to the measurement height on a tower above the urban ecosystem (z_t). The terms of the energy balance are - Q^* : net all-wave radiation, Q_E : anthropogenic heat flux density (electricity, fuel combustion, human metabolism), Q_H : sensible heat flux density, Q_E : latent heat flux density, ΔQ_s : storage heat flux density (ground, buildings, air). The terms of the urban water balance are - p : Precipitation, F : water released by combustion, I : water injected by irrigation, E : evapotranspiration, ΔW : storage change in soils, Δr : infiltration, surface and subsurface run-off. The terms of the urban CO₂ budget are - F_c : Net mass-flux of CO₂ between urban surface and atmosphere, ΔS : concentration change of CO₂ in measurement volume, C : CO₂ emitted by combustion, R_e : CO₂ emitted by urban ecosystem respiration (soil, plants, humans), P : CO₂ taken up by photosynthesis of urban vegetation (Modified from Feigenwinter et al. 2012).

Table 1 - Distribution of the urban flux measurement sites recorded in the Urban Flux Network database based on the location of the cities in global climate zones. The bias to sites to temperate mid latitude climates is evident. There is a clear gap on measurements on urban-atmosphere exchange in semi-arid and tropical climates.

	Fraction of world population	No of urban flux towers
Cities in tropical climates (A)	28%	3
Cities in arid and semiarid climates (B)	14.5%	3
Cities in temperate climates (C)	44.6%	40
Cities in continental climates (D)	12.4%	15
Cities in polar climates (E)	0.3%	0
Total	100%	61

layer heat island and enables better mixing of air pollutants. Another example is the presence of impervious surfaces and sewer systems which increase the run-off term in the urban water balance relative to the storage. Obviously this affects storm water management and can cause more severe flooding if the limit of the system is reached (higher peak discharge).

Understanding how the partitioning of the urban energy and water balance equations is affected by surface properties can help to mitigate some of the environmentally negative effects of urbanization and we can use building and urban design practices to intentionally modify the near-surface climates to our advantage – examples are albedo control, or the use of vegetation.

Why are urban flux towers needed?

Similar to the overall aims of FLUXNET to quantify controls on land-atmosphere exchange of energy, water and carbon, flux towers in cities allow us to infer the anthropogenic injections and/or the modified partitioning for a specific urban area. Unlike



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in non-urban areas, the determination of annual Net Ecosystem Exchange is rarely the goal, although a number of studies have quantified this for small components of the urban ecosystems (the specific tower source area). The objectives of researchers operating urban flux towers include measuring surface-atmospheric exchanges of energy, water and greenhouse gases to evaluate or verify urban land surface models under known conditions. Other studies have used flux data to evaluate emission inventories (greenhouse gases, pollutants, anthropogenic heat flux). Further, datasets from urban sites have been used to characterize

and parameterize constants used in numerical models, such as the albedo, the roughness length, or constants to describe turbulent transfer using similarity theory over urban surfaces.

Micrometeorological observation sites have been installed in cities across the world, (Table 1), however, given the different objectives compared to forest or grassland systems, only a small number of sites have been operating for multiple years and many towers were operated for short periods (i.e. a few weeks). Among the earliest flux measurements of momentum and energy were those conducted in St Louis as part of the METROMEX study

(Dabberdt and Davis 1978, Ching et al., 1983) and studies in Vancouver (Yap and Oke 1974, Yap et al. 1974). The first CO₂ flux observations above urban ecosystems were operated for only short periods (Grimmond et al. 2002, Nemitz et al. 2002). While the number of sites have increased through time (Figure 2), there are still relatively few sites that have been operational for multiple-years or are ongoing. Here we provide a brief overview of urban observation sites and draw attention to the international Urban Flux Network database that contains urban flux towers. The Urban Flux Network lists information on the cur-

rently 60 urban observation programmes from different cities worldwide.

Current representation of urban ecosystems in FLUXNET

Urban areas are very varied. Land use (residential, industrial, commercial) and the associated land cover (surface materials), structure (architectural styles), and urban metabolism (e.g. traffic patterns, population densities, energy consumption) all vary between and within cities. Most observations have been conducted in relatively dense (compact) settings with mid-height attached or detached buildings, or in open low-density areas with detached buildings (Figure 3).

The simplest way to characterize the urban surface is the division between vegetated (pervious) and impervious (buildings and paved ground) plan areas. Figure 3 provides some indication of the range of urban settings in which urban flux measurements have been conducted in the past. The range of surface cover, structure, but also the urban metabolism (including cultural-economic factors) result in

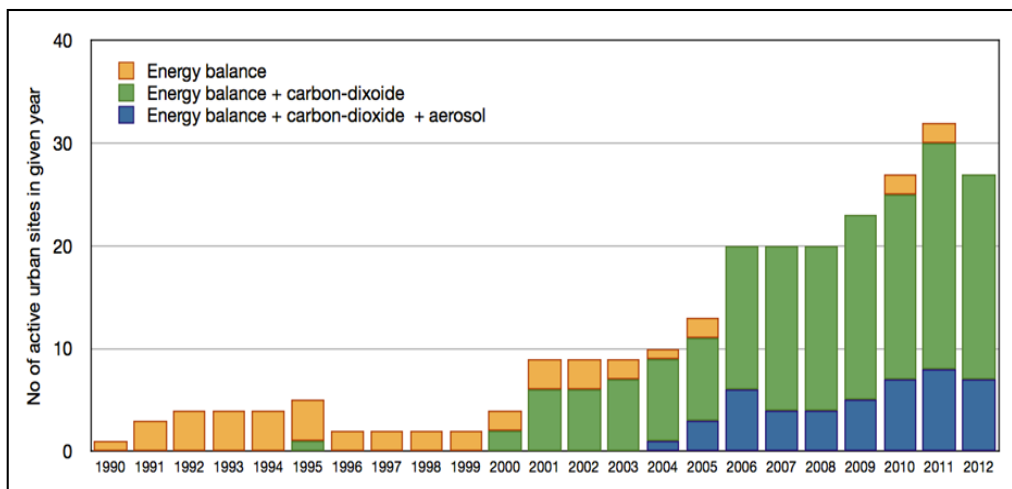


Figure 2 - Number of active urban flux sites active per year (1990-2012) and measured turbulent fluxes. Source of data: Urban Flux Network database (May 2012).



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a large range of energy partitioning, water availability and greenhouse gas emissions between cities and within cities. One overarching goal of urban flux measurements is to link the partitioning and magnitude of fluxes not only to environmental and cultural controls but also to the nature of the surface.

CO₂ exchange studies in urban ecosystems

By way of example, (Figure 4) shows 'fingerprints' of the measured CO₂ flux density for two contrasting urban ecosystems as a function of time of year and time of day. The left case shows observations conducted over 6 years in suburban Baltimore, USA, characterized by extensive tree cover and lawns (73%). The flux density of CO₂ shows clear evidence of carbon uptake during the daytime in the growing season and the fingerprint does not substantially differ from similar graphs over forest ecosystems, although one can note the overall higher emissions in winter due to space heating (Crawford et al, 2011). The right case summarizes 5 years of data

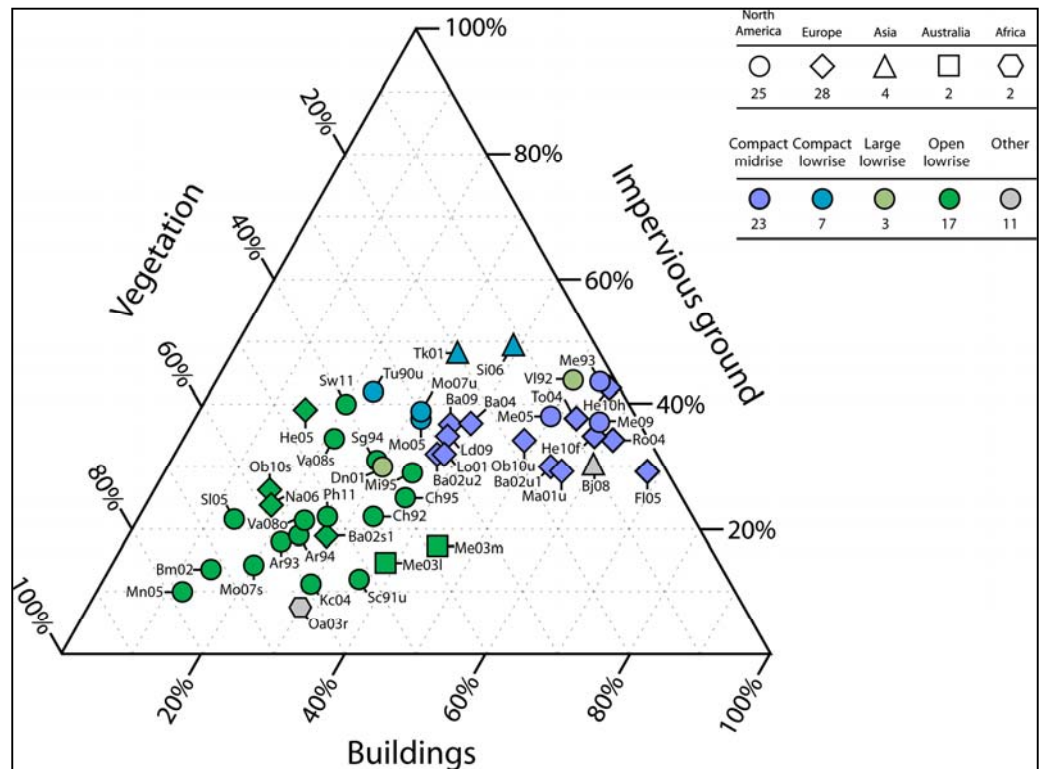


Figure 3 - The nature of the urban areas where flux measurements have been undertaken. The sites are characterized by the percentage of the plan area that is covered by building footprints, impervious ground (streets, parking lots, sidewalks) and vegetation (including open water and bare soil in some cases); the continent where the sites are located (symbol shape); and the Local Climate Zone (colour). The text associated with each symbol indicates the city, the year of observations and sometimes the site within the city. For more details about the site codes see Appendix. Numbers underneath each legend entry refer to the total number of urban flux sites reported from this continent / Local Climate Zone (Note: due to lack of cover data, not all sites in the database are shown on the graph). Modified based on Christen et al. (2009)

from Basel, Switzerland. This is a site with little vegetation in the footprint (24%) and a clear domination of transportation emissions (morning and evening rush hour). Smaller fluxes during the daytime are more evident in the warm period/growing season than in the winter

when space heating contributes to larger overall emissions throughout the day (Vogt, 2009).

Figure 5 shows the relationship between urban density (expressed as plan area fraction of buildings) and daily total summertime fluxes of CO₂ measured on 20 urban tower sites. Un-

surprisingly, with increasing urban density, the observed emissions increase. Only the highly vegetated low-density suburban areas of Montreal (Mo08s), Baltimore (Bm02) and a park in Essen (Es07[p]) remain weak sinks, where the mid-summer GPP offsets any local anthropogenic emis-

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sions. Note that the relation in Figure 5 shows density vs. per-area fluxes of the urban ecosystems and does not imply that per-capita emissions also increase with increasing density. Also note that such inter-site comparisons are very limited, in particular when extended to the heating (winter) season. Part of the energy required for space heating in buildings is satisfied by electricity or district heating systems,

which typically cause CO₂ emissions outside the tower source area. Only rarely is there a power plant in the source area of an urban flux tower (Sparks and Toumi 2010). Hence, the actually measured CO₂ fluxes at a site are strongly affected by the mix of locally emitting heating systems (natural gas, coal, wood) vs. externally emitting heating systems (electricity, steam). Another complication of inter

-site comparisons are the fact that traffic emissions in the source area - by their nature - come from mobile vehicles which are not easily attributable to local activities vs. activities not linked to the area under investigation (e.g. through-traffic). For example, the 'outlier' Va08s[a] in Figure 5 is caused by the close proximity of an arterial through-road with 50,000 vehicles per day that crosses the source area of this

tower (compare to Va08s [r] which shows the same dataset conditionally restricted to a wind sector without arterial roads). A corollary to this is the residents within the tower source area leave the area (e.g. commuters). Thus, the functional units of the urban metabolism ('carbon footprint' of a lifestyle / urban form) and the spatial representation of emissions (tower source area) are not coincident. Therefore the analysis of CO₂ flux data differs drastically from the 'traditional' forest and grassland sites in FLUXNET. Those complications call for other forms of experimental control (e.g. comparison of weekend vs. weekday fluxes) or a spatial source area analysis linked to geographical information systems of local emission sources. Often in a city emission sources in the tower's source area are geographically well located and known, and fluxes measured on urban flux towers can be a powerful tool to validate fine-scale emission models and infer emission factors (Velasco et al. 2005; Christen et al., 2011).

Some cities have had multiple CO₂ measure-

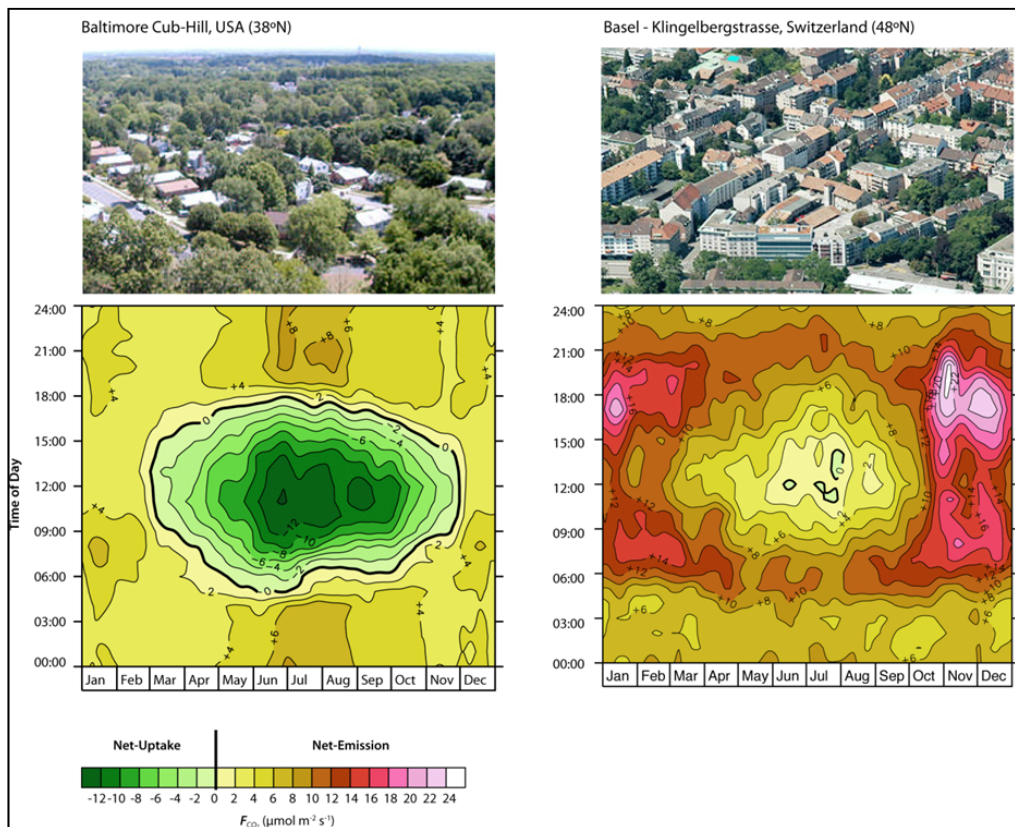


Figure 4 - Carbon fluxes by time of day and time of year for a highly vegetated suburban ecosystem in Baltimore, USA (based on data from Crawford et al., 2011) and a dense urban area in central Basel, Switzerland (based on data from Vogt et al., 2009).



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ment systems and flux towers simultaneously operated to study linkages across scales. For example, Baltimore, USA as an urban LTER site has had ongoing flux measurements since 2001 (Crawford et al. 2011). The urban area has been used as an end point on CO₂ and temperature transects for ecological response studies (Ziska et al. 2007). Montreal, Canada had a year-round operation of three sites with a density transect from the rural surrounding into the denser suburban and urban residential areas (Bergeron and Strachan, 2010). In London, UK, observations of CO₂ concentration have been conducted in the outskirts for a number of years (see, for example Lowry et al., 2001). More recently there have been flux measurements undertaken at three sites in central London: on the Imperial College London campus (Sparks and Toumi 2010), on the BT tower (Helfter et al. 2010, Wood et al. 2010) and at the King's College London Strand Campus (Kotthaus and Grimmond 2012).

In Beijing, long-term observations on a tall urban tower at the Institute of

Atmospheric Physics allow the effects of vast changes in the urban structure over time to be studied. Most recently Song and Wang (2012) have been able to analyze the impact of specific interventions on CO₂ exchanges, notably by looking at the change in CO₂ fluxes during the Olympic Games in 2008 when vehicle numbers and factory production were reduced.

This was sufficient to impact the annual total carbon flux (Liu et al. 2012).

In this issue of the newsletter there are three articles on urban flux measurements: the CO₂ exchange in urban ecosystems with an emphasis on vegetation and soils (McFadden, *this newsletter*); long term measurements in the core of a city in Poland are demonstrated

(Fortuniak et al., *this newsletter*); and comparison is made across the gradient from forest to suburb to megacity city centre (Kotthaus et al. *this newsletter*). At all sites there are a year plus of urban CO₂ flux measurements (and often energy and water balances) and at each, new avenues of understanding are profiled.

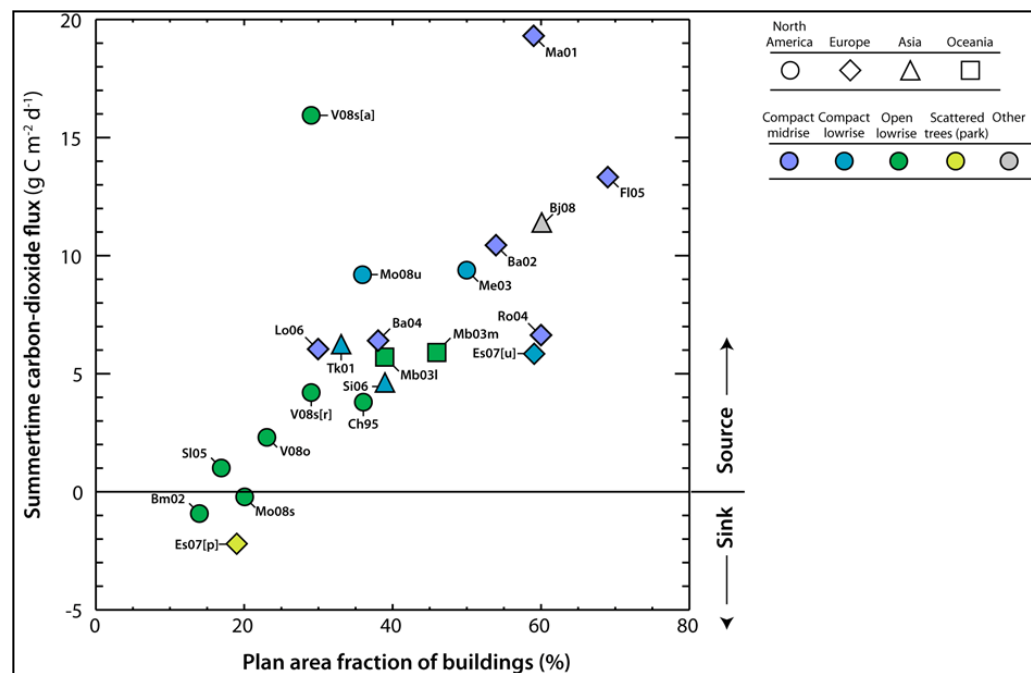
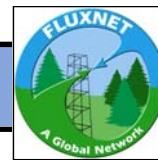


Figure 5 - Summertime carbon-dioxide fluxes measured in different urban ecosystems as a function of urban density (expressed as plan area fraction of buildings). The text associated with each symbol indicates the city, the year of observations and sometimes the site within the city. Two sites are split-up into ensemble averages for different wind sectors: Es07[p] is a sector containing a large urban park, while Es07[u] is the urban sector of this site. Va08s[r] is a residential sector with only local roads, whereas Va08s[a] is data from all wind sectors that contains busy arterial roads. For more details about the site codes see Table 4. Modified and expanded based on Christen et al. (2009).



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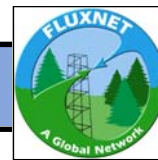
In the next issue the history of urban flux measurements from the 1970s to today at one of the oldest micrometeorological tower sites in Vancouver, Canada will be reviewed (Christen et al., *next newsletter*).

Further resources

To learn more about all urban flux sites and recent publications (or if your site is not listed in the Appendix – located at the end of the newsletter) then visit the website <http://urban-climate.com/wp3/resources/the-urban-flux-network>. Recent synthesis papers on urban flux measurements include Velasco and Roth (2010), which discusses eddy covariance observations of CO₂ fluxes in urban areas, and Loridan and Grimmond (2012), which provides an analysis of urban energy balance fluxes. A review of the techniques and challenges related to direct flux measurements in the urban environment can be found in the book “Eddy Covariance” edited by M. Aubinet, T. Vesala, and D. Papale in Chapter 16 (Feigenwinter et al., 2012).

References

- Anderson DE, Taggart J (2002) *Proc. 4th AMS Symp. Urban Environ.*, Norfolk, VA.
- Balogun AA et al. (2009) *Boundary-Layer Meteorology*, 1-23.
- Bergeron O, Strachan IB (2011) *Atmos. Environ.*, **45**, 1564-1573.
- Buckley SM, et al. (2011) *Eos Trans. AGU, Fall Meet. Suppl.*, Abstract B43B-0295.
- Changhyoun P et al. (2010) *Atmos. Environ.*, **44**, 2605-2614.
- Ching JKS et al. (1983) *Bound.-Layer Meteor.* **25**, 171-191.
- Christen A et al. (2009) *Eos Trans. AGU, 90(52), Fall Meet. Suppl.*, Abstract B31C-06.
- Christen A et al. (2011) *Atmos. Environ.*, **45**, 6057-6069.
- Coutts AM et al. (2007) *Atmos. Environ.*, **41**, 51-62.
- Crawford BR et al. (2009). *Proc. of 8th Symp Urban Environment*, Phoenix, AZ.
- Crawford BR et al. (2011) *Atmos. Environ.*, **45**. 896-905.
- Dabberdt WF, Davis PA (1978) *Bound.-Layer Meteor.*, **14**, 105-121.
- Dahlkötter F et al. (2010) *Meteorologische Zeitschrift* **19**, 565-575.
- Feigenwinter C, et al. (2012) Eddy covariance measurements over urban areas in Aubinet et al.. [Eds.] “Eddy Covariance - A Practical Guide to Measurement and Data Analysis”, Springer, 270 p.
- Frey CM, et al. (2011) *International Journal of Climatology*, **31**, 218-231.
- George K et al. (2007) *Atmos. Environ.*, **41**, 7654-7665.
- Grimmond CSB et al. (1993) *IAHS Publ.*, 212, 165–174.
- Grimmond CSB, et al. (1994) USDA FS General Tech. Rep. NE-186, 41–61.
- Grimmond, CSB, Oke TR (1995) *J. Appl. Meteor.*, **34**, 873–889.
- Grimmond CSB et al. (1996) *Climate Res.*, **6**, 45–57.
- Grimmond CSB Oke TR (1999) *J. Appl. Meteor.*, **38**, 922–940.
- Grimmond CSB et al. (2004) *JGR - Atmospheres*, **109**, D24101.
- Goldbach A, Kuttler W (2012) *International Journal of Climatology*, DOI: 10.1002/joc.3437.
- Helfter C, et al. (2011) *Atmospheric Chemistry and Physics*, **11**, 1913-1928.
- King T, Grimmond CSB (1997) 12th AMS Symp. on Boundary Layers and Turbulence, 455–456.
- Kordowski K, Kuttler W (2010) *Atmospheric Environment*, **44**, 2722-2730.
- Lemonsu A et al. (2004). *Journal of Applied Meteorology*, **43**, 312–327.
- Liu HZ, et al. (2012) www.atmos-chem-phys-discuss.net/12/7677/2012/
- Loridan T, Grimmond CSB (2012) *J. Appl Meteorol Climat*, **51**, 219-241
- Lowry D et al. (2001). *J. Geophys. Res. Atmospheres*, **106**, 7427-7448.
- Masson V et al. (2008) *Meteorology and Atmospheric Physics*, **102**, 135-157.
- Matese A et al. (2009) *J Appl Meteorol Clim.* **48**, 1940-1947.
- Moriwaki R, Kanda M (2004) “*J. Appl. Meteorol.* **43**, 1700-1710.



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- Nemitz E et al. (2002) *Environ. Sci. Technol.*, **36**, 3139–3146.
- Newton T et al. (2007) *Geographic Annaler*: 89 A (4) 331–347.
- Offerle B, et al. (2005) *Journal of Climate*, **18**, 3983–3995.
- Offerle B et al. (2006a) *Theor. Appl. Climatol.*, **84**, 103–115.
- Offerle B, et al. (2006b) *J Applied Meteorology*, **45**, 125–136.
- Oke TR et al. (1999) *Atmos. Environ.*, **33**, 3919–3930.
- Pawlak W et al. (2011) *International Journal of Climatology*, **31**, 232–243.
- Peters EB, McFadden JP (2012), *Journal of Geophysical Research-Biogeosciences*, In review.
- Ramamurthy P, Pardyjak ER (2011) *Atmos. Environ*, **45**, 73–84.
- Rigby M et al. (2008) *Atmos. Environ.* **42**, 8943–8953.
- Roth M et al.(2009). 8th AMS Symp on the Urban Environment, Phoenix, AZ
- Ruban V et al. (2011) *Bulletin du Laboratoire des Ponts et Chaussées*, 277, 5–18.
- Song T, Wang YS (2012) *Atmos. Res.*, **106**, 139–149, 2012.
- Sparks N, Toumi R, (2010) *Atmos. Environ*, **44**, 5287–5294
- Stewart I, Oke TR (2009) 8th AMS Symposium on Urban Environment, Paper J8.3.
- Velasco EVS et al. (2005) *Atmos. Environ.* **39**, 7433–7446.
- Velasco EVS, Roth M (2010) *Geography Compass*, **4/9**, 1238–1259.
- Velasco E et al. (2011) *Theoretical And Applied Climatology*, **103**, 501–517.
- Vesala T et al. (2008) *Tellus* **60B**: 188–199.
- Vogt R (2009) 7th Int. Conf. on Urban Climate, Yokohama, Japan,
- Vogt R et al. (2005). *Theor Appl Climatol.* **84**,117–126
- Yap D et al. (1974) *J. Appl. Meteorol.* **13**, 40–45.
- Yap D, Oke TR (1974) *J. Appl. Meteorol.* **13**, 880–890.

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CO₂, water vapor, and energy fluxes from urban vegetation and soils

Joe McFadden

Urban vegetation function

The role of vegetation in the micrometeorology of urban areas, particularly its aerodynamic, thermal, radiative, and evaporative functions, has long been recognized by the urban climate community (Oke, 1989). In contrast, studies of urban CO₂ fluxes began only during the past decade (Grimmond et al., 2002), and our understanding of how different processes (*e.g.*, photosynthesis and respiration by vegetation, emissions from fossil fuel combustion) contribute to the net CO₂ flux above urban areas lags behind the state-of-the-art for natural or agricultural environments. This is particularly important for residential and suburban landscapes

that have relatively high vegetation cover and that make up the largest area fraction of most metropolitan areas. For example, in Minneapolis–Saint Paul where our study site is located, 51% of the total land area is residential while 12% is commercial, institutional, and other built-up land use in the city center.

The net uptake of CO₂ by urban vegetation and soils is of interest not because it can offset the fossil-fuel CO₂ emissions of cities (unfortunately, far from it), but rather because developed land is a large, and often rapidly growing, fraction of the land use in most regions over which we want to construct carbon budgets. Yet the magnitudes of vegetation carbon

sinks and sources in developed land are poorly known, as are their seasonal dynamics and spatial patterns in different types of cities and climates. Water vapor fluxes in urban areas are of interest because of their potential benefits for reducing storm water runoff and the urban heat island effect, and because of their potential costs associated with the use of irrigation in arid climates, both of which affect energy use and, therefore, CO₂ as well.

My group is studying how different components of the urban vegetation and soil system contribute to CO₂, water vapor, and energy exchanges from the scale of an urban or suburban neighborhood to a met-

ropolitan region. Our goal is to develop a mechanistic understanding of the spatial and temporal drivers of these fluxes in the built environment and to provide the information needed to improve the representation of vegetation function in urban land surface schemes and biogeochemical models. Here, I want to provide an overview and some key results of a set of interlinked studies over a suburban landscape at the KUOM tall tower.

KUOM tower site

The study site is located in a suburban residential area (Fig. 1) of the twin cities of Minneapolis–Saint Paul, along the Mississippi River in east central Minne-

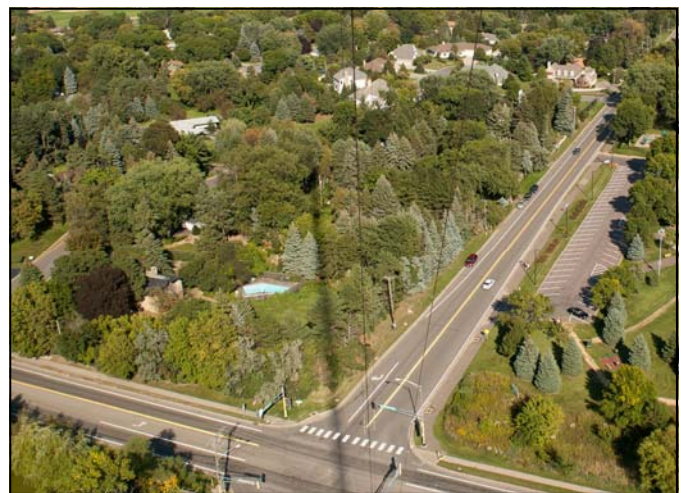


Figure 1. View to the northeast from the 150 m level of the KUOM tall tower in winter (left) and summer (right).

CO₂, water vapor, and energy fluxes from urban vegetation and soils

Joe McFadden

sota, USA (45°00' N, 93° 11' W, 300 m a.s.l.). This first-ring suburb is immediately outside the Saint Paul boundary and is situated about midway between the city centers of Minneapolis and Saint Paul

golf course, corresponding to Urban Climate Zone 5 (Oke, 2004). It has approximately 1000 inhabitants km⁻² and a housing density of 350 units km⁻². The plan area fractional cover within the residential

mate with a mean annual (1970–2000) temperature of 7.4°C (ranging from a January mean of -10.5°C to 22.9°C in July) and precipitation of 747 mm. Research at the site began in 2004 with an urban forest

150 m tall KUOM broadcast tower. Eddy covariance systems were installed at 40 and 80 m on the tower to permit investigation of footprint effects, and a four-component radiometer (CNR1) was installed at 150 m to obtain the largest possible footprint for radiative fluxes. The measurement heights were greater than twice the average 12-m height of the trees, which overtopped the roofs of the houses, so we could assume the measurements were obtained above the roughness sublayer. The mean roughness length z_0 was 1.2 m, a typical value for a suburban site.

Each eddy covariance system consisted of a 3-D sonic anemometer (Campbell CSAT3) and a closed-path infrared gas analyzer (LI-Cor LI-7000). Digital signals from the sonic anemometers were transmitted to the tower base by fiber optic cables to avoid RF interference from the broadcast tower. Air was sampled through 9.5 mm I.D. pure FEP tubing at a rate of 23 SLPM and a bypass flow of 7.5 SLPM through 4 mm I.D. pure PTFE tubing was delivered to the gas analyzers using a system of needle valves, mass-flow meters, and two



Figure 2. The typical configuration of streets, buildings, and vegetation at street level.

(6 and 9 km away, respectively). The study area experienced rapid residential development in the 1950s on land that had been used previously for nurseries and small vegetable farms.

The current land use within 1.5 km of the flux tower consists of 1 or 2 story single-family, detached houses (Fig. 2) and a

area is 43% tree canopy, 34% turfgrass lawns (total of 77% vegetated), and 22% impervious surfaces, although the total impervious fraction is greater when buildings and sealed surfaces under the tree canopy are considered (total of 34%).

Minneapolis–Saint Paul has a cold temperate cli-

inventory and biophysical measurement program, and flux measurements were active from 2005 to 2009.

Local-scale flux measurements

Fluxes at the scale of the suburban neighborhood were measured from the

CO₂, water vapor, and energy fluxes from urban vegetation and soils

Joe McFadden

rotary vane vacuum pumps (lag time of ~ 9 s). The gas analyzers, calibration tanks, and data acquisition systems were housed in two insulated, thermostatically controlled, heated and ventilated rack-mount enclosures at the tower base.

Component flux measurements

Turfgrass lawns. We concurrently operated a portable eddy covariance system over a 1.5 ha turfgrass field located within the tall tower footprint. It included a CSAT3 sonic anemometer and an open-path LI-Cor LI-7500 gas analyzer installed at 1.35 m above ground, along with a set of radiometers, soil heat flux, temperature, and volumetric moisture content sensors.

The dominant species in the lawn were the C₃ cool-season turfgrasses Kentucky bluegrass (*Poa pratensis*), tall fescue (*Festuca arundinacea*), and perennial ryegrass (*Lolium perenne*). The site was not irrigated and it received one application of fertilizer per year. The grass was mowed weekly to a height of 70 mm, and the clippings were left in place to decompose. The site was representative of low-maintenance lawns such as those found in a majority of residential yards in our study area.

Urban trees. During 2007 and 2008, continuous sap flow and leaf-level gas exchange measurements of trees in the urban area (Fig. 3) were made by Emily



Figure 3. Emily Peters making leaf-level gas exchange measurements on trees in the tall tower footprint.



Figure 4. A section of the sampling grid used for urban forest and biophysical measurements. The yellow circles represent 7.3 m radius (167 m^2) sampling plots ($N = 1168$ plots in total) that were randomly stratified within $1/1000^{\text{th}}$ size subsamples of an EMAP unit (yellow hexagons).

Peters for her Ph.D. project. The measured trees comprised seven different genera (*Fraxinus*, *Juglans*, *Picea*, *Pinus*, *Quercus*, *Tilia*, and *Ulmus*) and included evergreen needleleaf and deciduous broadleaf plant functional types. They were representative of the dominant canopy species that had been determined from an urban forest inventory following U.S. Forest

Service Forest Inventory and Analysis (FIA) protocol. Biophysical measurements, including LAI, surface radiative temperature, soil temperature, and soil moisture were monitored across the urban forest sampling grid throughout the growing season (Fig. 4).

Fossil fuel combustion. We collected a variety of



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data on CO₂ emissions from combustion sources and human respiration to constrain our bottom-up estimates of CO₂ exchange by vegetation and soils, and so that we could eventually produce complete CO₂

budgets for the suburban neighborhood. Vehicular traffic, the largest contributor to short-timescale variations in urban CO₂ exchange, was measured every 15 minutes using loop detectors under the

roadways nearest the tall tower. A series of 1–2 month campaigns with a fast-response vacuum UV resonance fluorescence carbon monoxide analyzer (AeroLaser AL-5002) were used to obtain the CO:CO₂ flux ratio, as a tracer of combustion-derived CO₂ fluxes. In addition, I am one of the PIs on an interdisciplinary team that used a survey, utility billing records, parcel data, remote sensing, and field measurements to quantify monthly carbon emissions from home energy use and human respiration across the metropolitan region (Fissore et al., 2011, 2012).

mates based on emissions factors of the passing vehicles.

Some key results on the relative contributions of individual vegetation types to local scale evapotranspiration and net CO₂ exchange are shown in (Fig. 5). There were 2–4 fold differences in both fluxes among vegetation types and marked seasonal variations associated with their physiology, such as the contrast between evergreen and deciduous trees, and the mid-summer decline of CO₂ uptake that is characteristic of cool-season C₃ turfgrasses. The total growing season (Apr–Nov) net CO₂ exchange of vegetation and soils in the residential area was –124 g C m⁻², while the total evapotranspiration was 324 mm, or 61% of precipitation at the site. When fluxes from each vegetation type were scaled up using a footprint model and a detailed land cover data set, they agreed well with measurements from the tall tower (Peters et al., 2011; Peters and McFadden, 2012).

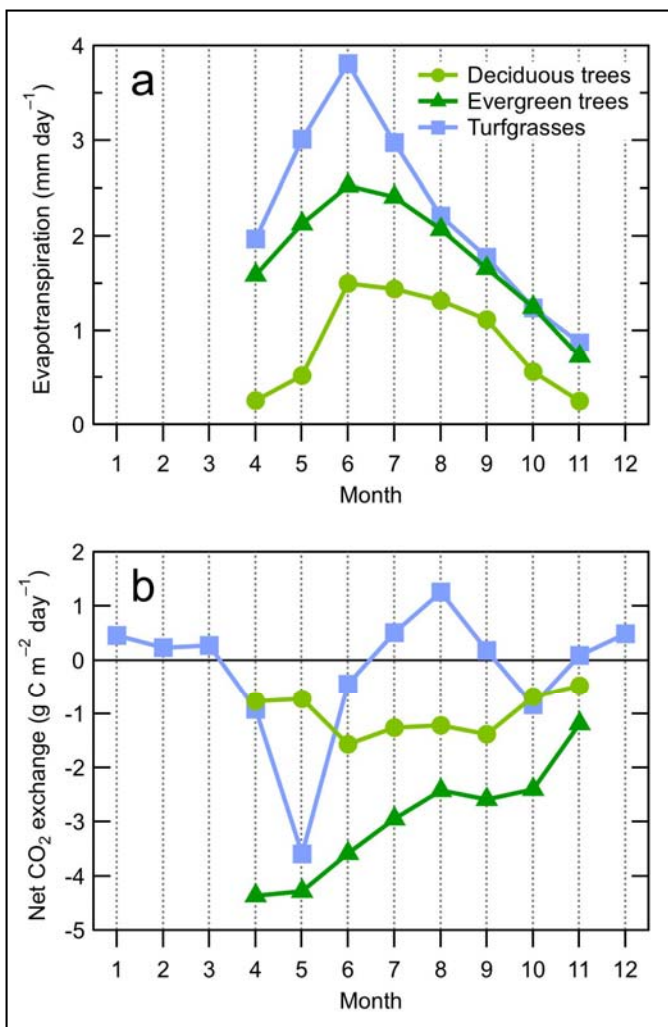


Figure 5: Mean daily fluxes in 2008 of (a) evapotranspiration and (b) net CO₂ exchange per unit area of canopy cover of deciduous broadleaf trees and evergreen trees measured by sap flow and leaf-level gas exchange, and non-irrigated turfgrasses measured by a portable eddy covariance system.

Key results

One of our first tasks was to assess CO₂ exchange over the turfgrass lawn, including the potential effects of point sources such as traffic. This work was carried out by Rebecca Hiller, a visiting researcher from Switzerland who has since gone on to complete her Ph.D. at ETH Zürich. Hiller et al. (2011) developed an empirical approach using a footprint model and measured traffic volume, and found that it agreed well with “bottom-up” esti-



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Current work

More recently, Olaf Menzer has joined my lab after completing his master's thesis in the model-data integration group at the Max Planck Institute for Biogeochemistry in Jena. For his Ph.D. project, among other things, he is evaluating machine learning methods for gap-filling the tall tower flux time series, a complex problem that requires time-varying drivers of both combustion and ecological fluxes, as well as spatial information about how the flux footprint changes with each 30-minute observation.

In 2008 my lab moved from Minnesota to U.C. Santa Barbara where, along with continued modeling and synthesis of KUOM data, we have begun new studies of vegetation function in semi-arid urban areas focusing especially on water use. Overall, despite the complexity and logistical challenges of urban sites, the results thus far have been encouraging that we are beginning to make sense of the role that vegetation and soils play in determining land-atmosphere fluxes in urban and suburban areas.

Acknowledgments

We thank more than 350 homeowners and the managers of two golf courses for granting us permission to conduct this research on their property; Larry Oberg, chief engineer of KUOM for access to the tall tower; Brian Horgan for access to the turfgrass research site; Duane Schilder of Ramsey County for traffic count data; the parks and recreation departments of Minneapolis and Saint Paul, Rainbow Tree Care, and S & S Tree Specialists for providing aerial lift trucks and operators for tree sampling. The following former undergraduate students and researchers from the lab contributed to the field work and instrument operation: Ahmed Balogun, Ben Freeman, Vikram Gowreesunker, Cheyne Hadley, Nicole Ifill, Vicki Kalkirtz, Rebecca Koetter, Mark McPhail, Julia Rauchfuss, Scott Shatto, and Yana Sorokin. I am grateful to Dean Anderson and Sue Grimmond for their advice and encouragement on the urban tall tower setup, and to NASA for a New Investigator grant that provided the major funding for this project (NNG04GN80G).

Further reading

Fissore, C., L. A. Baker, S. E. Hobbie, J. Y. King, J. P. McFadden, K. C. Nelson, and I. Jakobsdottir (2011), Carbon, nitrogen, and phosphorus fluxes in household ecosystems in the Minneapolis–Saint Paul, Minnesota, urban region, *Ecological Applications*, 21(3), 619–639.

Fissore, C., S. E. Hobbie, J. Y. King, J. P. McFadden, K. C. Nelson, and L. A. Baker (2012), The residential landscape: fluxes of elements and the role of household decisions, *Urban Ecosystems*, 15(1), 1–18.

Grimmond, C. S. B., T. S. King, F. D. Cropley, D. J. Nowak, and C. Souch (2002), Local-scale fluxes of carbon dioxide in urban environments: methodological challenges and results from Chicago, *Environmental Pollution*, 116, S243–S254.

Hiller, R. V., J. P. McFadden, and N. Kljun (2011), Interpreting CO₂ fluxes over a suburban lawn: the influence of traffic emissions, *Boundary-Layer Meteorology*, 138(2), 215–230.

Oke, T. R. (1989), The micro-meteorology of the urban forest, *Philosophical Transactions of the Royal Society of London, Series B*, 324, 335–349.

Oke, T.R. (2004), *Initial guidance to obtain representa-*

tive meteorological observations at urban sites. IOM Report 81, World Meteorological Organization, Geneva.

Peters, E. B., R. V. Hiller, and J. P. McFadden (2011), Seasonal contributions of vegetation types to suburban evapotranspiration, *Journal of Geophysical Research-Biogeosciences*, 116, G01003.

Peters, E. B., and J. P. McFadden (2010), Influence of seasonality and vegetation type on suburban microclimates, *Urban Ecosystems*, 13 (4), 443–460.

Peters, E. B., and J. P. McFadden (2012), Continuous measurements of net CO₂ exchange by vegetation and soils in a suburban landscape, *Journal of Geophysical Research-Biogeosciences*, In press.

Peters, E. B., J. P. McFadden, and R. A. Montgomery (2010), Biological and environmental controls on tree transpiration in a suburban landscape, *Journal of Geophysical Research-Biogeosciences*, 115, G04006.

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Urban flux measurements in Łódź, central Poland

Krzysztof Fortuniak, Włodzimierz Pawlak, Mariusz Siedlecki, and Mariusz Zieliński

Introduction

The topographical setting of the city, its size and building structure makes Łódź a good place for studies on modifications of local climate by urbanization. It is located in the central part of Poland on the big European lowlands, and with a population of about 750,000, it is among the biggest Polish cities. The area is relatively flat, and only slightly inclined south-easterly (altitudes range from 180 m to 235 m a.s.l.). The absence of significant topographical features, such as lakes, rivers, valleys, mountains, or the sea allows urban effects to be discerned without interference. In the city centre, buildings constructed about 100 years ago are mainly 15-20 m high and make up an extensive, fairly homogeneous and compact settlement of great density with clearly defined roof-level. The studies on urban climate in Łódź have a long history, going back to the 1930's when a pair of urban-rural stations worked for a few years providing standard meteorological data needed for detecting of the singularities of urban climate. After the war, the various elements of urban climate were investigated

in Łódź since the 1960's, but regular meteorological measurements of the urban-rural contrasts of the parameters started in 1992 (Kłysik & Fortuniak 1999, Fortuniak et al. 2006). Recently we have focused on the urban energy balance components and turbulent flux measurements in the city. Hereafter we wish to share our experiences in this field and present selected results from Łódź.

Long-term sites description and instrumentation

Flux measurements in Łódź started in November 2000 when Sue Grimmond and Brian Offerle (then of Indiana University) installed the first open-path eddy-covariance system at the top of a 20 m mast, and mounted it on the roof of a university building at Lipowa 81 str. (51°

$45'45''N$, $19^{\circ}26'43''E$, 204 m a.s.l.). The building (17 m) is at least as high as surrounding ones, so the measurement height (37 m) is close or just above the blending height. The site is located at the western edge of the old core of Łódź in dense development, where buildings are 7-13 m in height and covers 15-40% of surrounding area (Fig. 1). Dark tarred roofs and as-

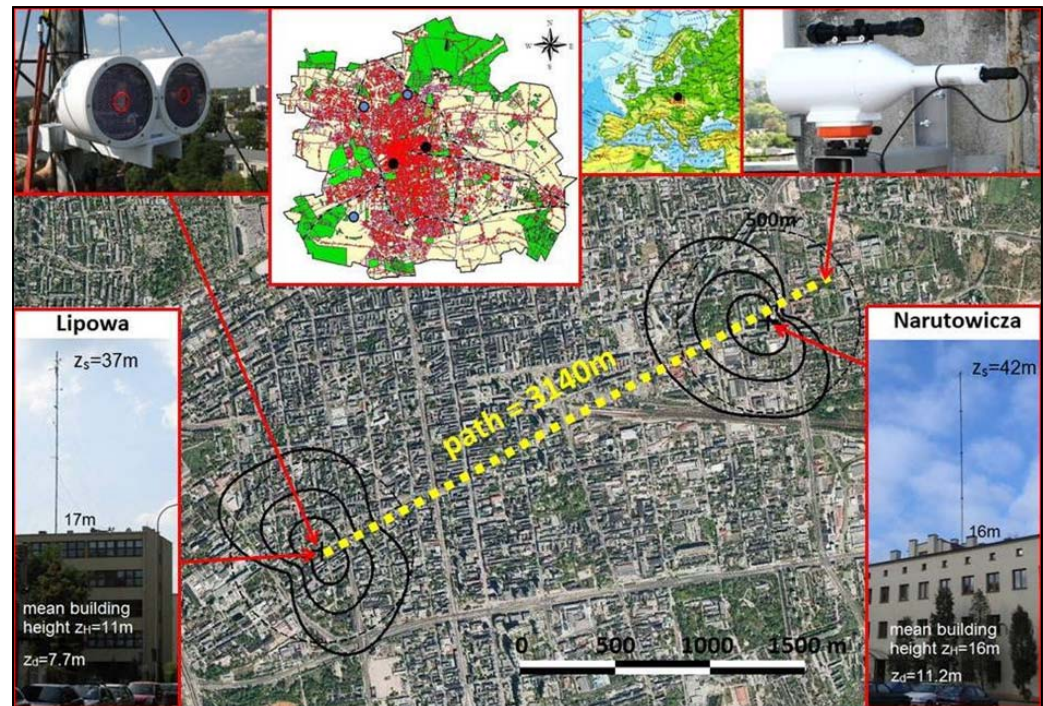


Figure 1: Area of investigation and location measurements sites. Solid lines surrounding the measurement point indicates source areas at $p = 50, 75$ and 90% calculated for turbulent fluxes measured in unstable stratification (all available data selected for calculations). Black point at upper map indicates long-term measurements sites, blue dots – short experiments in years 2002-2003. Aerial photo source: Municipal Centre of Geodesics and Cartographic Documentation of Łódź.

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phalt roads dominate the artificial cover of the surrounding measurement area, and result in low albedo in comparison to other cities (8%). Vegetation cover depends on geographic sector and varies from 10-20% in the north-

east sector to 30-55% in the west (Fig. 2). The aerodynamic roughness length for momentum calculated from the logarithmic wind profile for close to neutral stratification depends on flow direction, with an average of about 2 m.

In the first system, turbulent fluxes were measured by 3D sonic anemometer (SWS-211/3K Applied Technologies, Inc.) and a krypton hygrometer (KH20 Campbell Scientific). Moreover, fast-response temperature

was measured by a thermocouple wire. The fast-response data output was set as 10 Hz. Additional data included radiation balance components (measured by Kipp and Zonen CNR1), temperature and humidity, wind speed and direction and precipitation obtained from slow-response sensors. The eddy-covariance system worked up to September 2003 providing data on the urban energy balance (Offerle et al. 2005, 2006a,b), but standard meteorological measurements have been continued since that date. A new eddy-covariance system has been working at the same place since July 2006. The system is equipped with Li7500 infrared CO₂/H₂O gas analyzer enabling estimation of the net exchange of carbon dioxide in parallel with measurement of the energy balance components. Wind components and temperature fluctuations are measured by RMYoung 81000 sonic anemometer.

The second long-term eddy-covariance tower was established in June 2005 on the roof of the building of the Faculty of Geographical Science at Narutowicza 88 str. (51°46'24"N,



Figure 2: System maintenance and view from the top of mast at Lipowa site toward the city centre (eastward).

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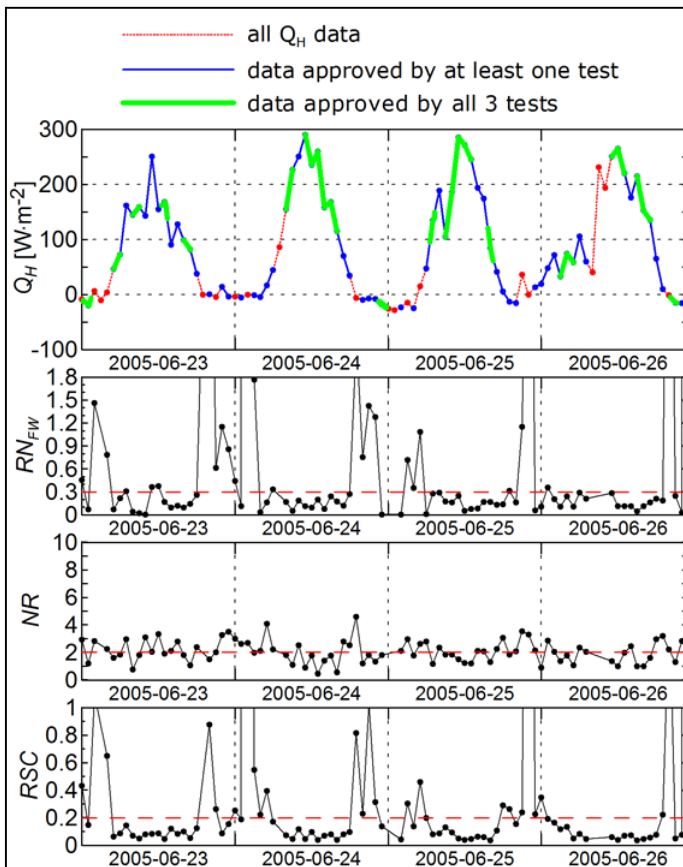


Figure 3: Example of three stationarity tests used in post-processing data quality control of sensible heat flux, Q_H : (See text for further explanation.)

19°28'52"E, 221 m a.s.l.). This site is located 2.7 km east from the first one in a slightly less compact settlement. The buildings around the site are slightly taller (average about 17 m). The tower itself is 25 m and it is mounted on the roof of a 16 m building. The fast-response sensors (RMYoung 81000 and KH20 krypton hygrometer, sample at a rate of

10 Hz) and are located on a horizontal arm at the top of the mast, giving a measurements height of almost 42 m, which should be just above the roughness sub-layer. Similarly to the Lipowa site, the roughness length for momentum is angular dependent and has an average close to 2 m.

Data management

The pre- and post-processing analysis as well as data management are similar for both sites and to that of other eddy-covariance groups. Fluxes are calculated for 1 hour periods by simple block averaging. This relatively extended interval is motivated by the possible existence of relatively large eddies generated above the rough, warm urban surface. A comparison of fluxes calculated for a 1-h period with a mean value of four consecutive fluxes based on 15-min periods shows that the second method underestimates fluxes by about 5%, owing to spectral losses. Before flux calculations are implemented, spike detection is carried out. All flux calculations are made in natural wind coordinates with double rotations. Due to the possible influence of sensor separation, covariance is maximized for the range ± 2 s. Final fluxes are corrected to account for the influence of humidity on sonic temperature, oxygen absorption over the krypton's bandwidth and density effects (WPL – Webb-Pearman-Leuning correction).

In the post-processing data quality assessment, we focus on verification of the stationarity postulate; theoretical requirements of the eddy-covariance method that require time series to be stationary in the averaging period. Three stationarity tests are used to check this postulate: the test proposed by Foken and Wichura (1996) with a critical value of $RN_{FW} = 0.3$; the non-stationarity ratio, NR, given by Mahrt (1998) with a critical value of $NR = 2$; and the relative covariance stationarity criterion introduced by Duttar et al. (1999) and modified by Nemitz et al. (2002) with a critical value of the relative covariance stationarity coefficient, $RCS = 0.5$ (Fig. 3). The problem, or questions that remain, are if the data should be accepted as a 'good' when it passes all three tests or only one of them. In the case of sensible heat flux, only about one-third of the data passes all three tests. Rejection of so much of the data set significantly reduces the amount of data available for further analysis (like estimation of the diurnal evolution of the energy balance, or cumulative fluxes). On the other hand, as it is shown in Fig. 3, much

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of the ‘good-looking’ data at night does not pass any of the tests.

The other problem related to quality assessment is verification of the postulate of well developed turbulence. The similarity relations of integral turbulence characteristics, normalised standard variations of wind components and temperature, are commonly used to test this postulate. Our results suggests that this criterion must be applied with caution. The universal functions for urban areas might differ from those suggested for flat rural surfaces, so the function’s parameters must be verified before application to avoid excluding potentially appropriate data (Fig. 4).

In addition to the standard procedures some

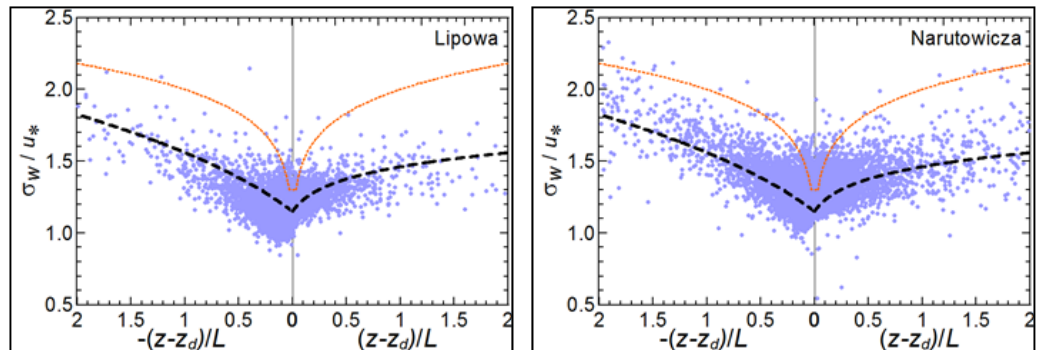


Figure 4: Normalized standard deviation of vertical wind component as a function of stability. Black dashed line – fit to the Łódź data, orange dotted line –function given by Foken and Wichura (1996).

further considerations might be needed to ensure high quality flux data for urban areas. For example, an analysis of the angular dependence of normalised variance of vertical wind components in neutral conditions at the Lipowa site shows three evident peaks (Fig. 5). The first around the 270° wind direction can be attributed to

the direct influence of the mast (flux sensors are placed on the boom at a location about 1 m east from the mast). Two other peaks are more difficult to explain, but they correspond to the azimuth of the streets passing next to the tower building. So, our speculation is that the street canyons modify flow. Therefore, data obtained

from these directions must be used with caution. Additional support for this hypothesis comes from the wind rose for the site. The gaps are observed for directions of the street azimuth, whereas typical wind roses for the region are more uniformly distributed. For the Lipowa site, the same, non-typical wind roses are recorded by two different anemometers for both sides of the mast, so a possible influence of the mast itself seems not to be the reason (Fortuniak et al. 2012).

Selected results

The relatively long term nature of our flux measurements allows for detailed studies of energy balance components, and a few examples are presented here. The most evident feature of the energy bal-

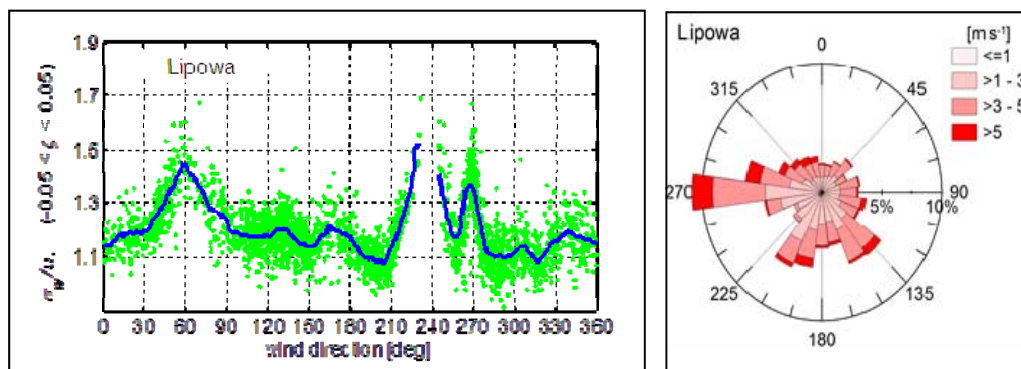


Figure 5: Normalised variance for vertical wind component, σ_w / u_{**} , by wind direction for neutral conditions ($|\zeta| < 0.05$) (left), and wind frequency distribution (15° intervals) classified according to different wind speed (1 h average) (right) for Lipowa site (after: Fortuniak et al. 2012).

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ance in this and other urban areas is the relatively large portion of energy partitioning devoted to sensible heat flux, Q_H (Fig. 6). In summer, at noon, this flux reach about 150 W m^{-2} on average at both sites, whereas latent heat, Q_E , remains at $80\text{--}100 \text{ W m}^{-2}$. Similar values of Q_H are observed in spring, but the lack of transpiration by vegetation causes Q_E to be significantly lower. The highest values of Q_H are more than 300 W m^{-2} on summer days. Conversely, a few examples of negative values of Q_H occur throughout the day during warm advection after a cold period. Extremes of Q_E are hardly detectable. Under fine weather, values can reach about 150 W m^{-2} . The maximum values are expected immediately following summer showers when rain falls on the hot urban surface. However, open-path eddy-covariance systems do not provide reliable data in such situations. Other characteristic results unique to built-up sites, are the positive value of Q_H in late afternoon/evening when the radiation balance, Q^* , turns negative. This phenomena can be attributed to the heat release from the city, and associated with the altered

thermal properties of a city, e.g. the large heat storage capacity. As in many other urban sites, during winter when Q^* is only positive for a few

hours a day, the sum of the turbulent fluxes remains primarily positive. Moreover, in Łódź we observe positive latent heat flux values most of

the time, even during night hours. Negative values of Q_E are extremely rare.

The long term measurements of the carbon dioxide flux, FCO_2 , demonstrate that the city is a significant source of this gas. The annual course of FCO_2 is the reverse of the temperature evolution. The monthly totals in winter are on the level of $1200 \text{ g m}^{-3} \text{ month}^{-1}$. Such high fluxes of CO_2 in wintertime are a result of anthropogenic emissions from domestic heating sources and the high density of urban traffic. In summer, both anthropogenic sources are reduced (no need for heating and smaller car traffic during vacation), and some amount of CO_2 is taken up by vegetation. As a consequence, the summer totals are about $500\text{--}700 \text{ g m}^{-3} \text{ month}^{-1}$.

The seasonal changes determined by different anthropogenic (heating, traffic) and natural factors (vegetation age, length of the day) are also clear in the diurnal pattern of FCO_2 (Fig. 7). During winter, a clear maximum of FCO_2 is observed between 9 am and 6 pm due to high emissions of CO_2 all day long. This maximum vanishes in the summer when only a small increase in emissions

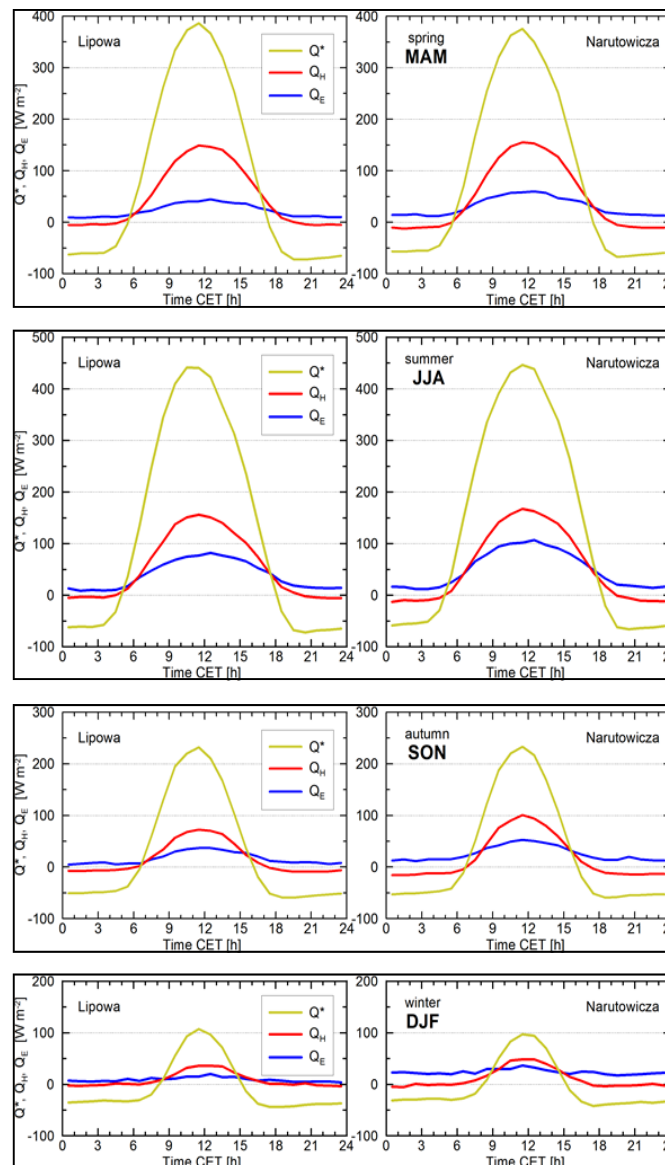


Figure 6: Average diurnal courses of energy balance components at two measurement sites in Łódź calculated on the base of all available data from the period 2005-2010.

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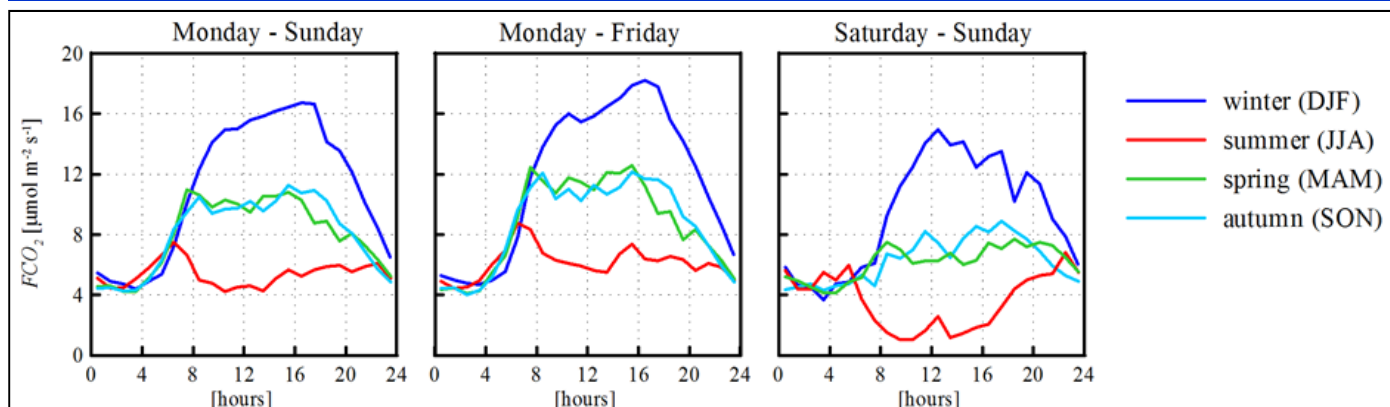


Figure 7: Mean diurnal course of FCO_2 in seasons at Lipowa site calculated separately for full weeks, weekdays and week-ends for the period July 2006 to May 2011.

is observed in morning rush hours. A separation of the week-ends and working days gives additional information about the net exchange of CO_2 in urban areas. On summer week-ends, a minimum of FCO_2 is observed during sunlight hours, which indicates a significant CO_2 uptake by urban vegetation through photosynthesis. The magnitude of carbon uptake almost compensates for the anthropogenic emission at the sites, and therefore, the net flux of CO_2 drops to 0. Spring and Autumn are characterised by higher values of FCO_2 during the day, even on the week-ends. In these seasons the reduction of net flux on non-working days is pronounced.

Other activity

In addition to the two

long term towers, short observations were carried out in the years 2002-2003 (Offerle et al. 2006b, Pawlak et al. 2011). Three sites were located in the post-industrial district, residential area, and suburban airport grassland. The results show the close adherence of flux partitioning to the surface characteristics, as

observed in other studies. Sensible heat fluxes have a positive relationship with the extent of impervious surface cover, and Bowen ratios show an inverse relationship with increasing vegetation cover. Net CO_2 flux is lower at all three sites than at Lipowa station. As expected, a negative (downward) flux

was observed above the grassland, reaching $-2.9 \text{ g m}^{-3} \text{ day}^{-1}$ in the summer of 2003 (the same time mean flux at Lipowa was $20.5 \text{ g m}^{-3} \text{ day}^{-1}$). In residential areas, daily totals were about $12 \text{ g m}^{-3} \text{ day}^{-1}$ lower than at Lipowa and in post-industrial areas, about $10 \text{ g m}^{-3} \text{ day}^{-1}$ lower.

Additional information on turbulence and sensible heat flux over the centre of Łódź is gained from the large aperture scintillometer (BLS 900, Scientec). The emitter is located on the mast of the Lipowa site 5 m below the top, and the receiver is mounted on the roof of a high University building 3.2 km east from the emitter, nearby Narutowicza site (Fig. 1). Thus a measurement path passes over the city centre. We started the measure-

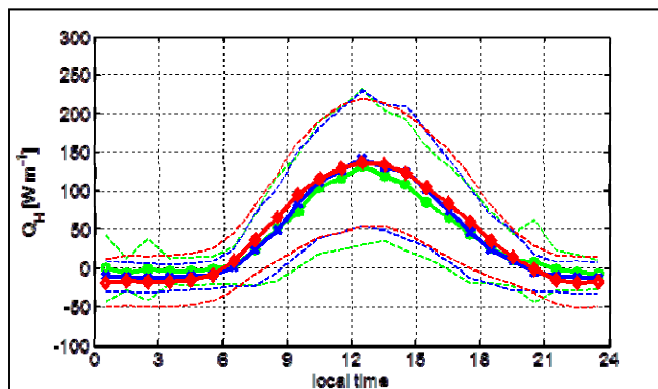
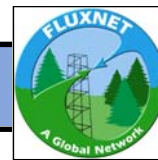


Figure 8: Diurnal evolution of sensible heat fluxes calculated from scintillometer (free convection assumption – red line), measured at Lipowa (green), and Narutowicza (blue) sites. Mean value \pm standard deviation for the period 11.06.2010 - 5.11.2010.



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ments in August 2009, but there are many gaps in the records because of different technical problems (the building with receiver was renovated in 2010 and 2011), and measurement limitations. The instrument specifications for the BLS 900 indicate it can be used for distances longer than our path, but it seems to be too long for polluted urban air. Especially during the winter, when air is close to saturation, the low visibility in the city centre reduces the signal below the threshold. In other seasons, scintillometry gives comparable results to the eddy-covariance method (Fig. 8), even with the free convection assumption.

In the near future we intend to initiate measurements of methane fluxes (undergoing purchase procedure of Li7700) at the Lipowa site. In addition, since last autumn we have been conducting open-path eddy-covariance system (including CO₂) measurements on a typical Polish farmland, about 60 km east from Łódź. The data from this system could be used as a reference to the urban stations. This summer we will start measurements (energy balance, CO₂, CH₄) at Biebrza wetland in eastern Poland.

Acknowledgements

Many thanks to Sue Grimmond and Brian Offerle who organised the first flux measurements in Łódź and who have supervised all experiments since 2003. We are also very grateful to Sue Grimmond and Laurie Koteen for their assistance in text improvement. Funding for this research was provided by the Polish Ministry of Science and Higher Education (State Committee for Scientific Research) under grants 2P04E 041 28 (2005-2007), N N306 276935 (2008-2010) and N N306 519638 (2010-2011).

References

- Dutaur L, Cieslik S, Carrara A, Lopez A (1999) The detection of nonstationarity in the determination of deposition fluxes. *Proceedings of EUROTRAC Symposium '98*, vol. 2. WIT Press: Southampton, 171–176
- Foken T, Wichura B (1996) Tools for quality assessment of surface-based flux measurements. *Agricultural and Forest Meteorology* 78: 83–105
- Fortuniak K, Pawlak W, Siedlecki M (2012) Integral turbulence statistics over a central European city centre. *Boundary-Layer Meteorology*, submitted
- Fortuniak K, Kłysik K, Wibig J (2006) Urban-rural contrasts of meteorological parameters in Łódź. *Theor App Climatol* 84: 91–101.
- Kłysik K, Fortuniak K, (1999) Temporal and spatial characteristics of the urban heat island of Łódź, Poland. *Atmospheric Environment* 33: 3885–3895
- Mahrt L (1998) Flux sampling errors for aircraft and towers. *Journal of Atmospheric and Oceanic Technology* 15: 416–429
- Nemitz E, Hargreaves KJ, McDonald AG, Dorsey JR, Fowler D (2002) Micro-meteorological measurements of the urban heat budget and CO₂ emissions on a city scale. *Environmental Science and Technology* 36: 3139–3146.
- Offerle B, Grimmond CSB, Fortuniak K (2005) Heat storage and anthropogenic heat flux in relation to the energy balance of a central European city centre. *Int J Climatol* 25: 1405–1419
- Offerle B, Grimmond CSB, Fortuniak K, Kłysik K, Oke TR (2006a) Temporal variations in heat fluxes over a central European city centre. *Theor App Climatol* 84: 103–115
- Offerle B, Grimmond CSB, Fortuniak K, Pawlak W (2006b) Intra-urban differences of surface energy fluxes in a central European city. *Journal of Applied Meteorology and Climatology* 45: 125–136
- Pawlak W, Fortuniak K, Siedlecki M (2011) Carbon dioxide flux in the centre of Łódź, Poland – analysis of a 2-year eddy covariance measurement data set. *Int J Climatol* 31: 232–243, DOI: 10.1002/joc.2247.

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Young Scientist Profile: Simone Kotthaus

Where do I work? My current research interests

Since 2009 I have been part of the Micrometeorological research group of Prof Sue Grimmond at King's College London (KCL), UK. I am now in the final year of my PhD. My work uses two different approaches to observe the exchange of sensible heat in urban areas. First, I measure sensible heat flux using the eddy covariance (EC) method, with observations of two flux towers situated in Central London (see pages 25-31 of this newsletter). Second, I use surface remote sensing techniques. At the flux sites, we are also collecting long-term datasets of radiation and turbulent fluxes of latent heat and carbon dioxide (Kotthaus et al. 2012, in preparation). My PhD is supervised by Prof Grimmond and Prof Wooster, with whom I am working on the remote sensing analysis.

EC flux measurements in the urban environment and the role of anthropogenic activities:

The measurement of surface fluxes using eddy covariance towers is inherently challenging in a highly urbanized environment. Urban-specific aspects of surface-atmosphere exchanges, such as heterogeneous and complex surface cover and anthropogenic activities, affect EC observations at various scales. Micro-scale emissions of heat, moisture and exhaust gases are very common, especially from non-residential buildings, and can have a distinct impact on the observed turbulent surface fluxes. I developed a filter in order to identify these emissions, which can show up as explicit signals in high frequency EC time series (Kotthaus and Grimmond 2012). This new technique is used to exclude the influence of micro-scale anthropogenic sources from the high-frequency observations so that the resulting turbulent fluxes can be analysed with respect to their local scale source area. We further apply this filter to quantify the anthropogenic contribution to heat, moisture and carbon dioxide fluxes at the building scale. This is one of the first attempts to directly observe the anthropogenic component of turbulent surface fluxes at



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the building scale. An example is presented here for one of our sites, where micro-scale anthropogenic sources are located east of the tower (Figure 1). The impact of building scale anthropogenic heat flux on the sensible heat exchange is highest during daytime when the building is in use and values can exceed 70 W m^{-2} . This order of magnitude is similar to results from other studies (e.g. Iamarino et al. 2011) and demonstrates the importance of anthropogenic emissions in the urban surface energy balance.

Despite their relevance to urban climate, anthropogenic heat flux is still difficult to quantify, and modelling approaches are often used to address their extreme spatial and temporal variability. Besides our observational studies, I

am also contributing to the latest development of the LUCY model (Allen et al. 2010) for anthropogenic heat flux estimates at various scales (Lindberg et al. 2012, in preparation). Another challenge for the analysis and interpretation of EC measurements is the determination of the local scale footprint; the latter being sensitive to surface roughness/zero plane displacement height. For the urban surface, various parameterizations have been proposed which allow for the calculation of these parameters based on building geometries and information which can be extracted from digital elevation models (Grimmond and Oke 1999). For our sites in central London, I implemented a procedure which allows us to calculate roughness parameters

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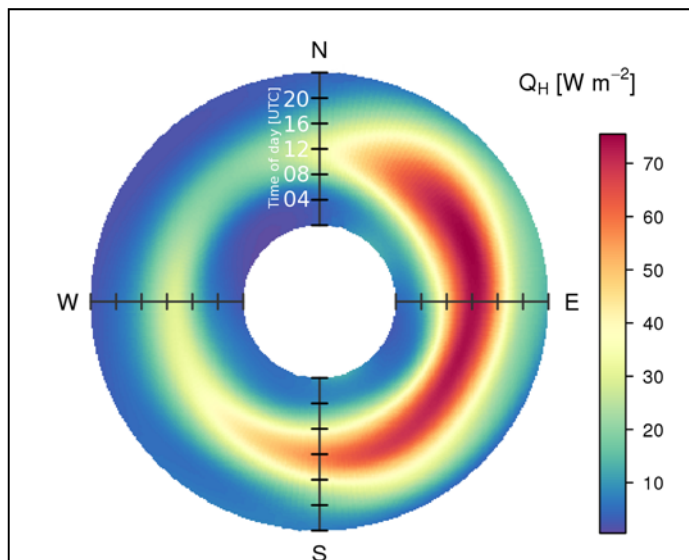


Figure 1: Anthropogenic contribution to sensible heat flux Q_H at the building scale as observed by Kotthaus and Grimmond (2012) at KSS site in Central London, by time of day and wind direction.

and source area locations iteratively with the analytical footprint model of Kormann and Meixner (2001).

Surface remote sensing in the urban environment:

In addition to flux measurement and processing, I use various remote sensing techniques in my PhD research. This enables me to observe spatially distributed sensible heat flux based on the aerodynamic resistance method (Voogt and Grimmond 2000). Currently, I am working on the retrieval of representative surface tem-

perature estimates to be used for sensible heat calculations. Due to the immense spatial heterogeneity of the urban surface and its complex, three-dimensional structure, we need to consider the effects on surface temperature as influenced by material properties, orientations of the surface facets (walls, roofs) and shadows from buildings and vegetation, among others. An example of the latter is illustrated by a transect of surface temperatures across a road in Central London (Figure 2). The cooling effect of vegetation and by the shadow cast by trees and buildings

is clearly evident in this figure. - I am planning to further explore the role of shadows in urban areas in controlling surface temperature variability, which again influences energy exchange via radiation and turbulent sensible heat flux. I am studying the effect of thermal anisotropy (Voogt and Oke 1998, i.e. the diversity of surface temperature found in the urban environment) based on thermal imagery collected with hand-held devices. These are also used in conjunction with thermal data from airborne measurements. Various observations were made during two airborne campaigns in central London 2008 and 2011, in collaboration with the Airborne Research & Survey Facility (ARSF) of the British National Environmental Research Council (NERC). I had the chance to specifically design the observations performed in 2011 to match my research requirements, with ground truth observations supported by NERC's Field Spectroscopy Facility (FSF). The fantastic cooperation with both facilities allowed me to create different flight line scenarios, to adjust sensor settings, and even to do a calibration of the airborne thermal imager

against a high quality black body system. During both, day- and night-time flights, many volunteers were involved in ground truth observations which I arranged to support the airborne data collection.

Multi- and hyperspectral data collected from these flights are used to create land cover maps with high spatial resolution and detailed information on surface material. Further observations are conducted to characterize emissivity of urban materials using Fourier Transform Infrared Spectroscopy (FTIR). These maps then serve as the basis for surface temperature calculations from thermal infrared images. Further, I am working towards the parameterization of the aerodynamic resistance for heat in the dense urban area around our flux sites. In conjunction with air temperature observations, I will be able to create maps of sensible heat flux and then to compare the results to EC observations.

How did I get here? My way to urban climate research

I came to London for two reasons, to discover the intriguing field of urban climate, and also because of

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the availability of a variety of measurement techniques involved in my PhD. A combination of EC flux observations and creative application of remote sensing techniques was just what I was looking for.

I studied Meteorology (Diploma degree, BSc + MSc) at the Institute of Geophysics and Meteorology at the University of Cologne, Germany. During this diverse course of study, I was exposed to the various different aspects of atmospheric physics and chemistry. Aside from my formal studies, I had my first practical encounter with boundary layer meteorology when I started to work as a student research assistant at Forschungszentrum Jülich, Germany, where I analysed data from airborne air quality observations. Soon I became interested in the work of the Tropical and Subtropical Meteorology research group of Prof Andreas Fink. As a student research assistant in his group, my work contributed to two projects concerned with the West African Monsoon (AMMA, www.amma-international.org) and the climate of Benin in particular (IMPETUS, www.impetus.uni-koeln.de). Understanding

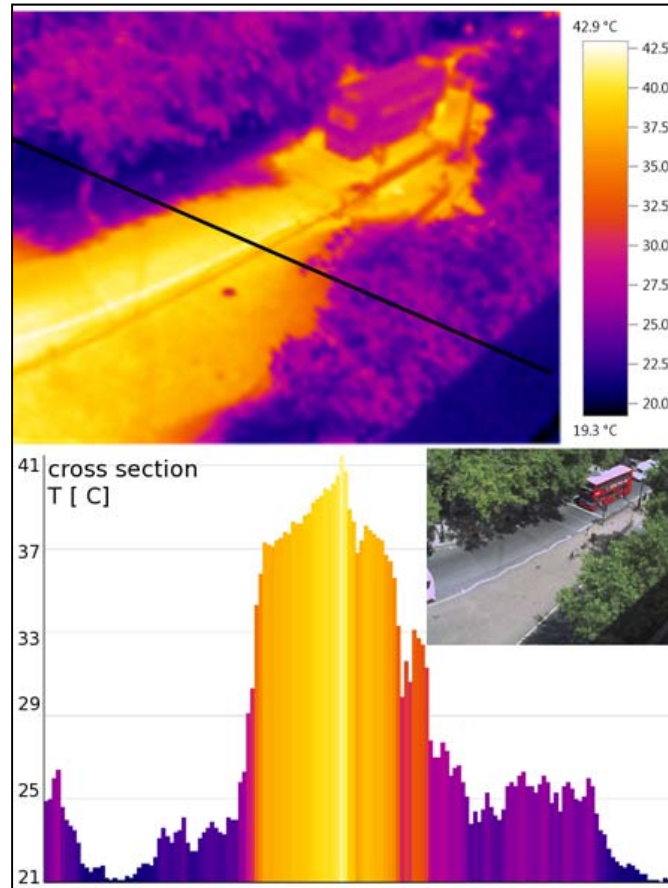
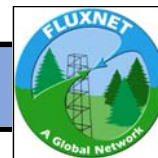


Figure 2: Thermal and visible image (TESTO hand-held thermal imager) of road in Central London (03/06/2011 at 13BST) with transect of temperatures along cross section: indicated by black line in thermal image. Radiative temperatures in °C, not corrected for emissivity.

the dynamics of the West African climate and its interdependency with global circulation patterns is crucial for the improvement of forecast abilities in an area so highly dependent on scarce rainwater availability. However, the impact of synoptic phenomena in this region is even more far-reaching, given that some

hurricanes hitting the US East coast have their origin in circulation patterns (African Easterly Waves) forming here. At that time, some of my work was concerned with the forecast potential of West African rainfall for Atlantic hurricane activity (Fink et al. 2010). Also, I was part of the team operating an

extensive observational network in Benin and Niger, which involved a series of field trips for instrument maintenance and data collection. This gave me the chance to actually experience the different weather conditions we were aiming to understand. It was here that I started to work with a flux tower for the first time, which then became one core aspect of my final Diploma thesis. My work explored the response of surface energy exchange as observed at a tree-savannah flux site to synoptic conditions in the year 2006. During this time I learned a lot about the usage of observational data, especially EC processing. In addition, I used model data (ECMWF re-analysis), satellite remote sensing images (Meteosat) and radiosonde data for the analysis of meso scale weather patterns and clouds. Our research group was responsible for the radiosonde data collection in Benin during an extensive AMMA field campaign in 2006 (Parker et al. 2008). The experience gathered in West Africa laid the cornerstone for my interest in field work, the practical use of instruments and the analysis of observational data. Finally, the opportunity to



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learn more about remote sensing techniques and to combine it with my knowledge on flux measurements brought me to London where I am now using both in the application of urban climate research.

References

- Allen, L., F. Lindberg, and C.S.B. Grimmond, 2011: Global to city scale urban anthropogenic heat flux: model and variability, *Int. J. Climatol.*, 31, 1990–2005. DOI: 10.1002/joc.2210
- Fink, A. H., J. M. Schrage and S. Kotthaus, 2010: On the Potential Causes of the Nonstationary Correlations between West African Precipitation and Atlantic Hurricane Activity. *J. Climate*, 23, 5437–5456.
- Grimmond, C. and T. Oke, 1999: Aerodynamic properties of urban areas derived from analysis of surface form. *J. Appl. Meteor.*, 38, 1262-1292.
- Iamarino, M., S. Beevers, and C.S.B. Grimmond, 2011: High-resolution (space, time) anthropogenic heat emissions: London 1970-2025. *Int. J. Climatol.* doi: 10.1002/joc.2390
- Kormann, R. and F.X. Meixner, 2001: An Analytical Footprint Model for Non-Neutral Stratification. *Bound. Lay. Met.*, 99, 207–224.
- Kotthaus, S. and C.S.B. Grimmond, 2012: Identification of Micro-scale Anthropogenic CO₂, Heat and Moisture sources – Processing Eddy Covariance Fluxes for a Dense Urban Environment. *Atmos. Environ.*, 10.1016/j.atmosenv.2012.04.024
- Parker, D.J., Fink, A., Janicot, S., Ngamini, J.-B., Douglas, M., Afiesimama, E., Agusti-Panareda, A., Beljaars, A., Dide, F., Diedhiou, A., Lebel, T., Polcher, J., Redelsperger, J.-L., Thorncroft, C.D, Wilson, G.A. 2008: The AMMA radiosonde program and its implications for the future of atmospheric monitoring over Africa, *BAMS*. 89, 1015-1027.
- Voogt, J. and C.S.B. Grimmond, 2000: Modeling surface sensible heat flux using surface radiative temperatures in a simple urban area. *J. Appl. Meteor.*, 1681, 1679-1669.
- Voogt, J. and T. Oke, 1998: Effects of urban surface geometry on remotely-sensed surface temperature. *Int. J. Remote Sensing*, 19, 895-920.

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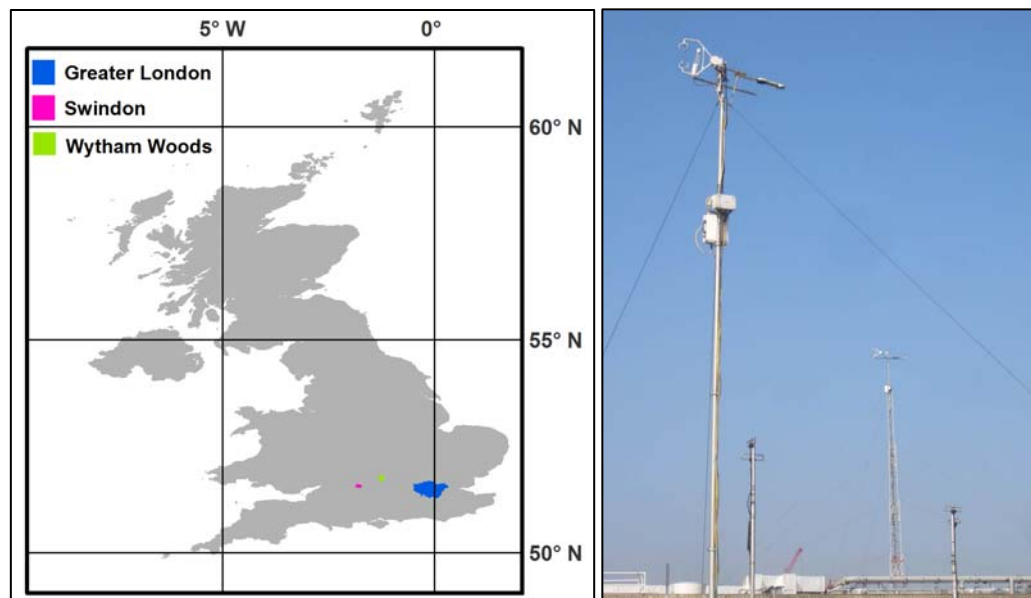


Urban Flux Measurements in Southern England, by KCL and CEH

Simone Kotthaus, Helen C. Ward, Sue Grimmond and Jonathan G. Evans

The micrometeorology research group at King's College London (KCL) and the Centre for Ecology and Hydrology (CEH) are operating flux sites in different urban environments in southern England. While the KCL sites are located in a highly urbanized area in Central London, CEH focuses on suburban characteristics in the town of Swindon, situated 120 km west of London (Figure 1). The population density of southern England is high, particularly in the south east (population 8,523,074 in mid-2010, excluding London, Office for National Statistics, ONS), and still rapid population increase is anticipated.

The climate is characterized as temperate marine, with the influence of mid-latitude cyclones crossing the UK from West to East. Passages of the frontal systems account for precipitation, clouds and increased wind speeds; the prevailing wind direction is from the south west. However, the easternmost part of the British Isles, is relatively sheltered diminishing the impact of low pressure systems and since it is close to the European mainland, continental weather conditions can extend to this area. Despite enhanced



Figures 1 & 2: Locations of Swindon, Wytham Woods and Greater London in the United Kingdom (1) and flux towers in London, KSK & KSS (2).

convective activity, the area is still relatively dry (compared to the rest of the UK) with the lowest amounts of precipitation occurring in the Thames Valley and the London area. On average, annual rainfall in central and South East England is 777 mm. The mean minimum temperature is 1.2°C in February, and the mean maximum temperature is 21.7°C in July.

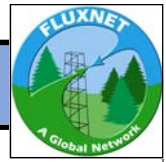
KCL flux sites in Central London

The UK capital is a growing metropolitan area with the population of Greater London already

exceeding 7.8 million in 2010 (ONS) in an area of 1572 km². The KCL flux sites are located at the KCL Strand Campus (Table 1), just north of the River Thames, in a very dense urban environment in Central London. Loridan et al. (2012) classified the surrounding area as High Density UZE (Urban Zone for Energy partitioning, Loridan and Grimmond, 2012) and according to an image-based classification approach (Stewart and Oke, 2009), it can be described as compact midrise LCZ (Local Climate Zone). With 43% impervious ground and 38% buildings, the surrounding surface

cover is clearly dominated by anthropogenic materials. Due to the proximity to the River Thames, 14% of the surface is open water, leaving only about 5% to vegetation (grass and street trees).

Two measurement towers are installed above roofs (Figure 2). First, observations started at the KSK site in October 2008 using a single tube mast (triangular tower, Clark Masts CSQ T97/HP). In November 2009 the second site (KSS), approximately 60 m to the north of the first site, became operational. Here instruments are mounted on top of an extendable triangular tow-



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er (Aluma T45-H). The latter was moved to the west end of the building in March 2012, forming the third KCL flux site in London referred to as *KSSW* (Figure 3). Measurement height a.g.l. is 39 m at KSK, 49 m at KSS and 50.3 m at KSSW, which is equivalent to a ratio of 1.9, 2.2 and 2.3 compared to mean building height z_H , respectively.

All three sites are

equipped with eddy covariance (EC) systems (see list of instrumentation in Table 1), allowing for the observation of turbulent exchange of sensible heat, latent heat and carbon dioxide. EC measurements are sampled at a frequency of 10 Hz and fluxes are calculated based on 30 min block averages. Meteorological observations from the weather station and the rain gauge are cleaned and

gap-filled (Kotthaus and Grimmond, 2012). Eddy covariance fluxes are calculated using ECPack (van Dijk et al., 2004) with a series of pre- and post-processing steps which are implemented in order to improve the quality of the results and to maximise data availability. A detailed description of the data processing procedure is presented by Kotthaus and Grimmond (2012). These

tests comprise a new despiking approach and an automatic Identification of Microscale Anthropogenic Sources (IMAS, Kotthaus and Grimmond, 2012). The latter is used to filter effects of micro-scale emissions so that the calculated fluxes are representative for the local scale source area.

CEH flux measurements in Swindon

A key aim of the Swindon field campaign is to provide energy, water and carbon fluxes for a suburban environment within the UK. Datasets are fairly rare for urban environments in general and UK campaigns have tended to focus on heavily built areas. Nevertheless, suburban areas are an important land use and house over 80% of the UK population (Gwilliam et al., 1998). The mosaic nature of surface cover found in these areas, comprising green space, buildings, a mixture of pervious and impervious surfaces coupled with human behaviour patterns and seasonal variations in vegetation makes the suburban environment a complex location to study, where many different natural and anthropogenic factors combine. Through observation and

		Swindon	KSS (KSK/KSSW), Central London
Location		51°35' N 1°48' W Suburban	51°30' N, 0°7' W Central business district
Climate conditions		Temperate marine (mid-latitude)	
Period of operation		May 2011 – present	Oct 2008 – present
Observed fluxes		Q^* , Q_H , Q_E , F_c	Q^* , Q_H , Q_E , F_c
Instrumentation	Sonic	R3, <i>Gill Instruments</i>	CSAT3, <i>Campbell Scientific</i>
	Gas analyser	Li7500, <i>LiCOR Biosciences</i>	Li7500/Li7500A, <i>LiCOR Biosciences</i>
	Radiometer	NR01, <i>Hukseflux</i>	CNR1/CNR4, <i>Kipp&Zonen</i>
	Weather station	WXT 510, <i>Vaisala</i>	WXT510/WXT520, <i>Vaisala</i>
	Rain gauge	Tipping Bucket, <i>Casella</i>	ARG100, <i>Campbell Scientific</i>
UCZ (Local Climate Zone)		open lowrise	compact midrise
Surface cover	Impervious ground	40%	43%
	Buildings	19%	38%
	Vegetation	36%	5%
	Open water	0%	14%
	Other	4% (gravel, bare soil)	0%
Mean building height z_H (m)		5.5	21.9
Zero-plane displacement height z_d (m)		~ 3.9 (0.7 z_H)	14.2
Roughness length z_0 (m)		~ 0.5 (0.1 z_H)	1.9
Sensor height z_s (m)		12.5	49 (39, 50.3)

Table 1: Site characteristics and instruments used at the two urban sites

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analysis of these factors and the resulting fluxes, improvements in understanding the physical process can be made. In turn these can help to support more informed decisions about future development in terms of sustainability, the environment and human health.

Measurements are located in the town of Swindon (population 175 000), one of the fastest growing towns in Europe. The land use within Swindon is typical of UK suburbia, comprising residential and commercial areas, transport links and green space. The study area is located north of the town centre; buildings are generally 1-2 storeys (mean

building height 5.5 m) and vegetation forms a significant proportion of the surface cover (37%), with major contributions from gardens, green corridors and roadside grass or trees. Being urbanised, a large proportion of the ground is covered with impervious materials, including public roads, parking and playgrounds as well as paved driveways and patios.

In addition to the fluxes measured using eddy covariance (results presented here), there are three scintillometers installed over Swindon, enabling sensible and latent heat flux estimates to be made that are representative of a larger scale (2-5 km²) and potentially for shorter time

periods than EC. The EC instrumentation is mounted at 12.5 m above ground, which is 2.3 times mean building height (Figure 4, mast location marked in orange). Details of additional instruments that appear at these sites are presented in Table 1.

Urban Surface Energy Balance

Three components of the surface energy balance are observed at both locations, London and Swindon, namely net all-wave radiation (Q^*) and the turbulent fluxes of sensible heat (Q_H) and latent heat (Q_E). Data collected in summer 2011 (JJA) and winter 2011/12 (DJF) are

presented (Figure 5) in the form of median diurnal cycles (shading represents the inter-quartile range (IQR)) to show how surface energy exchange varies with season in the two urban areas in Southern England. Further, the comparison of the two locations (London, KSS and Swindon) reveals how a different degree of urbanization influences the surface fluxes. This becomes especially apparent in the residual of the three energy fluxes ($RES = Q^* - Q_H - Q_E$). The interpretation of the residual, however, should be done carefully because it includes all uncertainties, errors and differences between the processing. All four components exhibit a



Figures 3 & 4: Aerial photo (NERC ARSF) of KCL Strand Campus with locations of flux towers (3), and Aerial photograph (©GeoPerspectives) of Northern Swindon showing the location of the flux mast (orange star), and pictured right (4).

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clear diurnal pattern in the two seasons. At both sites, radiation is the main source of energy during summer when median Q^* reaches up to about 400 W m^{-2} during daytime. During winter months net all-wave radiation is found to be higher in Swindon (daytime max. median 117 W m^{-2}) compared to London (80 W m^{-2}), which also holds true for night time values. This can be explained by larger outgoing long wave radiation fluxes in London. A higher degree of urbanization (expressed by for example, a larger fraction of impervious surfaces with high heat capacities and deeper street canyons) favours surface heat storage during daytime. The heat is then transported upwards, partly via radiative fluxes during night time (Christen and Vogt 2004). The smaller heat storage capacity of the suburban environment in Swindon further leads to a weaker urban heat island effect so that the relatively cooler surface exhibits less radiative heat loss, even during daytime.

In addition to radiative input and surface heat storage, the anthropogenic heat flux Q_f , is an important component of the urban surface energy balance. It includes latent and sensible

heat within the urban canopy layer that are produced by buildings, traffic and human metabolism. Even though it is still difficult to quantify, its impact is clearly evident when look-

ing at the turbulent fluxes of sensible and latent heat. Daytime sensible heat fluxes are higher during summer than winter at both sites, however pronounced differences appear in the London vs. Swindon comparison. In Swindon Q_H

responds to Q^* with upward fluxes during daytime and downward heat transport during the night. The latter is weaker in the summer when the temperature gradient between

ment of Central London. Here, turbulent sensible heat flux is transporting heat upwards even during the night, and the median values never drop below 50 W m^{-2} . Positive night time

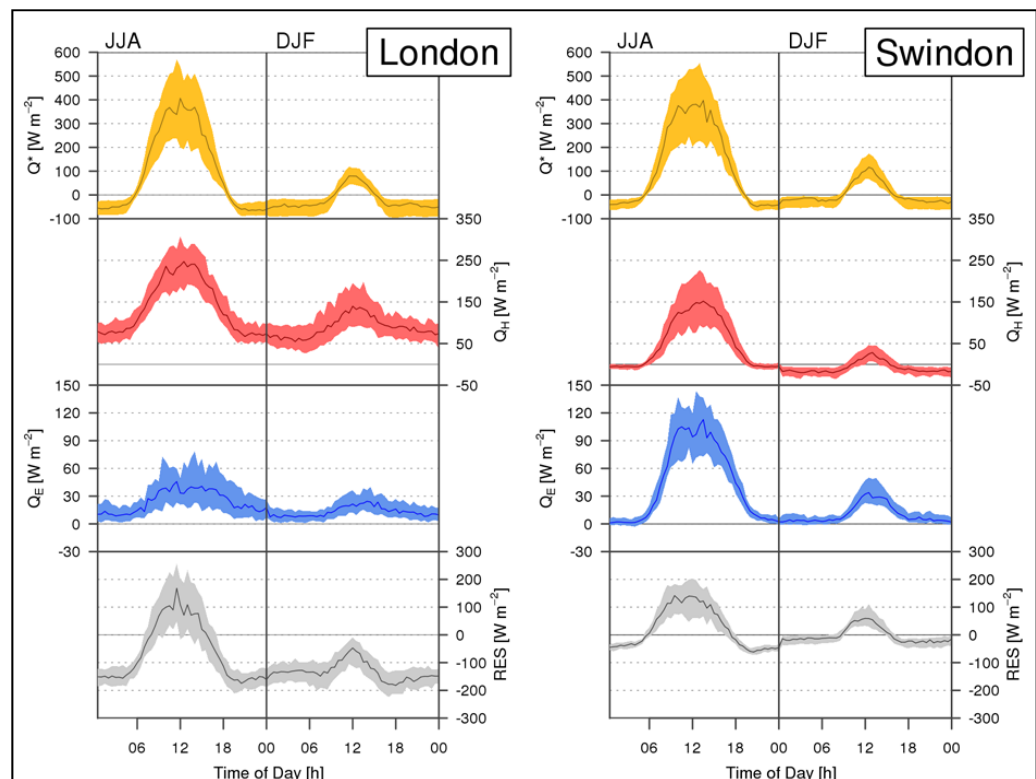


Figure 5: Median diurnal pattern of surface energy balance components for summer (JJA) and winter (DJF) at London (KSS) and Swindon: net all-wave radiation Q^* , turbulent sensible heat flux Q_H , turbulent latent heat flux Q_E and residual RES.

ing at the turbulent fluxes of sensible and latent heat. Daytime sensible heat fluxes are higher during summer than winter at both sites, however pronounced differences appear in the London vs. Swindon comparison. In Swindon Q_H

surface and overlying air is smaller. Here, anthropogenic heat flux does not seem to play a major role in determining the diurnal patterns. In contrast, Q_f significantly alters the surface energy balance in the very dense urban environ-

sible heat fluxes in winter have been observed in other cities (e.g. Helsinki, Järvi et al., 2009). Heat from anthropogenic emissions maintains wintertime sensible heat fluxes larger than the net all-wave radiation, even during daytime.



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This persistently strong sensible heat flux inhibits stable atmospheric stratification for most of the time. In terms of energy partitioning, both the dense urban and the suburban environment show dominant sensible heat flux dur-

seasons. During winter, latent heat flux in Swindon rises to the same order of magnitude as the sensible heat flux. The residual calculated from the three energy balance components summarizes the discussed analysis. In London the

ment. Also in Swindon heat is stored in the urban canopy, but the anthropogenic heat flux would be expected to be of smaller magnitude.

Carbon Fluxes across different land uses

physical processes governing the carbon flux (F_C) in each case (Figure 6). Each site has a visible diurnal pattern in both summer and winter; overall F_C is lower in summer for all sites. Looking at the three sites together, it is possible to pick out similarities and differences that result from the relative importance of biogenic and anthropogenic activity. Wytham is essentially a natural environment: an ancient woodland close to the River Thames near Oxford (51°46' N 1°20' W, see Thomas et al. (2011) for full details) where any impact of human activity is negligible in comparison to the vegetation.

The woodland acts as a substantial carbon sink, assimilating $0.75 \text{ mol C m}^{-2} \text{ day}^{-1}$ for the summer period shown here. In comparison, London acts a source of similar magnitude ($0.68 \text{ mol C m}^{-2} \text{ day}^{-1}$), whilst Swindon lies in between the two extremes and is a small source, emitting $0.06 \text{ mol C m}^{-2} \text{ day}^{-1}$ for the three days in summer shown here. For both seasons the release of CO_2 increases as the level of urbanization increases and vegetative fraction decreases.

Similar trends can be seen in the diurnal cycles.

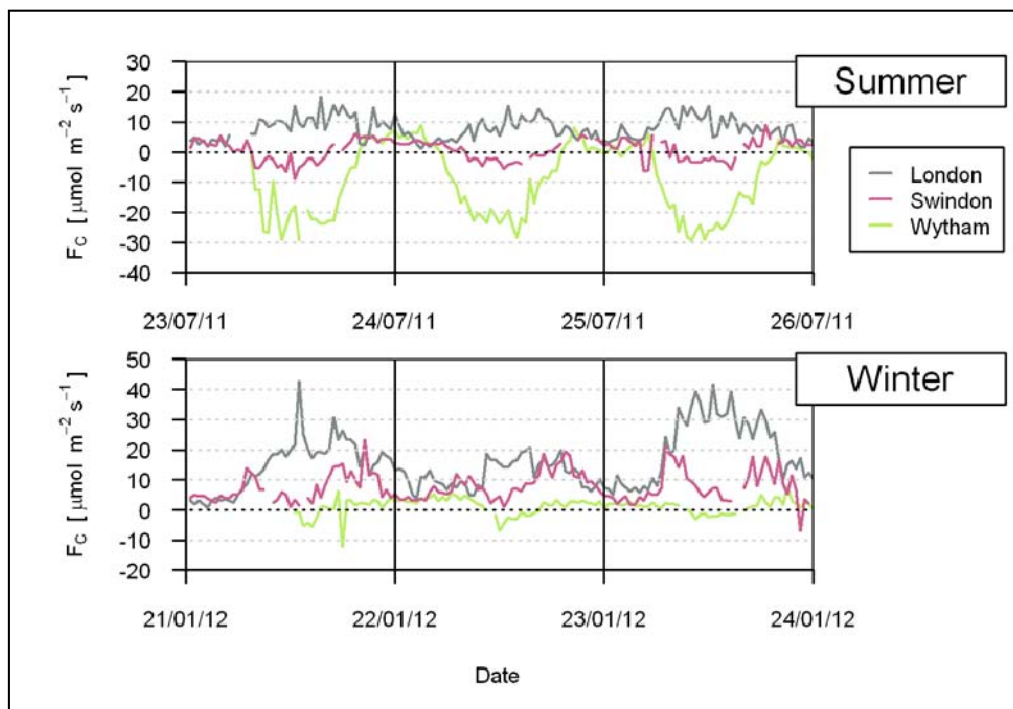
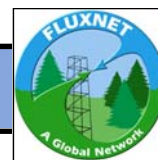


Figure 6: Carbon fluxes for three case study days in summer and winter for the city centre (London), suburban neighbourhood (Swindon) and woodland (Wytham).

ing summer month. However, the impact of the larger vegetation fraction (36%) in Swindon is obvious where turbulent flux of latent heat is about twice as high as in London where restricted moisture availability favours sensible heat flux instead, during both

sum of the turbulent fluxes exceeds energy supplied by radiation during night time in general and also during daytime in winter; the resulting negative residual includes the anthropogenic heat flux and surface storage, both of importance in this dense urban environ-

Case studies of a few example days comparing a heavily urbanised city centre (London), suburban residential (Swindon) and deciduous woodland (Wytham) in southern England provide some insight into the relevant



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London is always a source of CO₂, although much smaller in summer (peak values around 15 μmol C m⁻² s⁻¹) than in winter (peak values over 40 μmol C m⁻² s⁻¹). Swindon shows some carbon uptake during summer daytimes – evidence of significant photosynthetic activity by suburban vegetation, accounting for 36% of surface cover. During summer months, when solar radiation and leaf area index are at a maximum, the uptake by vegetation almost balances the anthropogenic and respiration source terms here, but has a much smaller effect in London where the vegetation fraction is small (5%) and population density is much higher. At this time of year the importance of gardens and urban green spaces for offsetting urban emissions can be seen on a daily basis in Swindon. However the presence of other (non-vegetative) land uses and emissions from human activity (traffic, water heating, air conditioning, respiration) mean the uptake is much smaller than for the woodland site (peak values less than 10 μmol C m⁻² s⁻¹ in Swindon compared to almost 30 μmol C m⁻² s⁻¹ for Wytham).

All three sites are

sources of CO₂ during night time. For Wytham, the night time release is due to respiration (mainly stem (Fenn et al., 2010)) and is generally larger in summer than winter due to warmer temperatures. In Swindon there is likely to be a smaller contribution from plant respiration (due to the reduced surface cover) but a significant contribution from human respiration, which will be larger still in London. Human exhalation was found to account for 38% of the summer time CO₂ flux in Tokyo (Moriwaki and Kanada, 2004), although more densely populated than London.

It is during winter that patterns in human behaviour can be most clearly seen for the urban locations. The influence of vegetation is minimal, as many species are dormant and solar radiation is low (illustrated by low daytime uptake / night time release at Wytham), so that other activities dominate the observed urban fluxes. London is a major source of CO₂, with building and water heating, traffic emissions and respiration all contributing. For these study days, peak emissions in London are lower than were found in Edinburgh in

November 2000 (Nemitz et al., 2002), possibly due to colder temperatures leading to increased heating demand in Edinburgh, improved fuel efficiency and different characteristics of the source area. In London the CO₂ flux is highest during winter daytimes, when human activity is at a maximum. In Swindon, the night time fluxes are not very different between the seasons but during winter there is no uptake of CO₂ – in the middle of the day emissions from human activities cannot be offset by minimal photosynthetic activity.

There is a clear traffic signal observable in the wintertime CO₂ flux from Swindon. Peaks corresponding to morning and evening rush hour are pronounced; this is particularly evident for 23/01/12 (Monday) but is much less marked at the weekends. A strong traffic signal would be expected from this residential suburban site, where the roads can get busy with many people travelling to and from work or school within the rush hour periods. The rush hour signal is much weaker in London, usually only discernible in the morning, reflecting the importance of other

sources of CO₂ and roads that are busy throughout the day.

These case studies demonstrate seasonal changes, highlight interesting features of the diurnal cycles and exemplify differences between natural, suburban and city centre environments. Overall the urbanised areas act as CO₂ sources, whilst the woodland is a sink, and London emits far more CO₂ per unit area during winter-time than Wytham can assimilate during summer. The presence of vegetation and lower population density in Swindon in the summer mean it exhibits trends more comparable to rural environments than those seen in heavily built-up London or Edinburgh, whereas during winter the largely dormant vegetation plus increased emissions from home heating and the influence of traffic results in fluxes dominated by anthropogenic activities. Comparison between these three sites offers information about the impact of human behaviour, the role of urban vegetation and the response of the atmosphere to land use change and urbanization.



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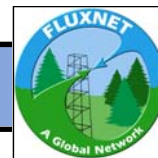
References

- Christen, A. and R. Vogt (2004) Energy and Radiation Balance of a Central European City. *Int. J. Climatol.*, 24,1395-1421.
- Fenn K, Malhi Y, Morecroft M, Lloyd C and Thomas M (2010) Comprehensive Description of the Carbon Cycle of an Ancient Temperate Broadleaved Woodland. *Biogeosciences Discuss.* 7(3):3735-3763.
- Gwilliam M, Bourne C, Swain C and Pratt A (1998) Sustainable Renewal of Suburban Areas. Joseph Rowntree Foundation, York: pp.
- Järvi, J., H. Hannuniemi, T. Hussein, H. Junninen, P. Aalto, R. Hillamo, T. Mäkelä, P. Keronen, E. Siivola, T. Vesala, and M. Kulmala (2009) The urban measurement station SMEAR III: Continuous monitoring of air pollution and surface-atmosphere interactions in Helsinki, Finland. *Boreal Env. Res.*, 14 (suppli. A), 86-109.
- Kotthaus S and CSB Grimmond (2012) Identification of Micro-scale Anthropogenic CO₂, Heat and Moisture Sources - Processing Eddy Covariance Fluxes for a Dense Urban Environment. *10.1016/j.atmosenv.2012.04.024*
- Loridan T & CSB Grimmond (2012) Characterization of energy flux partitioning in urban environments: links with surface seasonal properties *Journal of Applied Meteorology and Climatology* 51,219-241 doi: 10.1175/JAMC-D-11-038.1
- Loridan, T., F. Lindberg, O. Jorba, S. Kotthaus, and C.S.B. Grimmond (2011): High resolution simulation of surface heat flux variability across central London with UZE urban zones, submitted.
- Moriwaki R and Kanda M (2004) Seasonal and Diurnal Fluxes of Radiation, Heat, Water Vapor, and Carbon Dioxide over a Suburban Area. *J Appl Meteorol.* 43(11):1700-1710.
- Nemitz E, Hargreaves KJ, McDonald AG, Dorsey JR and Fowler D (2002) Meteorological Measurements of the Urban Heat Budget and Co₂ Emissions on a City Scale. *Environ Sci Technol.* 36(14):3139-3146.
- Stewart, I.D., and T.R. Oke (2009) Newly developed "thermal climate zones" for defining and measuring urban heat island magnitude in the canopy layer. Preprints, T.R. Oke Symposium & Eighth Symposium on Urban Environment, January 11-15, Phoenix, AZ.
- Thomas MV, Malhi Y, Fenn KM, Fisher JB, Morecroft MD, Lloyd CR, Taylor ME and McNeil DD (2011) Carbon Dioxide Fluxes over an Ancient Broadleaved Deciduous Woodland in Southern England. *Biogeosciences.* 8 (6):1595-1613.
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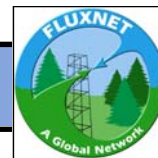
Environmental Monitoring and Modelling Group, Department of Geography



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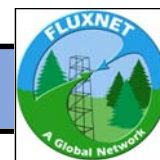
Code	City, Country Site-Name	LCZ ^(a)	Land-use ^(b)	z _{fl} (m)	z _m	E	C	A	O	Study period	Operated by	Primary Reference on flux measurements
Bm02	Baltimore , USA (Cub Hill)	Open lowrise	R	5.6	41	•	•			2001 - *	Indiana University / UMBC/USFS	Crawford et al. (2011)
Ba09	Basel , Switzerland (Aeschenplatz)	Compact midrise	R C	16.7	40	•	•			2009 - *	University of Basel	
Ba02s1	Basel , Switzerland (Allschwil)	Open lowrise	R	13	16	•				06/2002 - 07/2002	ETH Zürich / University of Basel	Christen and Vogt (2004)
Ba04	Basel , Switzerland (Klingelbergstrasse)	Compact midrise	R S O	17	39	•	•			01/2004 - *	University of Basel	Vogt (2009)
Ba02u2	Basel , Switzerland (Spalenring)	Compact midrise	R C	13	38	•				08/1994 - 09/2002	University of Basel	Christen and Vogt (2004)
Ba02u1	Basel , Switzerland (Sperrstrasse)	Compact midrise	R C	15	31	•	•			06/2002 - 07/2002	University of Basel	Vogt et al. (2006)
Bj08	Beijing , China (IAP 325m tower)	Compact highrise	R C S O	30	47	•	•	•	•	01/1991 - * CO ₂ since 2006	Chinese Academy of Sciences	Song and Wang (2012)
Be05	Berlin , Germany (Steglitzer Kreisel)	Compact midrise	R C	N/A	125		•			05/2005 - *	Technical University Berlin	
Ch92	Chicago , USA (Suburban)	Open lowrise	R	6.7	N/A	•					Indiana University	Grimmond et al. (1994)
Ch95	Chicago , USA (Dunning)	Open lowrise	R	6.3	27		•			06/1995 - 08/1995	Indiana University	Grimmond et al. (2002)
Dn01	Denver , USA (South Denver)	Large lowrise	R C I S O	7	60	•	•		•	05/2001 - 09/2007; 01/2011-*	U.S. Geological Survey	Anderson and Taggart (2003)
Db09	Dublin , Ireland (Marrowbone Lane)	Compact midrise	R C	N/A	N/A	•	•			08/2009 - *	Nat. Univ. of Ireland Maynooth & UCD	
Ed00	Edinburgh , UK (Nelson Monument)	Mixed	R C I	10.8	65		•			10/2000 - 11/2000	CEH Edinburgh	Nemitz et al. (2002)
Es07	Essen , Germany (Grugapark)	Mixed	R C	15	26		•			09/2006 - 11/2007	University of Duisburg-Essen	Kordowski and Kuttler (2010)



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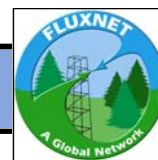
Code	City, Country Site-Name	LCZ ^(a)	Land- use ^(b)	z _H (m)	z _m	E	C	A	O	Study period	Operated by	Primary Reference on flux measurements
Fl05	Florence , Italy (Ximeniano)	Compact midrise	R C	25	33	●	●	●	●	2005 - *	Italian National Research Council	Matese et al. (2009)
Gz07	Giza , Egypt (Cairo University)	Open highrise	S O	22	35	●	●			11/2007- 2/2008	University of Basel	Frey et al. (2011)
Gl10	Gliwice , Poland (SUT)	Compact midrise	S O	20	28	●	●			04/2010- 03/2011	University of Basel	
He05	Helsinki , Finland (Kumpula)	Mixed	R I	20	31	●	●	●		12/2005 - *	University of Helsinki	Vesala et al. (2008)
He10f	Helsinki , Finland (Fire Station)	Compact midrise	C	22	42		●	●		06/2010 - 01/2011	University of Helsinki	
He10h	Helsinki , Finland (Hotel Tornio)	Compact midrise	C	24	60		●	●		09/2010 - *	University of Helsinki	
Ho07	Houston , USA (Northside Village)	Open lowrise	R C I	5	60	●	●		●	07/2007 - *	Texas A&M Uni- versity	Changhyoun et al. (2010)
Kc04	Kansas City , USA, (Greenwood)	Open lowrise	R	6.9	35	●				08/2004	University of Missouri	Balogun et al. (2009)
Lo06	Lodz , Poland (Lipowa)	Compact midrise	R S O	11	37	●	●			2000-2003 / 2006 - *	University of Lodz	Pawlak et al. (2011) and this newsletter
Lo05	Lodz , Poland (Narutowicza)	Compact midrise	R S O	16	42	●				06/2005 - *	University of Lodz	Offerle et al. (2006a,b)
Ld06	London , UK (BT Tower)	Compact midrise	R C S O	8.8	19 0		●			10/2006 - *	CEH Edinburgh	Helfter et al. (2011)
Ld08	London , UK (KSK)	Compact midrise	S O	22.8	48	●	●			10/2008 - *	King's College London	Kotthaus & Grimmond (2012)
Ld09	London , UK (KSS)	Compact midrise	S O	22.8	60	●	●			10/2009 - *	King's College London	Kotthaus & Grimmond (2012),& this newsletter
Sc91u	Sacramento , USA, (Urban)	Open lowrise	R	4.8	N/ A	●				08/1991	Indiana University / UIC	Grimmond et al. (1993)
Sg94	Los Angeles , USA, (San Gabriel)	Compact lowrise	R	4.7	18	●				07/1994	Indiana University	Grimmond et al. (1996)
Ar94	Los Angeles , USA, (Arcadia)	Open lowrise	R	5.2	33	●	●			1993-1995	Indiana University	Grimmond et al. (1996)
Ar93	Los Angeles , USA, (Arcadia)	Large lowrise	R	5.2	31	●				07/1993 - 08/1993	Indiana University	Grimmond and Oke (1995)
Ma01	Marseille , France (CAA)	Compact midrise	R C	15.6	44	●	●			06/2001 - 07/2001	UIC / Indiana University	Grimmond et al. (2004)
Mb03m	Melbourne , Australia (Preston)	Open lowrise	R	12	40	●	●			08/2003 - 08/2004	Monash University	Coutts et al. (2007)



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Code	City, Country Site-Name	LCZ ^(a)	Land- use ^(b)	z_H (m)	z_m	E	C	A	O	Study period	Operated by	Primary Reference on flux measurements
Mb03l	Melbourne , Australia (Surrey Hills)	Open lowrise	R	12	N/ A	•	•				Monash University	Coutts et al. (2007)
Me93	Mexico City , Mexico (School of Mines)	Compact midrise	R	18. 4	N/ A	•				11/1993 - 12/1993	University of British Columbia	Oke et al. (1999)
Me06	Mexico City , Mexico (Escandon)	Compact midrise	R C	12	42	•	•	•	•	03/2006; 02/2009 - *	WSU/MCE2 (2006) MCE2/INE/SMADGF (2009*)	Velasco et al. (2011)
Me03	Mexico City , Mexico (Iztapalapa)	Compact lowrise	R S O	12	37		•		•	04/2003	Washington State University	Velasco et al. (2005)
Mi95	Miami , USA (West Miami)	Open lowrise	R	8	40	•				05/1995 - 06/1995	UBC / Indiana Uni- versity	Newton et al. (2007)
Mn05	Minneapolis , USA (Roseville, KUOM)	Open lowrise	R	6	40	•	•		•	11/2005 - 06/2009	UC- Santa Barbara	Peters and McFadden (2012), this newsletter
Mo07u	Montréal , Canada (Rue des Ecores)	Compact lowrise	R	8	24	•	•			10/2007 - 10/2009	McGill University	Bergeron and Strachan (2009)
Mo05	Montréal , Canada (Rue Fabre)	Compact lowrise	R	9.5	21	•	•			03/2005 - 04/2005	Environment Canada	Lemonsu et al. (2008)
Mo07s	Montréal , Canada (Roxboro)	Open lowrise	R	7	24	•	•			11/2007 - 10/2009	McGill University	Bergeron and Strachan (2009)
Mu06	Münster , Germany (Manfred-von- Richthofen-Kaserne)	Compact midrise	R C	15	65		•	•		03/2011 - 06/2011 08/2006	University of Münster	Dahlkötter et al. (2010)
Na06	Nantes , France (SAP / ONEVU)	Sparsely built	R	6	27	•	•	•		02/2006 - *	IRSTV	Ruban et al. (2011)
Oa03	Ouagadougou , Burki- na Faso (Residential)	Not classified	R	N/ A	N/ A	•				02/2003	Indiana University/ Göteborg University	Offerle et al. (2005)
Ob10s	Oberhausen , Germa- ny (suburban)	Sparsely built	R	6.2	30	•				08/2010 - 07/2011	University of Duisburg -Essen	Goldbach and Kuttler (2012)
Ob10u	Oberhausen , Germa- ny (urban)	Com- pact midrise	R C	14	32	•				08/2010 - 07/2011	University of Duisburg -Essen	Goldbach and Kuttler (2012)
Ph11	Phoenix , USA (West Phoenix)	Compact lowrise	R	4.5	22	•	•			12/2011 - *	Arizona State Univer- sity	
Ro04	Rome , Italy (Collegio Romano)	Compact midrise	R C	20	56		•			2004 -2006	Italian National Re- search Council	
Sl05	Salt Lake City , USA (Murray)	Open lowrise	R	4.4	37	•	•			2005, 2007 - *	University of Utah	Ramamurthy and Pardjak (2011)



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Code	City, Country Site-Name	LCZ ^(a)	Land- use ^(b)	z_H (m)	z_m	E	C	A	O	Study period	Operated by	Primary Reference on flux measurements
Si06	Singapore, Singapore (Telok Kurau)	Compact lowrise	R	9.1	21	•				03/2006- 03/2007; 09/2007- 03/2008	National University of Singapore	Roth et al. (2009)
Sw11	Swindon, UK (BWY)	Open lowrise	R	5.5	13	•	•			05/2011 -	CEH Wallingford	See this newsletter
Sy10u	Syracuse, USA (Center)	Not clas- sified	C	N/A	N/A		•			06/2010 - *	SUNY	Buckley et al. (2011)
Sy10p	Syracuse, USA (Park)	Not clas- sified	R	N/A	N/A		•			06/2010 - *	SUNY	Buckley et al. (2011)
Ta06	Taichung, Taiwan (University)	Compact midrise	R	28	56	•	•			03/2006 - 04- 2006	National Chung Hsing University	
Tk01	Tokyo, Japan (Kugahara)	Compact lowrise	R	7.3	29	•	•			2001 - 2007	Ehime University	Moriwaki and Kanda (2004)
Tu90u	Tucson, USA (Sam Hughes)	Light- weight lowrise	R	5.2	25.6	•				06/1990	Indiana University	Grimmond and Oke (1995)
To04	Toulouse, France (Monoprix)	Compact midrise	R C S O	14.9	48	•	•	•		02/2004 - 02/2005	CNRM / Météo- France CNRS	Masson et al. (2008)
Vl92	Vancouver, Canada (Light Industri- al)	Large lowrise	I	5.8	28	•				07/1992 - 08/1992	Indiana U. / Univ. of British Columbia	Grimmond and Oke (1999)
Va08o	Vancouver, Canada (Oakridge)	Open lowrise	R	5.8	29	•	•			07/2008 - 08/2008; 07/2009 - 08/2009	University of British Columbia	Crawford et al. (2009)
Va08s	Vancouver, Canada (Sunset)	Open lowrise	R C	5.3	28	•	•		•	Intermittent since 1977; 2001 - 2002; 05/2008 - *	University of British Columbia	Christen et al. (2011) See also this newsletter

^(a) Local climate zone according to Stewart and Oke (2009) [updated version]

^(b) Land-use in the tower source area - R: residential, C: commercial, I: industrial, S: institutional, O: other (in most cases recreational).