Environmental measurements in BRIDGE case studies

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ENVIRONMENTAL MEASUREMENTS IN BRIDGE CASE STUDIES

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INTRODUCTION

"Urban metabolism" refers to the exchange and transformation of energy and matter between a city and its surroundings. Urban environments can be regarded as ecosystems (Pincetl et al., 2012) with their metabolism determined by the quantification of input and output flows. From a physical point of view, energy enters the system in the form of radiation and heat and influences local climate while being transported, transformed, stored and emitted. Quantitative information on the magnitude of energy flows is needed for management and environmental protection, while special emphasis is presently given to the exchange of carbon and water by the urban ecosystems, given their implications in global climate change issues.

A methodological framework to study urban metabolism was established in Chapter 4. In this Chapter an observational approach to the study of urban metabolism across contrasting city environments is presented.

CORE MEASUREMENTS CARRIED OUT IN BRIDGE CASE STUDIES

The collection of meaningful data representative of a broad variety of conditions requires a careful choice of case studies, encompassing an extensive range of environmental and anthropogenic factors. In the BRIDGE project (Chrysoulakis et al. 2013), turbulent fluxes and significant components of urban flows were measured in five diverse European cities in terms of urban metabolism and influenced by different policy and resource availability. Urban fluxes are strongly affected by the urban surface characteristics and modifications in land use (e.g. new buildings construction, increase of green areas etc.), notably at local and regional scales.

Five case studies were drawn from different parts of Europe, as presented in detail in Chapter 3: Helsinki, Athens, London, Firenze and Gliwice. Exchanges of energy, heat, moisture, carbon and pollutant were measured using different techniques, during the project, along with case study specific biophysical variables (Table 5.1). A common core of micrometeorological measurements was carried out in all cities except Athens, where it was not feasible to install an observation flux tower. These core measurements included: meteorological data, radiation budget and turbulent fluxes of latent heat, sensible heat and carbon dioxide (CO_2). The characteristics of each study site and the measurement activities undertaken are described in the rest of this Section.

	London	**Athens**	**Firenze**	**Helsinki**	**Gliwice**
Turbulent fluxes	✓		✓	✓	✓
Meteorological	✓	✓	✓	✓	✓
Air Quality (AQ)	✓	✓	✓	✓	✓
Urban vegetation	✓			✓	
Urban soils	✓			✓	✓
Stormwater/hydrology	✓			✓	✓
Dust turbulent fluxes			✓	✓	
Bio-monitoring of AQ			✓		
Indoor AQ		✓			
Urban heat island		✓			
Lidar dust profiling			✓		

Table 5.1. *Measurements carried out in BRIDGE case studies*

London

In London the focus was the 'Central Activity Zone' (CAZ) (for details see Chapter 3). Two measurement towers were installed on the Strand Campus of King's College London (KCL, 51°30' N, 0°7' W), an area characterized as a High Density urban zone for energy partitioning (Loridan & Grimmond 2012; Loridan et al. 2013) and as a compact midrise local climate zone (Stewart & Oke 2012, Kotthaus & Grimmond 2013a,b). The towers, approximately 60 m apart, had sensors at 49 m (KSS) and 39 m (KSK) above ground level which equates to about 2.2 and 1.9 times the mean building height. Full descriptions of the sites and the observations can be found in Kotthaus & Grimmond (2012, 2013a,b).

Three components of the surface energy balance were directly measured: net all-wave radiation and the turbulent fluxes of sensible and latent heat. The lower site (KSK) was established in 2008 and the other (KSS) in 2009. The radiation fluxes were measured with a net radiometer (CNR1 and CNR4, Kipp&Zonen); 15 min averages are recorded. Cloud cover and height were determined from atmospheric backscatter measured with a ceilometer (CL31, Vaisala).

Turbulent latent and sensible heat fluxes were observed with Eddy Covariance (EC) systems consisting of a CSAT3 sonic anemometer (Campbell Scientific) and a Li7500 (Li7500A) open-path infrared gas analyser (LiCOR Biosciences) sampling at10 Hz. Fluxes were determined from 30 min block averages. Automatic weather stations (WXT510 and WXT520, Vaisala) sampled air temperature, station pressure, horizontal wind speed and direction, and relative humidity at 5 s intervals. Precipitation from tipping bucket rain gauges (ARG100, Campbell Scientific) was totalled for 15 min periods. The sonic anemometer, gas analyser, rain gauge and net radiometer were connected to Campbell Scientific CR3000 and CR5000 data loggers. Computers directly sampled the weather stations.

Additional measurements taken within the footprint of the EC flux towers included the water temperature of the River Thames obtained using Tinytag TG -4100 sensors at 0.2 m below the surface. The River Thames typically has a 6 m tidal range in the CAZ. In nearby parks (Embankment) and gardens (Middle Temple), soil temperature and moisture were measured using Delta-T Devices SM300 sensors buried approximately 0.1 m below the surface.

Natural Environment Research Council, Airborne Research & Survey Facility (NERC ARSF) flights occurred over Greater London during the study. This included a flight at an altitude of 900 m above ground level on 14 August 2008.On board a 1064 nm wavelength Optech ALTM 3033 LiDAR system recorded first and last returns plus intensity values with a pulse frequency of 33 kHz using a maximum off-nadir view angle of 20°. The flight included a north to south transect area (approx. 0.65 km x 50 km) passing over the CAZ. This resulted in an on the ground mean point density of 0.71 m^{-2}. To avoid the large off-nadir angles at the edge of the field of view with a lower density points, 19 study areas were selected from the centre of the transect. The methods used to process the data are described in Lindberg & Grimmond (2011). From the data, surface cover information including vegetation characteristics were determined. Height attributes for each vegetation pixel were compared with a bare-earth Digital Surface Model (DSM) and those lower than 2.5 m above ground were removed from the dataset. This means urban features such as building walls, power lines, masts etc. were still present and had to be removed in order to generate a vegetation canopy DSM. Vegetation has small gaps that allow laser light to penetrate and record additional returns at lower elevation. This was used to obtain a rough estimate of the crown base height needed to generate the trunk zone DSM.

Athens

This case study is focused on the municipality of Egaleo, a densely built urban area in the western part of Athens. The observations were performed at city, neighbourhood and building scale using different methodologies. Meteorological measurements were taken at the Thission meteorological station (37° 58' N, 23° 46' E) of the National Observatory of Athens. Hourly data for air temperature, relative humidity, wind speed and direction, precipitation, diffuse and total solar radiation, sunshine duration and air pressure were collected. Air quality data were retrieved from a network of stations installed in the greater Athens area measuring air pollution (SO_2, NOx, CO, O_3, PM10, PM2.5, C_6H_6) operated by the Directorate of Air Pollution and Noise of the Greek Ministry of Energy, Environment and Climate Change (Greek Ministry of Energy, Environment and Climate Change, 2010). The stations close to Egaleo were used for analysis. Traffic data, i.e. number of vehicles that passed through specific measurement locations (per hour), were also collected from the Ministry of Transport and Communication for 2009-2010.

In order to study the Urban Heat Island (UHI) phenomenon in the greater Athens area, a network of 17 fixed temperature stations was set up in different zones grouped into western, eastern, southern and northern zone stations according to their geographical location and thermal balances. In all stations the data were measured with fully calibrated high precision automatic miniature sensors (TinyTag), which were placed in white wooden boxes with lateral slots approximating the Stevenson screen to be protected for solar radiation and rain. Temperatures were measured at 15 minute intervals for 2009 and 2010. In order to assess the quality of the outdoor environment of the case study area the following measurements have been carried out using a mobile meteorological station and portable instrumentation:

- Concentrations of PM1, PM2.5, PM10 (Lighthouse 3016 IAQ Laser Particle Counter)
- Wind speed and direction by anemometers that have been placed at three different heights - 3.5, 7.5, 15.5 m – on the antenna of a mobile station.
- Air temperature, RH, air velocity and radiant temperature at a height of 1.5m.
- Measurements of the surface temperature of the urban fabric (building facades, roads and pavements) using an infrared thermometer (Cole Palmer) and camera (Thermovision 570).

Measurements were conducted during several days the summer of 2009 between 10:00 and 17:30, in several locations in Egaleo area. The analysis of the results showed that increased surface and air temperatures and low wind speeds result in thermal discomfort for the people in the area.

In addition, an assessment of the impact of the outdoor environmental conditions (mainly thermal comfort and air pollution) on the indoor environment of residential buildings in the case study area was performed. The process followed is outlined below:

- Selection and data collection of ten representative buildings of the Egaleo's building stock
- Distribution of questionnaires answered by the residents
- Indoor thermal comfort measurements: Air temperature, relative humidity (Tiny Tag), Air velocity (Dantec) and mean radiant temperature (INNOVA 1221)
- Measurements of PM1, PM2.5, PM10 concentrations (Model 8520 DUSTTRAKT)

Firenze

The observations were performed at city and neighbourhood scale, using different methodologies, while the core micrometeorological measurements exploited the existence of a pre-existing measurement tower operational when BRIDGE was started. All sensors were installed at the Ximeniano Observatory located in the city centre (43° 47' N, 11° 15' E) and were operated continuously for the duration of the project. The EC flux station was installed on a 3 m mast mounted on a typical tile roof of an ancient building of the Observatory. This roof is taller than the average surrounding buildings, free of obstacles, 7 m above the Observatory roof level and at 33 m above the street level (Matese et al. 2009, Gioli et al. 2012).

Turbulent fluxes of CO_2, momentum, and sensible heat were collected, using a sonic anemometer and an open-path CO_2/H_2O infrared gas analyser (Li7500). Raw data were acquired at the frequency of 20 Hz by Compact Eddy system (Matese et al. 2008), while flux data were computed at a 30 min resolution, and quality checked with state of the art procedures (Foken et al. 1996). Data were averaged over various time scales, to resolve daily, weekly, monthly and seasonal patterns of energy balance and surface. Averaging was undertaken only on the quality-checked dataset. The tower was complemented with a new micrometeorological apparatus providing hourly measurements of particulate matter net flux by means of the EOLO system (Eddy cOvariance-based upLift Observation system, Fratini et al. 2007). This comprised of a sonic anemometer (Metek USA-1) and a concentration system that includes an OPC (CI-3100 series, Climet Instruments Co., Redlands, CA, USA) and Multi-Channel Analyzers (MCA8000, Amptek Inc., Bedford, MA, USA). This data was useful to compare with the outputs of the WRF-ACASA (Weather and Forecast model, Advanced-Canopy-Atmosphere-Soil Algorithm, Marras et al. 2011) simulation models for energy and mass fluxes in the city centre and for the dust deposition modelling framework (Tallis et al. 2011), to estimate the influence of the proposed green space within the Parco San Donato would have on the local PM10 environment.

Meteorological observations were collected at the Ximeniano Observatory, an improvement of the preexisting weather station, following the guidelines in the BRIDGE observation protocol. The average temperature recorded was 15.8 °C; an anomaly of +1.2 °C from 1960-1991 baseline (warmest month July, mean temperature 26.3 °C and coldest month January, mean temperature 7.1 °C). Average annual rainfall was 934.9 mm; 24.2 mm above the climatological average.
An innovative microjoule LiDAR developed in cooperation with ENEA was installed and tested on the Ximeniano Observatory. This resolved the first 5 km of atmosphere, providing measurements of horizontal and vertical profiles of dust as well as the height of the planetary boundary layer. A GRIMM aerosol spectrometer, capable of analysing the distribution of dust particles in 20 spectral bands in the range between 0.23 µm to 20 µm, was installed to complement remote observations of the LIDAR with detailed in situ information on the nature of the dust.

To better assess the quality of the outdoor environment measured above roof level and thus representative of mean air quality of the historic city centre, a 2BTECH 202 UV monitor and a UNITEC ETL2000 thick film sensor were installed for O_3 and CO concentrations respectively. Additional measurements taken within the footprint of the EC flux towers and in the neighbourhoods were provided by Tuscany Regional Agency for Environmental Protection (ARPAT) who measured concentrations of pollutants (PM10, CO_2, NO_x, SO_2, CO) for a network of 5 air quality ‘traffic-oriented’ monitoring stations including heavy and medium-traffic and urban-background sites. Air quality was also monitored by means of suitable bio-indicators, providing a time-averaged picture of air quality at street level for the estimation of atmospheric trace metal deposition in the urban area of Firenze. At each site moss bags were exposed during three campaigns of measurement conducted during the periods March-April, May-July, and August-October 2010. Two moss bags, used as control, were not exposed. After each campaign moss samples were analysed for As, Cr, Cu, Fe, Ni, Pb, V, and Zn by Inductively Coupled Plasma Atomic Emission Spectrometry.

Gliwice

The flux measurements in Gliwice were located 500 m west of the city centre on a building of the Silesian University of Technology on a balcony at the side of a gable roof (50°17'38.01"N, 18°40'53.21"E). The building height is approximately 25 m and an 8 m mast was installed on the balcony. The top of the mast was 3 m above the gable and the horizontal distance to the gable was 6 m. The line gable-to-mast pointed towards SW. The effective height of the turbulent flux measurements above ground level was 29 m.

The set-up consisted of an EC system (sonic RM Young 81000V, LiCOR open-path gas analyzers LI7500), a net radiometer (Kipp&Zonen CNR1) and sensors for air temperature and humidity (Vaisala HMP45). A data logger (Campbell CR1000) processed the data using the methods outlined in Aubinet et al. (2012). In addition the raw data (10 Hz) were kept for further analysis. In total 23% of the data had to be discarded from flux calculations due to a range of conditions including rain/snow and maintenance. Monthly totals were calculated from monthly daily means to account for missing data. The measurements were carried out from the end of March 2010 until the end of February 2011.
Wind measurements were variable, thus three main wind directions were identified. As part of a weak diurnal wind regime night-time winds from east were more frequent, while during daytime winds were more often coming from NW and SSW. The month to month variation was dominated by synoptic conditions. The fetch of the approaching flow in these three sectors was typically around 1 km and consisted of built-up areas. Due to the relatively low measurement height the fluxes were affected by local-scale heterogeneities.

Characteristics of air quality were identified based on the continuous measurements carried out at the Voivodeship Inspectorate of Environmental Protection monitoring station in Gliwice. The station is located about 1 km from the Silesian University of Technology in Gliwice.

Helsinki

In Helsinki, most of the measurements carried out in the BRIDGE project have been made at the urban measurement station SMEAR III (Järvi *et al.*, 2009a). The main site is the semi-urban Kumpula site located 5 km north-east of the centre of Helsinki. The meteorological variables, pollutant concentrations and turbulent fluxes of sensible and latent heat, CO_2 and aerosol particles have been measured continuously with the first observations in 2003.The fluxes are measured using the EC technique and the setup consists of an ultrasonic anemometer (USA-1, Metek GmbH, Germany), and open- and closed-path infrared gas analyzers (LI-7000 and LI-7500), and an particle counter (WCPC, TSI-3781, TSI Incorporated, USA). During the project, the turbulent flux measurements were extended to the Helsinki centre to two locations (Hotel Torni and Erottaja fire station) where the surface cover is highly built-up (Nordbo *et al.*, 2013).

The EC technique requires detailed planning both in terms of location and choice of instrumentation in urban areas. Typically either open-path infrared gas analyzers, or closed-path analyzers with long measurement tubes are used. The open-path measurements are interfered by the surface heating correction in the case of CO_2 emissions (Järvi et al. 2009b), whereas the long measurement tubes result in increased attenuation of water vapour as a function of relative humidity (Nordbo et al. 2012a).

In addition to the atmospheric measurements, the ecophysiology of urban trees was monitored in Viikki, 5 km north-east of Kumpula. The measurements of e.g. sap flow, soil temperature and CO_2 concentration were made in two streets where the trees were planted in 2002.

Storm water runoff was monitored from three water catchments located around Helsinki. The areas differ in their population density and fraction of impervious surfaces and are accordingly called low-density, medium-density and high-density catchments. In addition to water quantity, quality was also analysed, in terms of nutrients and potentially toxic elements.

RESULTS

The richness of measurement protocols carried out, yielded a variety of datasets suitable for use in BRIDGE in modelling activities, as well as in the development of the Decision Support System (DSS). A brief outline of the outcome of the common core micrometeorological measurements is reported here. All urban sites had shortcomings in terms of the representativeness of the flux observation for the whole area that the DSS needs to address. Thus, measured emissions must be considered in the context of the source area being measured, since the tower footprint covered only a fraction of the DSS areas of interest and the range of urban canopy types.

A more detailed analysis of energy and carbon fluxes might explain the different behaviour of the cities under investigation, by taking into account anthropogenically related variables, such as delivery rate of gas for heating or traffic intensity, the nature of the urban canopy and the presence of vegetation in the tower footprint. That analysis is beyond the scope of this Chapter, but some of these issues been included in articles discussing the individual sites (Firenze: Gioli et al. 2012; Gliwice: Lesniok et al. 2010, Helsinki: Järvi et al. 2009a,b,c, 2011, Nordbo et al. 2012a,b, Vesala et al. 2008; London: Kotthaus & Grimmond 2012, 2013a,b, Ward et al. 2014).

Carbon dioxide fluxes

Turbulent exchanges of carbon dioxide (F_c) varied markedly across the sites, with differences in mean values spanning one order of magnitude (Figure 5.1), but with clear seasonal dynamics at each site. In all cities mean fluxes remained positive and cities acted as sources of carbon dioxide.

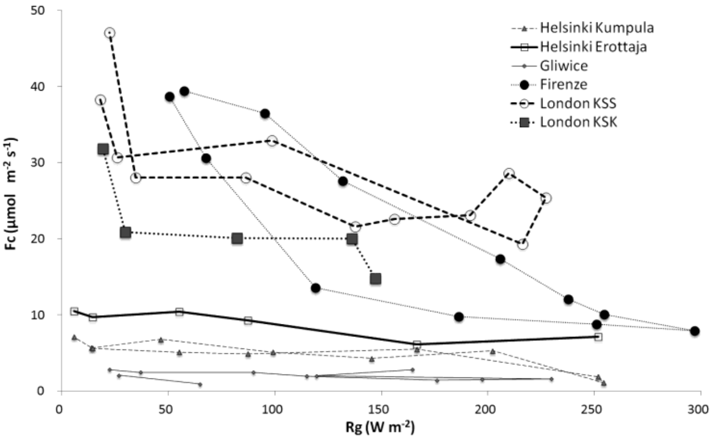

Figure 5.1: *Monthly mean values of net carbon dioxide exchange (Fc) in BRIDGE case studies, as a function of incoming global radiation (R_g).*

Unlike terrestrial ecosystems, cities are dominated by anthropogenic CO_2 emissions so that the budget of this greenhouse gas is less driven by incoming solar energy. Rather, urban CO_2 emissions are mainly attributed to human activities (e.g. traffic, space heating) and photosynthesis is reduced to urban green spaces, which often cover smaller areas compared to the impervious surfaces. This leads to emphasizing the importance of land cover controls, urban planning (Nordbo et al. 2012b) and heating activities (Kotthaus & Grimmond 2012). Still, global radiation (R_g) can be used as a proxy for many anthropogenic activities related to carbon emissions (e.g. from combustion).

In all case study cities, monthly mean net carbon dioxide fluxes are highest in Winter with maximum values around 40 µmol m^{-2} s^{-1} observed in London and Firenze and one month (Dec 2011) at the London KSS site reaching even 47 µmol m^{-2} s^{-1} (Figure 5.1). At Firenze, long-term CO_2 fluxes measured (Gioli et al. 2012; 2013) have always been a net source, with a small inter-annual variability associated with a high seasonality, ranging from 11.4 µmol m^{-2} s^{-1} during periods contributions from heating to 34.6 µmol m^{-2} s^{-1}during winter. This results in a strong, linear correlation between the flux and air temperature ($R^2 = 0.74$, $T_{air} < 288$ K). The relative contributions of road traffic and domestic heating to the observed emissions have been estimated through multivariate analysis combined with inventory data and emission proxies such as traffic counters and gas network flow rates. This analysis revealed that domestic heating accounts for more than 80% of observed CO_2 fluxes in the winter and for about half of the fluxes in summer.

Seasonal hysteresis was evident in the relation between global radiation and carbon fluxes for Firenze. The fluxes of the first six months of the year were higher than those recorded in the following months, for equivalent levels of radiation. In London, April and May 2011 have had exceptionally persistent periods of high pressure weather conditions so that global radiation actually exceeds those recorded in June and July. Hence, the hysteresis pattern is less evident.

Northern cities showed a marked linear decrease in emissions from December through April ($R^2 = 0.72$ and 0.77, for Helsinki, Kumpula and London KSS, respectively), while a steady decline from January through July was evident in Firenze ($R^2 = 0.98$).

The CO_2 emissions in the centre of Helsinki (Erottoja) were higher or of the same order of magnitude as the emissions measured downwind from a large road at the semi-urban Kumpula site (Nordbo et al. 2013). Seasonality plays an important role in both aerosol particle and CO_2 emissions. While aerosol particle emission factors increased with decreasing temperature (Ripamonti et al. 2013), the timing of the growing season was evident in CO_2 emissions resulting in a CO_2 sink of 10 µmol m^{-2} s^{-1} (Järvi et al. 2012). This indicates the importance of urban green areas especially in relatively green cities such as Helsinki. Besides CO_2 uptake, vegetation plays a role also as nocturnal emitter via soil respiration and in Kumpula an annual estimate for this are 550 and 645 g C m^{-2} in 2008 and 2009, respectively (Järvi et al., 2012).

Fluxes in Gliwice were mostly consistent year round - with a trend of increased emission activity starting in December and lasting until April (R^2=0.92). Thus they reflect typical features of urban areas. From October to April the monthly averaged diurnal patterns show a maximum of 6 to 4 µmol m^{-2}s^{-1} around midday, with nocturnal values around 1 to 2 µmol m^{-2}s^{-1}. From May to August, the midday values decrease with some uptake in July and August. When weekends and weekdays were separately analyzed, the influence of the traffic on CO_2 fluxes were clearly detected. During weekdays the fluxes were around 4 to 6 µmol m^{-2}s^{-1} higher than on weekends. It is even possible to detect the difference between Saturdays and Sundays, where the latter have the least traffic and show uptake values of around -3 to -4 µmol m^{-2}s^{-1}. Overall, however, the emissions dominate. The net monthly averages are all positive indicating that the area is a net source of CO_2. Based on monthly mean net fluxes, the estimated total annual flux is 2.8 kg CO_2 m^{-2} year^{-1}. This is a low value compared with other studies. The relation between mean monthly air temperature and total monthly CO_2 exchange shows a well behaved negative relation.

Aerosol particle fluxes

In Firenze and Helsinki aerosol particle fluxes were also measured. The aerosol particle fluxes in Firenze have a less pronounced seasonal trend compared to *Fc*. However, the PM2.5 fluxes exhibit a pronounced weekend decrease (-39%) highlighting that the contribution of heating to particle emissions is relatively small compared to road traffic (Gioli et al. 2013). Similarly, in Helsinki, both the long term CO_2 and aerosol particle number emissions depend strongly on the amount of local traffic indicating the importance of vehicles in urban metabolism (Järvi et al. 2009c, 2012).

Energy Balance fluxes

All urban canopies, partitioned most of the radiation load as sensible heat, with the exception of the semi-urban site of Helsinki Kumpula. This site, with a large amount of vegetation in one sector, had comparable values for sensible heat and latent heat fluxes. The case study sites show some clear differences in the magnitude of sensible heat in relation to the total incoming solar radiation (Figure 5.2). When looking at the linear relation between the two energy fluxes, the lowest increase of sensible heat with increasing solar radiation was found at the Helsinki Erottaja site (H proportional to 0.22 R_n) while the highest increase (0.29) was observed in Firenze and the other Helsinki site (Kumpula). Erottaja and the two London sites (KSK and KSS) reveal the largest sensible heat fluxes for times with low/no incoming solar energy. At these urbanized sites, night time sensible heat fluxes can be significant due to storage heat fluxes and considerable anthropogenic contributions (Kotthaus & Grimmond 2013a). In Gliwice, the sensible heat flux still dominates the latent heat flux during the whole year, as is typical in urban areas, with a Bowen Ratio of around 2, reflecting the vegetation and water availability in Gliwice during the measurement period.

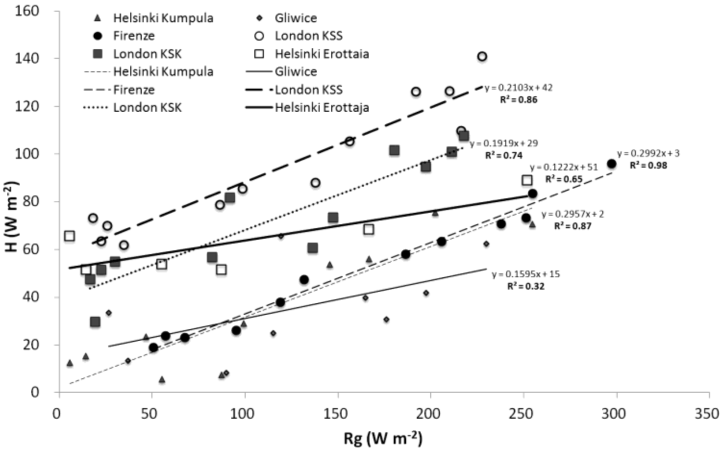

Figure 5.2: *Monthly mean values of sensible heat flux in BRIDGE case studies, as a function of incident global radiation. Lines are linear regressions; R^2 values, as well as regression parameters are also reported.*

Similarly, the monthly mean latent heat flux with incoming solar radiation were compared for each site. In Helsinki Kumpula, there is more green space in the tower footprint than at the other sites so there is a larger slope for this site than the others (Figure 5.3). The area with the smallest amount of vegetation is in London, so at this site there is no indication of a clear relation with solar radiation. The source of moisture to support the latent heat flux is from rainfall, when the surface is wet (Kotthaus & Grimmond 2013b). As this occurs throughout the year and when there is less cloud present, the relation with solar radiation is not evident at the monthly time scale (Kotthuas & Grimmond, 2013a,b). Similarly, in Firenze, the latent heat are very small (averaged only 10 W m^{-2}) given the very small (less than 4%) green area in the tower footprint.

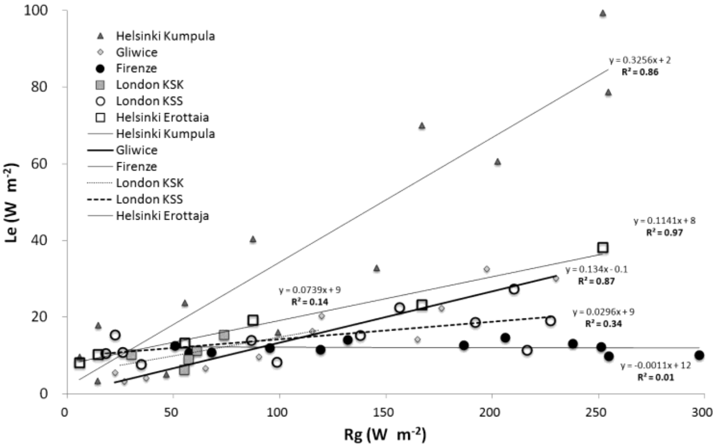

Figure 5.3: *Monthly mean values of latent heat flux in BRIDGE case studies, as a function of incoming solar radiation. Lines are linear regressions; R^2 values, as well as regression parameters are also reported.*

Air Quality

The differences in urban fabric also influenced air quality, which varied markedly among cities (Table 5.2). London emissions, are dominated by high levels of NOx, while PM and CO were noticeably high in winter in Gliwice, whereas it is summertime O_3 in Firenze and Athens. When analysing across sites, significant relationships between air quality traits and mean CO_2 emissions were evident. Fluxes were an inverse function of CO air concentration both in wintertime (R^2 = 0.85) and in summertime (R^2 = 0.97) and directly related to NOx (R^2 = 0.86 and R^2 = 0.97, in wintertime and summertime, respectively. In Athens, PM10 and NO_2 exceeded limits at a number of measurement stations. O_3 concentration exceeded the alert threshold (240 µg m^{-3})

during several days at stations close to Egaleo. These exceedences were due mostly to the high levels of sunshine and high temperatures that favour the formation of O_3.

Table 5.2. *Mean and standard deviation values of summer and winter concentration of the main air pollutants in BRIDGE case studies (all data in* $\mu g\ m^{-3}$*).*

	London		**Athens**		**Firenze**		**Helsinki**		**Gliwice**	
	summer	*winter*	*summer*	*winter*	*summer*	*winter*	*summer*	*winter*	*summer*	*winter*
PM 10	35.5 ± 6.4	41.6 ± 8.6	37.5 ± 2.9	45.7 ± 6.6	26.0 ± 1.8	41.7 ± 0.5	15.5	13.7	33.25 ± 4.0	88.5 ± 26.6
PM 2.5	20.7 ± 4.7	25.1 ± 7.2	32.2 ± 6.7	25.3 ± 3.3	14.7 ± 3.1	24.8 ± 2.7	8.58	10.3	18.75 ± 4.9	74.25 ±24.3
O_3	19.6 ± 2.9	12.4 ± 1.3	75 ± 12.3	39.2 ± 16.5	74.4 ± 6.4	27.3 ± 6.0	50.3 ± 27.1	45.8 ± 22.6	50.75 ± 13.6	22 ± 6.9
NO_x	220.2 ± 47.4	252.9 ± 40.9	7.6 ± 3	31 ± 19	82.4 ± 16.3	158.4 ± 13.8	9.6 ± 10.8	18.8 ± 21.8	31.75 ± 7.4	69.5 ± 22.6
CO	0.7 ± 0.05	0.7 ± 0.08	0.5 ± 0.1	1.1 ± 0.9	0.52 ± 0.02	0.85 ± 0.04	-	-	1.15 ± 0.6	4.3 ± 1.1
SO_2	5.1 ± 1.5	7.45 ± 2.5	6.5 ± 2.2	13.3 ± 3.2	1.1 ± 0.1	1.6 ± 0.1	0.50 ± 0.13	0.79 ± 0.22	8 ±1.1	27 ± 9.5
Benzene	-	-	4.4 ± 1.2	6.1 ± 1.3	-	-	-	-	3.13 ± 1.1	7.7 ± 2.7

The micro-scale moss bags trace metals concentrations, measured during different campaigns, have the expected highest concentrations for almost all elements at the high-traffic road sites, and lower values near sites with less traffic density in Firenze (Pellizzaro et al. 2013).

In Athens, particle number concentration measurements indoors were generally correlated with outdoor concentration characteristics in the absence of important indoor sources. Although concentrations outside the residences were quite high, for well airtight buildings concentrations were significantly lower (given the fact that no internal PM sources were found inside). In contrast, poor construction and high infiltration rates due to, for example, old wooden door and window frames resulted in high indoor concentrations. The presence of internal sources e.g excessive smoking and cooking (e.g. frying) as expected resulted in high concentrations during the activity.

In the Gliwice case study, the high values for PM, SO_2, NO_x and CO in winter time reflect the issue of “low emissions” typical of the Silesian region, where the majority of isolated houses are heated by coal combustion with poor control of the emitted gases (Lesniok et al. 2010).

Indoor and outdoor thermal environment

The studies in Athens were carried out at a different scale with respect to the other cities, mainly addressing the outdoor and indoor microclimate. The case study area has high solar radiation levels and sunlight availability throughout the year and air temperatures range from 3°C (February) to 40°C (July). The yearly average value of relative humidity is about 60%. Dominant wind direction is from the North-East with an average wind speed of 3 ms^{-1}. Precipitation levels are quite low, especially during the summer.

The UHI analysis showed that the case study area suffers from a strong UHI effect. Measurements between Egaleo and a suburban station indicate a mean UHI intensity for the monitoring period of 2 -3 °C, reaching however in many occasions a difference of 6 - 8 °C. Modelling combined with measurements showed that the impact of increased outdoor temperatures in Egaleo compared to temperatures recorded in a suburban area (i.e. the UHI effect) results in an 74% increase in cooling load. In addition the analysis of the results of the outdoor experimental campaign in the case study area showed that increased surface and air temperatures and low wind speeds result in thermal discomfort for the people in the area.

Measurements inside the selected buildings showed that indoor thermal discomfort is a serious problem. It was found that over 40% of the maximum indoor temperatures are up to 35 °C, while 70% of the mean indoor temperatures are up to 30°C for the specific monitoring period. Indoor temperatures up to 38ºC have been recorded as well as hot spells of almost 21 consecutive hours over 34ºC. Comparative analysis of the occupants’ responses received from questionnaires and the measured indoor conditions indicate that the thermal comfort perception of the users is in agreement with the air temperature measurements. Also, particle number concentration measurements indoors is generally correlated with outdoor concentration characteristics in the absence of important indoor sources. In addition, although concentrations outside the residences were quite high, for well airtight buildings, concentrations were significantly lower (given the fact that no internal PM sources were found inside). On the contrary, poor construction and high infiltration rates due to e.g. old wooden frames resulted in high indoor concentrations. The presence of internal sources, like excessive smoking and cooking (e.g. frying) as expected resulted in high concentrations during the activity.

CONCLUSIONS

Urban metabolic fluxes were observed at both local scale micro-scale in BRIDGE case studies. They provided a composite picture of the various cities, with different seasonal characteristics of carbon, energy and pollutants exchanges. It was observed that CO_2 flux and air quality were significantly related, attributed to the importance of vehicle emissions for both. The measurements presented in this Chapter created a valuable input dataset in BRIDGE for both modelling exercise (see Chapters 7, 8, 9, 10 and 11 for details) and DSS development (see Chapter 16 for details).

REFERENCES

Aubinet, M., Vesala, T. & Papale, D. (2012). *Eddy Covariance. A Practical Guide to Measurement and Data Analysis*. Springer, Heidelberg, p. 430.

Britt, C., & Johnston, M. (2008). Trees in towns II: a new survey of urban trees in England and their condition and management. *Research for amenity trees*, No. 9. Department for Communities and Local Government.

Chrysoulakis, N., Lopes, M., San José, R., Grimmond, C.S.B., Jones, M.B., Magliulo, V., Klostermann, J.E.M., Synnefa, A., Mitraka, Z., Castro, E., González, A., Vogt, R., Vesala, T., Spano, D., Pigeon, G., Freer-Smith, P., Staszewski, T., Hodges, N., Mills, G., & Cartalis, C. (2013). Sustainable urban metabolism as a link between bio-physical sciences and urban planning: the BRIDGE project. *Landscape and Urban Planning*, 112, 100 - 117.

Foken T, Wichura B (1996) Tools for quality assessment of surface-based flux measurements. *Agricultural & Forest Meteorology*, 78: 83-105.

Fratini, G., Ciccioli, P., Febo, A., Forgione, A. & Valentini, R. (2007). Size-segregated fluxes of mineral dust from a desert area of northern China by eddy covariance. *Atmospheric Chemistry and Physics*, 7, 2839 - 2854.

Fuller, R., Smith, G.M., Sanderson, J.M., Hill, R.A. & Thompson, A.G. (2001). The UK Land Cover Map 2000:construction of a parcel-based vector map from satellite images. *Cartographic Journal*, 39, 15 - 25.

Gioli, B., Toscano, P. Zaldei, A., Fratini, G. & Miglietta, F. (2013). CO2, CH4 and particles flux measurements in Florence, Italy. *Energy Procedia*, 40, 537 - 544.

Gioli, B., Toscano, P., Lugato, E., Matese, A., Miglietta, F., Zaldei, A. & Vaccari, F.P. (2012). Methane and carbon dioxide fluxes and source partitioning in urban areas: The case study of Florence, Italy. *Environmental Pollution* ,164, 125 - 131.

GLA (2007). *Chainsaw massacre: A review of London's street trees*. Greater London Authority.

Greek Ministry of Environment Energy and Climate Change (2010). *Annual Report on Atmospheric Pollution*, Directorate of Air Pollution and Noise. Available online at: http://www.ypeka.gr/LinkClick.aspx?fileticket=NIpIqbQgp4U%3d&tabid=490

Järvi, L., Hannuniemi, H., Hussein, T., Junninen, H., Aalto, P. P., Hillamo, R., Mäkelä, T., Keronen, P., Siivola, E., Vesala, T. & Kulmala, M. (2009a). The urban measurement station SMEAR III: Continuous monitoring of air pollution and surface-atmosphere interactions in Helsinki, Finland. *Boreal Environmental Research*, 14 (Suppl. A), 86 - 109.

Järvi L, Mammarella I, Eugster W, Ibrom A, Siivola, E., Dellwik, E., Keronen, P., Burba, G. & Vesala, T. (2009b*)*. Comparison of net CO_2 fluxes measured with open- and closed-path infrared gas analyzers in urban complex environment. *Boreal Environmental Research*, 14, 499 - 514.

Järvi, L., Rannik, Ü. ,Mammarella, I. , Sogachev, A. , Aalto, P. P. , Keronen, P. , Siivola, E., Kulmala, M. & Vesala, T.(2009c). Annual particle flux observations over a heterogeneous urban area. *Atmospheric Chemistry and Physics*, 9, 7847 - 7856.

Järvi, L., Nordbo, A., Junninen, H., Riikonen, A., Moilanen, J., Nikinmaa, E. & Vesala, T. (2012). Seasonal and annual variation of carbon dioxide surface fluxes in Helsinki, Finland, in 2006-2010. *Atmospheric Chemistry and Physics*, 12, 8475 - 8489.

Kotthaus S. & Grimmond, C.S.B. (2012). Identification of Micro-scale Anthropogenic CO_2, Heat and Moisture Sources – Processing Eddy Covariance Fluxes for a Dense Urban Environment. *Atmospheric Environment*, 57, 301 - 316.

Kotthaus S. & Grimmond, C.S.B. (2013). Energy exchange in a dense urban environment - Part I: temporal variability of long-term observations in central London. *Urban Climate*, Available online. ISSN 2212-0955, http://dx.doi.org/10.1016/j.uclim.2013.10.002.

Kotthaus S. & Grimmond, C.S.B. (2013). Energy exchange in a dense urban environment - Part II: impact of spatial heterogeneity of the surface. *Urban Climate*, Available online, ISSN 2212-0955, http://dx.doi.org/10.1016/j.uclim.2013.10.001.

LAEI (2006). *London Atmospheric Emissions Inventory 2006. Modelling maps*. Air quality team, environment group, Greater London Authority http://legacy.london.gov.uk/mayor/environment/air_quality/research/emissions-inventory.jsp

Lesniok M, Malarzewski L. & Niedzwiedz T. (2010). Classification of circulation types of Southern Poland with an application to air pollution concentration in Upper Silesia. *Physics and Chemistry of the Earth*, 35, 516 - 522.

Lindberg F. & Grimmond, C.S.B. (2011). Nature of vegetation and building morphology characteristics across a city: influence on shadow patterns and mean radiant temperatures in London. *Urban Ecosystems*, 14, 617 - 634.

Loridan T. & Grimmond, C.S.B. (2012). Characterization of energy flux partitioning in urban environments: links with surface seasonal properties. *Journal of Applied Meteorology and Climatology*, 51, 219 - 241.

Loridan T., Lindberg, F., Jorba, O., Kotthaus, S., Grossman-Clarke, S. & Grimmond, C.S.B. (2013). High resolution simulation of surface heat flux variability across central London with Urban Zones for Energy partitioning. *Boundary Layer Meteorology* DOI: 10.1007/s10546-013-9797-y

Marras, S., Pyles, R. D. Sirca, C., Paw U, K.T., Snyder, R.L., Duce, P. & Spano, D. (2011). Evaluation of the Advanced Canopy-Atmosphere-Soil Algorithm (ACASA) model performance over Mediterranean maquis ecosystem. *Agricultural and Forest Meteorology*, 51, 730 - 745.

Matese, A., Gioli, B., Vaccari, F. P., Zaldei, A. & Miglietta, F. (2009). Carbon Dioxide Emissions of the City Center of Firenze, Italy: Measurement, Evaluation, and Source Partitioning. *Journal of Applied Meteorology and Climatology*, 48, 1940 - 1947.

Matese, A., Alberti, G., Gioli, B., Toscano, P., Vaccari, F.P. & Zaldei, A. (2008). Compact(-)Eddy: A compact, low consumption remotely controlled eddy covariance logging system. *Computers and Electronics in Agriculture*, 64, 343 - 346.

Nordbo, A., Järvi, L. & Vesala, T. (2012a). Revised eddy covariance flux calculation methodologies – effect on urban energy balance. *Tellus B*, 48, 18184. http://dx.doi.org/10.3402/tellusb.v64i0.18184

Nordbo, A., Järvi, L., Haapanala, S., Wood, C. & Vesala, T. (2012b*)*. Fraction of natural area as main predictor of net CO_2 emissions from cities. *Geophysical Research Letters*, 39, L20802, DOI:10.1029/2012GL053087.

Nordbo, A., Järvi, L., Haapanala, S., Moilanen, J. & Vesala, T. (2013). Intra-city variation in urban morphology and turbulence structure in Helsinki, Finland. *Boundary-Layer Meteorology*, 146, 469 - 496.

Perry M. & Hollis D. (2005). The generation of monthly gridded datasets for a range of climatic variables over the UK. *International Journal of Climatology*,25, 8, 1041-1054. Current spatial maps of met data from: http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/download/monthly/gridded_monthly.html

Pincetl, S., Bunje, P., Holmes, T. (2012). An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes. *Landscape and Urban Planning*, 107(3): 193 - 202.

Riikonen, A., Lindén L., Pulkkinen M. & Nikinmaa E. (2011*)*. Post-transplant crown allometry and shoot growth of two species of street trees. *Urban forestry & Urban greening*, 10, 87 - 94.

Ripamonti, G., Järvi, L., Mølgaard, M., Hussein, T.,Nordbo, A. & Hämeri, K. (2013*)*. The effect of local sources on aerosol particle number size distribution, concentrations and fluxes in Helsinki, Finland. *Tellus B*, 65, 19786, http://dx.doi.org/10.3402/tellusb.v65i0.19786.

Stewart, I. D. & Oke, T. R. (2012). *"Local Climate Zones" for urban temperature studies*. *Bull. Amer. Meteor. Soc.*, 120525055949004, doi:10.1175/BAMS-D-11-00019.1.

Tallis, M.J., Freer-Smith P.H., Sinnett D. & Taylor G. (2011). Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. *Landscape and urban planning*, 103, 129 - 138.

Vesala T., Järvi L., Launiainen S., Sogachev A., Rannik Ü., Mammarella I., Siivola E., Keronen P., Rinne J., Riikonen A. & Nikinmaa E. (2008). Surface-atmosphere interactions over complex urban terrain in Helsinki, Finland. *Tellus B*, 60, 188 - 199.