Insights from more than ten years of CO_2 flux measurements in the city of Basel, Switzerland

Introduction

Urban micrometeorology has a long tradition in Basel, Switzerland. Flux tower measurements started as early as in 1992 with the installation of a 15 m high tower on the terrace at the 5th floor of the former location of the institute of Meterorology, Climatology and Remote Sensing of the University of Basel (MCR) at Spalenring (BSPA in Fig. 1). Though the site was far from ideal (the building had a pitched roof and the chimney was pretty close to the sensors…) and latent heat flux was only sporadically measured, the tower was an important symbol for the institute's activities and attracted several urban climatology and turbulence projects.

In these early years, the main research topic was the vertical structure of turbulence in and above the urban canopy layer, also strongly influenced by the early work of M.W. Rotach in Zurich (e.g. Rotach, 1993a,b). With the help of Rotach's group, a 51 m high antenna tower (BMCH in Fig. 1) was equipped with sonics at three levels (z/h = 1.5, 2.1 and 3.2) on a 21 m high building at Messe Schweiz (BMCH in Fig. 1) between July 1995 and February 1996. Results of this campaign described for the first time the vertical dependence of velocity spectra in the urban roughness sub-layer (RSL) by the analysis of a large number of simultaneously measured multi-level turbulence time series (Feigenwinter et al., 1999). This study also confirmed that profiles of velocity variances and spectra of wind components could be parametrized within the framework of Monin-Obukhov similarity theory (MOST), if local scaling is applied. Feigenwinter and Vogt (2005) analyzed the same dataset with respect to profiles of coherent structures and showed that organized motions are not only a feature of vegetation canopies but can also be detected over rough urban surfaces.

With BUBBLE (Basel UrBan Boundary Layer Experiment) in 2002, Basel and MCR became definitely established in the Urban Climatology community. Despite no common funding, Roland Vogt and Andreas Christen accomplished to bring world leading urban climatologists to Basel for one of the longest and most detailed urban boundary layer programs (Rotach et al., 2005), including flux towers at Spalenring and Sperrstrasse (BSPA and BSPE in Fig. 1). The open data policy of BUBBLE led and still leads to numerous publications using the BUBBLE dataset, notably also for the validation of LES and CFD models (e.g. Gartmann et al., 2012). Christen and Vogt (2004) provide a comprehensive overview of the main findings of BUBBLE in terms of the urban energy and radiation balance. Within the framework of BUBBLE, research of MCR also started to focus on profiles of urban CO_2 concentration and fluxes. Vogt et al. (2006) tested the applicability of MOST to CO_2 flux-gradient relationships and found acceptable agreement for the top level at the upper boundary of the roughness sub-layer at 2 z_h (e.g. Feigenwinter et al., 2012). As a main conclusion they stressed the need for detailed analysis of surface properties (i.e. vegetation fraction) and anthropogenic CO_2 emissions (traffic, combustion) in the source area of flux towers when comparing with other urban studies.

As a consequence, research in Basel further concentrated on the analysis of CO_2 fluxes and concentrations with respect to the underlying urban structure. Simultaneously with the movement of MCR in 2003 to its present location, the flux tower from Spalenring was re-installed on the roof of the new building at Klingelbergstrasse (BKLI). An additional flux tower was installed on a slim 36m high building at Aeschenplatz (BAES) in 2009. In the following, the main findings from three papers analyzing data from the two flux towers BKLI and BAES are discussed, considering spatial scales from street canyon to neighborhood and temporal scales from months to years to decades.

Basel flux towers

Figure 1 shows the locations of active (BKLI and BAES) and former flux towers (BSPA-Spalenring, BSPE-Sperrstrasse and BMCH-Messe Schweiz) in the context of a digital object model (DOM) for buildings and trees. Footprints are calculated by the Kormann and Meixner (2001) algorithm and show the annual mean flux footprint of the respective flux tower. All flux towers were and are equipped with state of the art Eddy Covariance (EC) systems including an open path infrared gas analyzer (IRGA) and measurement devices for extended standard meteorology (temperature, humidity, wind and radiation (4 components)). At the BKLI site, numerous additional measurements are performed, including e.g. measurement of direct and diffuse radiation. Up to date instrumentation of BKLI and BAES flux towers is described in detail in Schmutz et al. (2016) and Lietzke et al. (2015), respectively; for further details about BMCH, BSPE and BSPA sites and instrumentation please refer to the respective papers.

The street canyon view

For the study of Lietzke and Vogt (2013) an additional 18 m high flux tower (B) with 5 levels of turbulence measurements was installed at the center of the adjacent

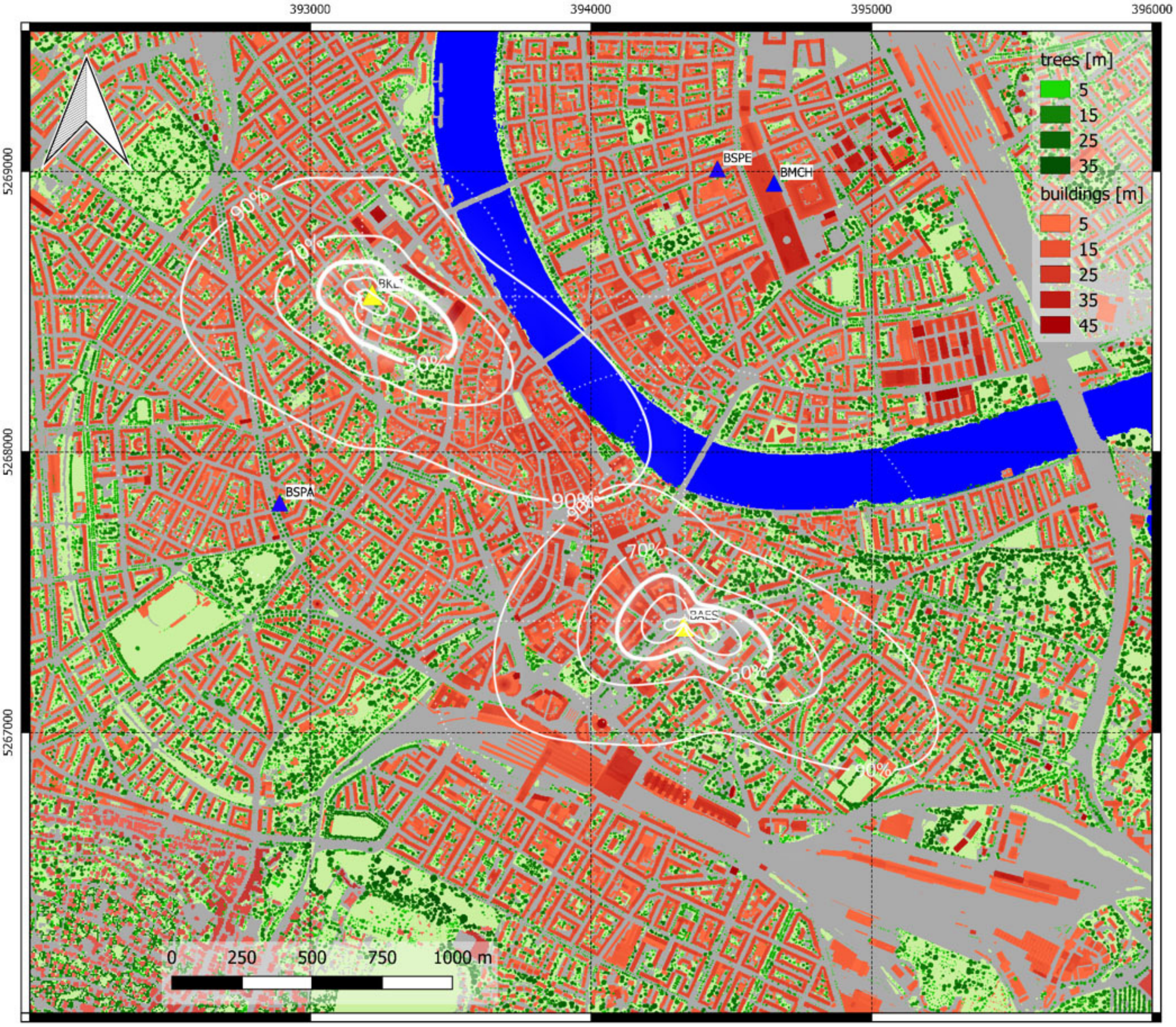

Figure 1. BASEL digital object model DOM with building heights (red), tree heights (green) and flux towers: former (blue) and active (yellow) towers with mean annual footprints. Light green areas refer to low vegetation (lawn), gray areas refer to impervious surfaces (roads, plazas) and railway tracks. Coordinate system is UTM 32N (EPSG: 32632).

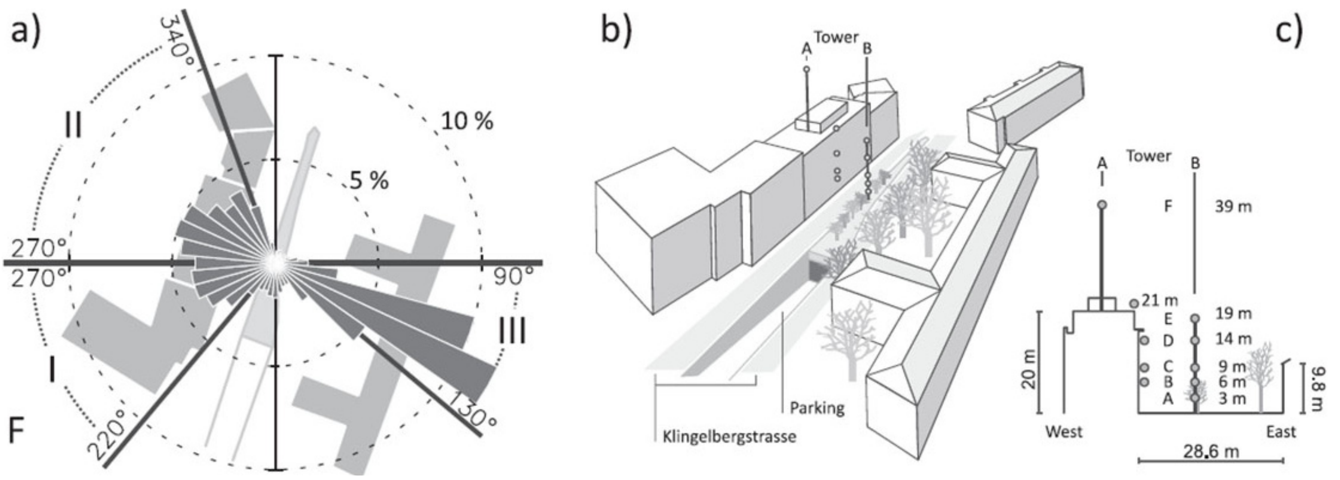

Figure 2. (a) BKLI Wind rose at 39 m (F) and plan area of the surrounding buildings. (b) 3D-view from the south. (c) cross section at the tower location (adapted from Lietzke and Vogt, 2013)

street canyon to BKLI flux tower (A), providing a full-year dataset for 2010. Figure 2 gives an overview of the experimental setup. The street canyon orientation (20°) is approximately perpendicular to the main wind directions. As a result, in-canyon air flow forms a vortex that shows a corkscrew-like lateral motion, the direction of which is dependent on the direction of the wind above. Eastern (90-130°) and western winds from less than 270° lead to northward flowing air masses inside the canyon whereas western winds from directions greater than 270° result in a southwards directed flow, as shown in Figure 3. The flow regime of wind coming from the area west of the site is expected to be 'skimming flow' (Oke, 1987) as the underlying building structure is relatively dense. The street canyon itself has a non-ideal cross section. The height to width ratio is 0.7 for the building to the west and 0.34 for the building to the east. Thus, the local flow regime for the canyon for east wind situations might be characterized as 'wake interference flow' (Oke, 1987).

CO_2 concentrations

Daytime in-canyon distribution of CO_2 concentration depends heavily on these vortex structures and traffic emissions. Mean diurnal courses of CO_2 concentrations are comparable to that of other cities but spatial differences reveal some interesting patterns. Basically, the concentration level is coupled to the height of the urban boundary layer. Traffic as the dominant CO_2 source in the street canyon has only a minor influence on absolute concentrations at all heights. However, traffic emissions result in a superimposed effect that is generally stronger closer to the ground. This fact is represented by the vertical differences between the bottom or top of the canyon and 39 m as shown in Figure 4. These differences reflect the diurnal course of traffic density well and also allow for a clear distinction between working day and weekend courses.

CO_2 fluxes

Traffic is obviously the determining factor for CO_2 fluxes (F_C) since mean diurnal courses of traffic density and $F_C(19)$ in Figure 5 have almost identical characteristics. In accordance with traffic density, $F_C(19)$ shows distinct working day/weekend differences and the one hour shift in morning traffic increase during periods with/without daylight saving time. Strong linear correlations support the assumption of a distinct relationship. We are well aware that $F_C(19)$ is measured in the roughness sub-layer (RSL) and the influence of individual roughness elements cannot be avoided. A height dependency of turbulent fluxes in the urban canopy layer (UCL) was expected and the sensor at 19 m was intended to capture the influence of the traffic of this busy street and to see how far up this influence reaches. The excellent qualitative agreement of the $F_C(19)$ flux patterns with the diurnal patterns of traffic confirms this approach and demonstrates the applicability of the EC method for such a specific purpose. Obviously sufficient mixing blends the traffic emissions to a representative flux.

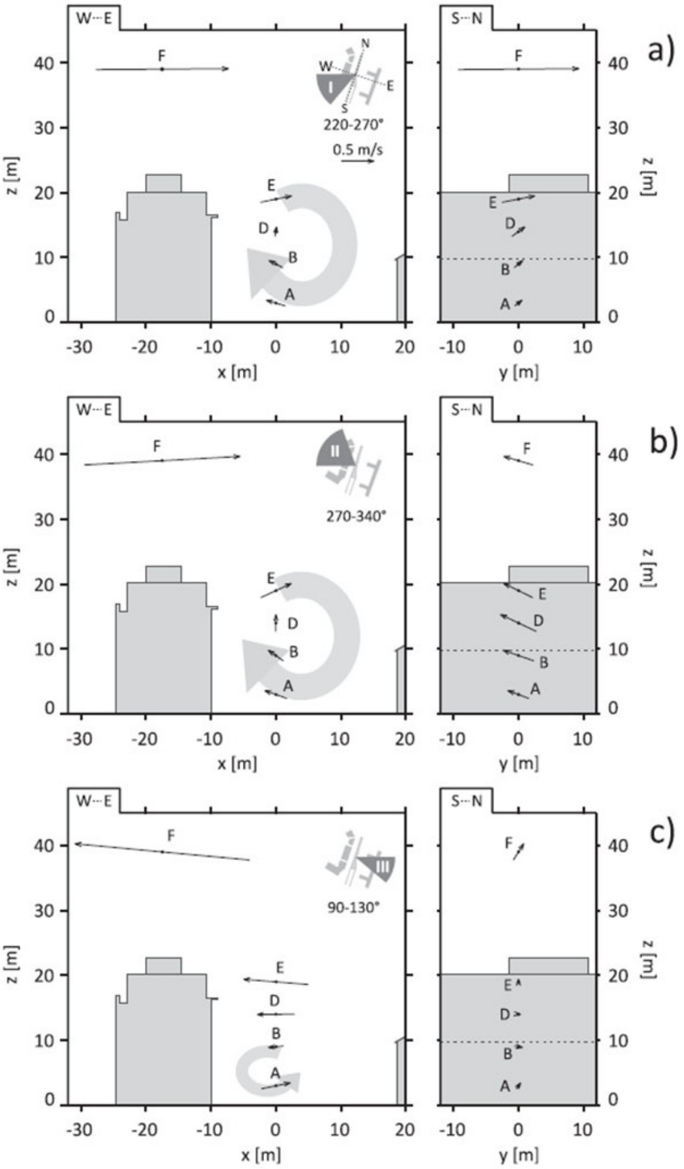

Figure 3. Cross (left column, W-E) and lateral (right column, S-N) sections of the street canyon for three different ambient wind sectors (a, b & c). Arrows depict average wind vector components in the respective planes at the measurement locations A, B, D, E and F. Typical expected vortex structures are shown for each wind sector (adapted from Lietzke and Vogt, 2013).

As a first consequence, it can be argued that urban CO_2 fluxes at a height of approximately 2 z_h are extremely sensitive to the placement of the tower. A few tens of meters of horizontal displacement may lead to totally different diurnal regimes depending on prevailing wind directions combined with the given canyon orientation and configuration. The authors therefore stress the need for reliable source area determination in order to compare flux towers at different locations.

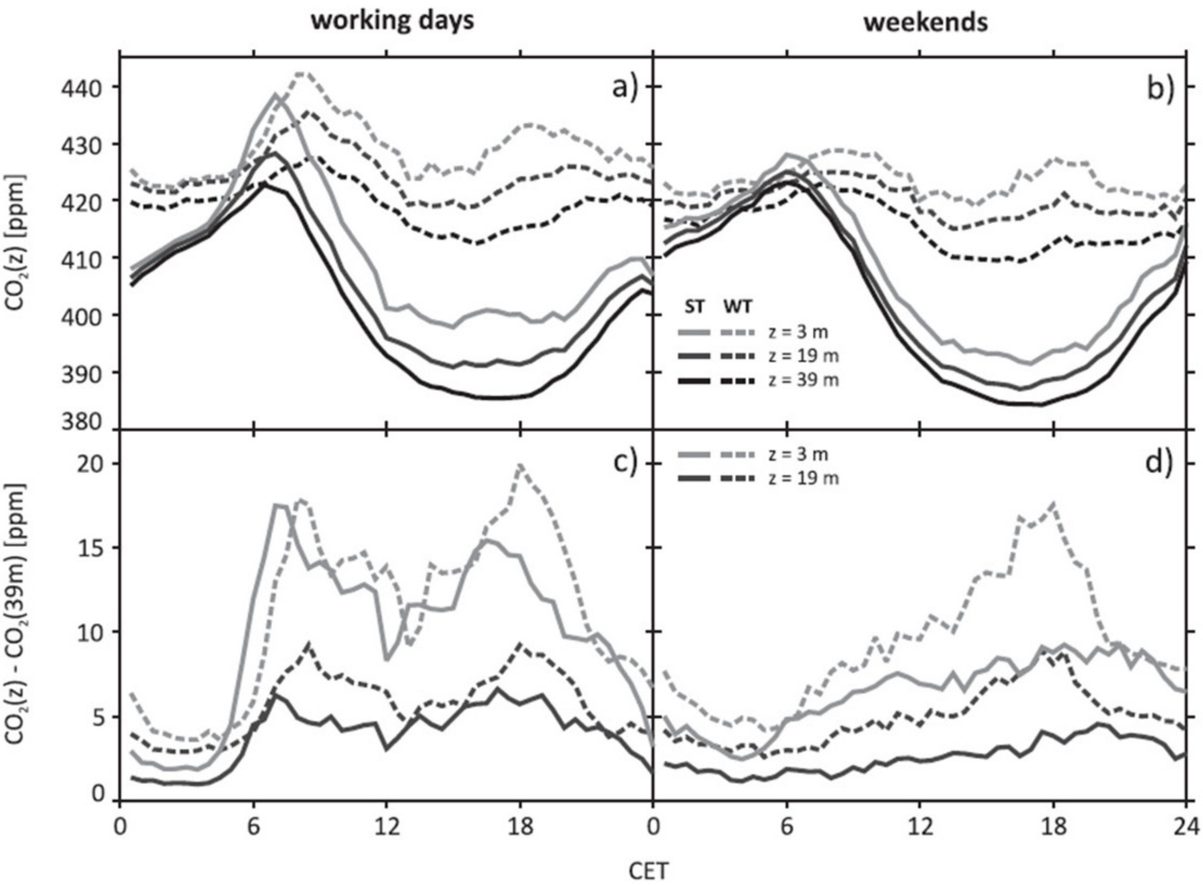

Figure 4. Mean diurnal courses of CO_2 concentrations at two heights in the canyon center and above the roof for working days (a) and weekends (b). Data is separated for summer-(ST) and wintertime (WT). (c) & (d): Corresponding differences relative to top level (adapted from Lietzke and Vogt, 2013)

The neighborhood view

Lietzke et al. (2015) analyzed the controlling factors responsible for the variability of urban CO_2 fluxes based on a 4-year dataset of Basel flux tower BAES. In their study the authors provide a review of more than 40 urban studies trying to find a common relationship between CO_2 flux, traffic density and land cover fraction (Figure 6). Despite the huge uncertainties resulting from non-standardized methods for measurement procedures (reference height, tower location, data processing) and for determination and classification of surface characteristics, even the greenest locations with high vegetation fractions show a positive CO_2 budget and fossil fuel emissions (traffic and heating related combustion) have a strong influence on the size of CO_2 fluxes.

In order to make results from different locations and different cities better comparable, the authors for the first time introduced the concept of "expected fluxes" eF_C based on the sectoral analysis of F_C. Ideally a dataset provides an equal representation of each sector, which is never the case in the real world. The method is based on the gap filling method with mean diurnal cycles (MDC) (e.g. Järvi et al., 2012), where missing F_C data are replaced based on a set of MDC for the existing data. Each MDC accounts for different conditions (e.g. season, working days/weekends, wind sectors, etc.). Sectoral eF_C is derived by splitting F_C into nine sectoral datasets and filling the missing values with MDC data derived for the respective sector. The average of all sectoral eF_C is the average expected flux and the sum of all sectoral *eNEE* ("Net (urban) ecosystem exchange") is the average expected *eNEE*, respectively. eF_C as an up-scaled measure is expected to give a more accurate average representation of the heterogeneous surroundings than F_C as the latter represents only a patchwork of single, temporally restricted and wind direction dependent images of the surroundings.

Relating sectoral eF_C instead of F_C to urban surface fractions of buildings and vegetation results in a better agreement (also with data from other studies), as shown in Figure 7.

Provided sufficient data availability (EC fluxes, Land Use/Land Cover maps (LULC), morphology, urban form, etc.) the concept of eF_C and *eNEE* may be of help for the interpretation of measured carbon fluxes at other urban sites, especially those surrounded by areas with different emission characteristics and unequally distributed wind directions. As eF_C relies on statistical up-scaling, its application is restricted to long-term measurement sites. An interesting option for future applications would be the combination with LCZ classification (Stewart and Oke,

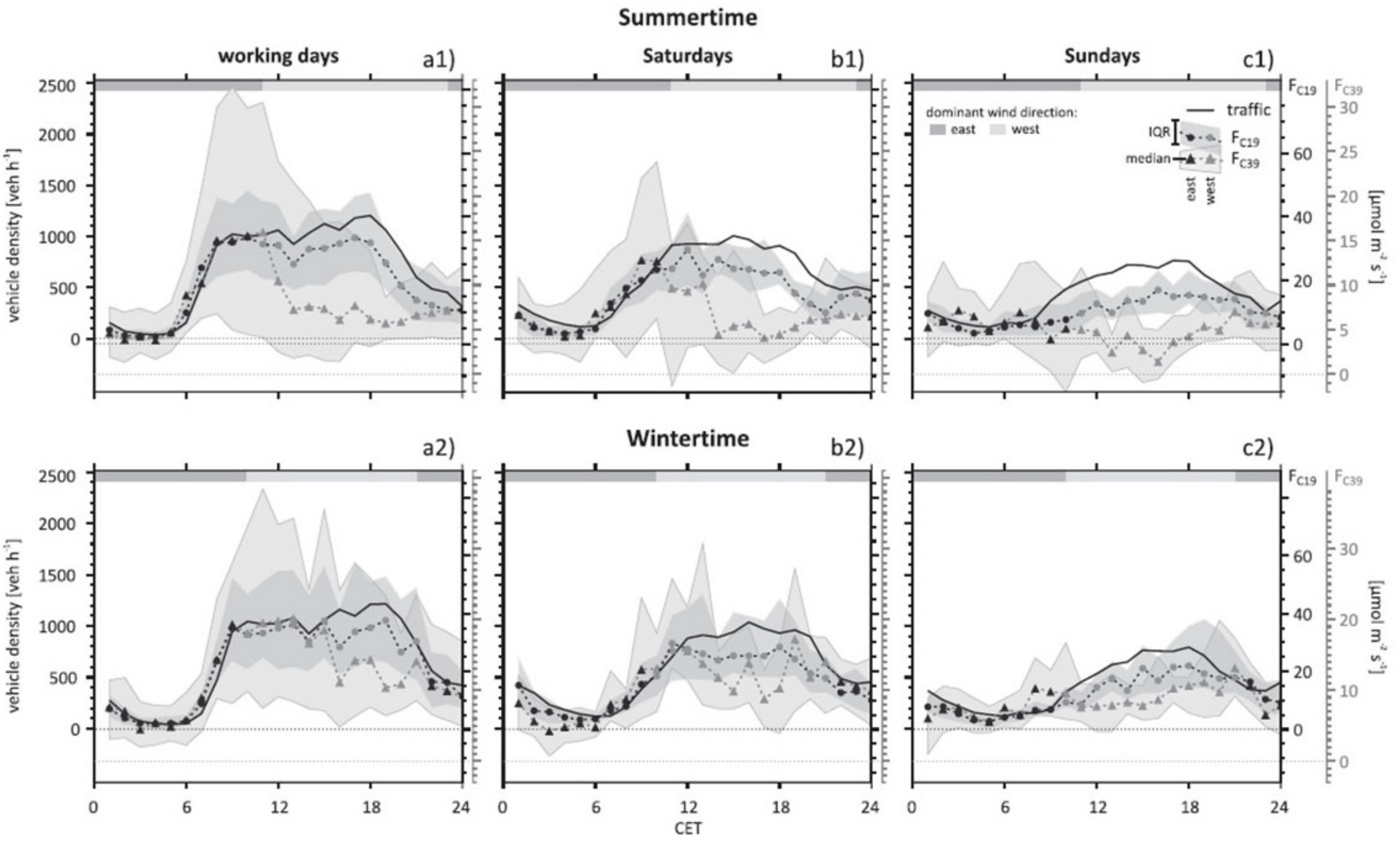

Figure 5. Average diurnal courses of vehicle density (black line), F_C(19) (circles) and F_C(39) (triangles) for ST (upper row) and WT period (lower row). Hourly averaged median data for (a) working days, (b) Saturdays and (c) Sundays. Shaded areas represent the interquartile ranges. The light gray bar at the top of each plot denotes > 50% winds from western directions (20-200°), the dark gray > 50% from eastern directions (200-20°). Correspondingly, F_C values measured under west wind (east wind) influence are marked with lighter gray (darker gray) symbols (adapted from Lietzke and Vogt, 2013)

2012) which could lead to a more standardized implementation.

The longterm view

After moving the flux tower from BSPA to its current location at Klingelbergstrasse BKLI in 2003, a lot of effort was put into maintenance work and sensor calibration. Numerous recalibrations of the EC system as well as several wind tunnel experiments with the sonic anemometer have been performed (Vogt & Feigenwinter, 2004), which made it possible to run the EC system without considerable gaps up to the present day, covering almost 14 years of continuous flux data. Schmutz et al. (2016) present results from the first decade of CO_2 flux measurements, which is the longest urban CO_2 flux time series currently published in literature.

Decadal trends of CO_2 flux and concentration

Comparing the CO_2 concentration at BKLI to regional background concentration records from Global Atmosphere Watch (GAW) stations Schauinsland (SAL, 40 km north of BKLI, 1205 m asl) and Jungfraujoch (JFJ, 120 km south of BKLI, 3580 m asl) reveals good agreement of the data in terms of seasonal patterns and long term trends (Figure 8). At all three sites an average linear trend near 2.0 ppm y^{-1} was calculated, which is in good agreement with results reported in the IPCC report 2013 (IPCC, 2013) derived from Mauna Loa and South Pole data. The seasonal course of the CO_2 concentration is mainly shaped by the varying photosynthetic activity of the vegetation. However, the average concentration level is around 10 ppm higher in the city compared to the reference sites. Interestingly, the coupling between local and background concentration follows a hysteresis, whereas the winter peak is delayed by up to three month and the summer peak by around one month at JFJ and SAL (Figure 9). This shows the time needed to mix the signal of the ongoing source and sink processes within the boundary layer into the lower troposphere during stable conditions in wintertime and convective conditions in summertime.

In order to analyze the long-term trend of F_C, the concept of "expected fluxes" introduced by Lietzke et al. (2015) was refined and further developed in Schmutz et al. (2016). The use of moving look-up tables increases the statistical robustness and eliminates the need of multi-year time series for the calculation of what is now called horizontal averages (denoted by angle brackets). While

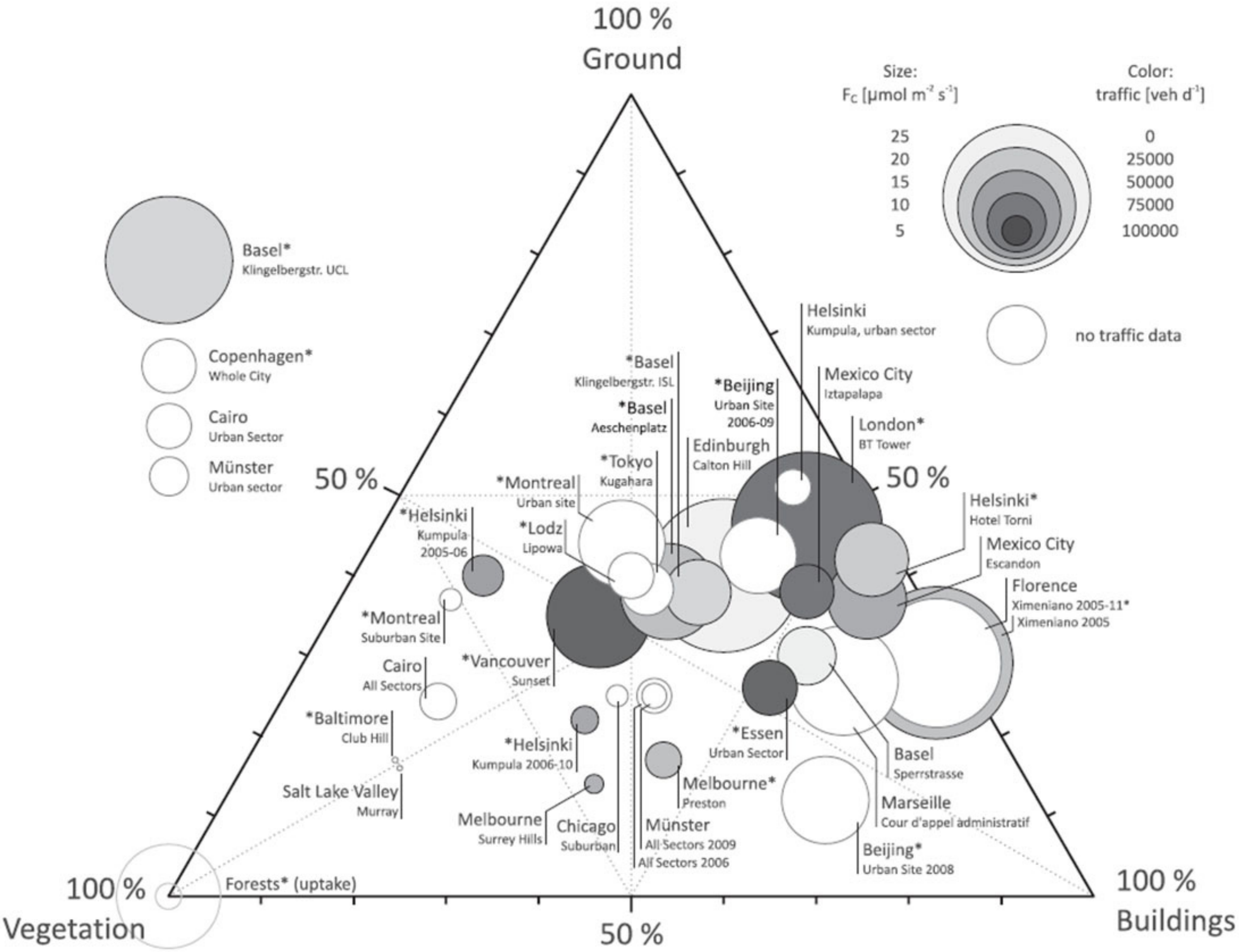

Figure 6. Ternary plot of selected urban studies. The centre point of each circle gives the plan area fractions. The size represents F_C and the gray tone represents the reported traffic density if available in vehicles per day (see legend). An asterisk indicates that the F_C data coverage was at least one whole year. Where only vegetation cover was listed, the remaining fraction was assumed to be equally split between buildings and ground. For circles outside the plot no plan area fractions were reported. Refer to Tab. 1 in Lietzke et al. (2015) for full references. (Adapted from Lietzke et al., 2015)

varying wind systems may considerably superimpose the measured CO_2 fluxes by advecting the signal of varying sources over the course of time, horizontal averages mostly eliminate this effect and reveal the effective variability and long-term trends at the measurement site. F_C at BKLI was thereby reduced by 5 % between 2005 and 2014, which can be explained by the reduced traffic volume around BKLI due to new city bypass roads. Still, the year-to-year variability of F_C is much larger than the calculated linear trend (compare Fig. 8), which makes it difficult to further discuss long-term tendencies of F_C at BKLI. Despite the large inter-annual variability, a lower limit of F_C was found around 5 µmol m^{-2} s^{-1} consistent over the entire measurement period. This implies a base-load of the urban metabolism during minimal source activity in early morning, especially in summertime, introduced by e.g. human respiration and the fact that main sources like traffic or heating activity are never zero.

Outlook

A short history and the most recent research from the flux towers in Basel, Switzerland, were presented. As the value of long-term flux measurements is evident, also considering the enormous efforts and investments in long-term infrastructure and monitoring programs like ICOS (www.icos-ri.eu) and NEON (www.neonscience.org), we are confident to find future funding to continue our high quality measurements in Basel. Long-term EC measurements in urban environments are essential for the assessment of urban climate models and remote sensing applications. Currently, the Basel flux towers BKLI and BAES provide invaluable data for the evaluation of satellite derived sensible and latent heat fluxes (Feigenwinter et al., 2017) in the frame of the Horizon 2020 URBANFLUXES project (Chrysoulakis et al., 2017; www.urbanfluxes.eu). Since the number of urban flux towers is still increasing and a lot of the permanent urban flux tow-

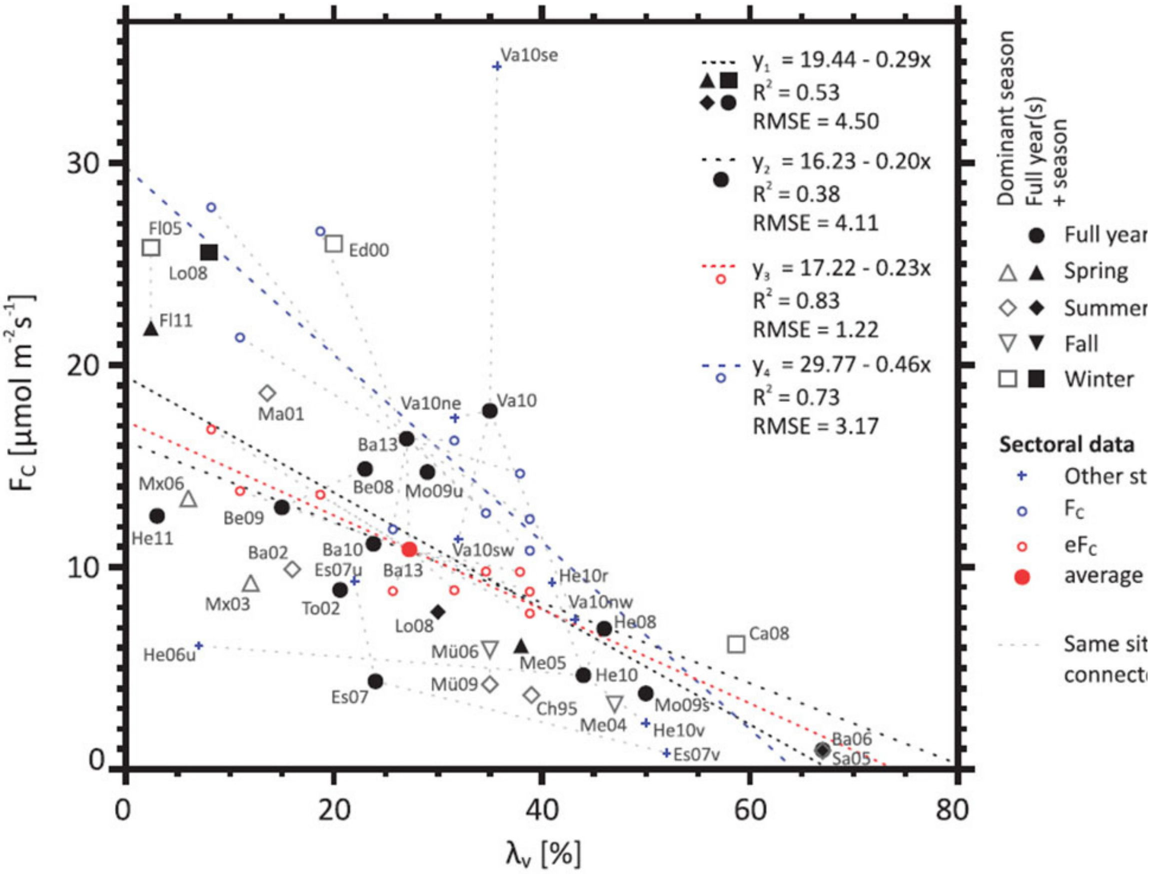

Figure 7. Average F_C as a function of vegetation fraction λv for selected studies. Open symbols define the season of measurements. Filled circles represent measurements of one or more full years, all other filled symbols stand for full years plus an additional part of the respective season. Sectoral average F_C and eF_C (derived from *eNEE*) of this study are denoted by the small open circles. Regression equations (y1-y4) are for the respective groups of data as labelled. Other dashed lines connect different results from one single site (e.g. for sectors or years) and show site-specific variability. (Adapted from Lietzke et al., 2015)

ers meanwhile have time series of more than a decade, it may be time for a refreshment of the URBAN FLUX NETWORK (see also IAUC Newsletter from June 2009), e.g. in form of a La Thuile–like synthesis dataset (http://fluxnet.fluxdata.org/data/la-thuile-dataset/).

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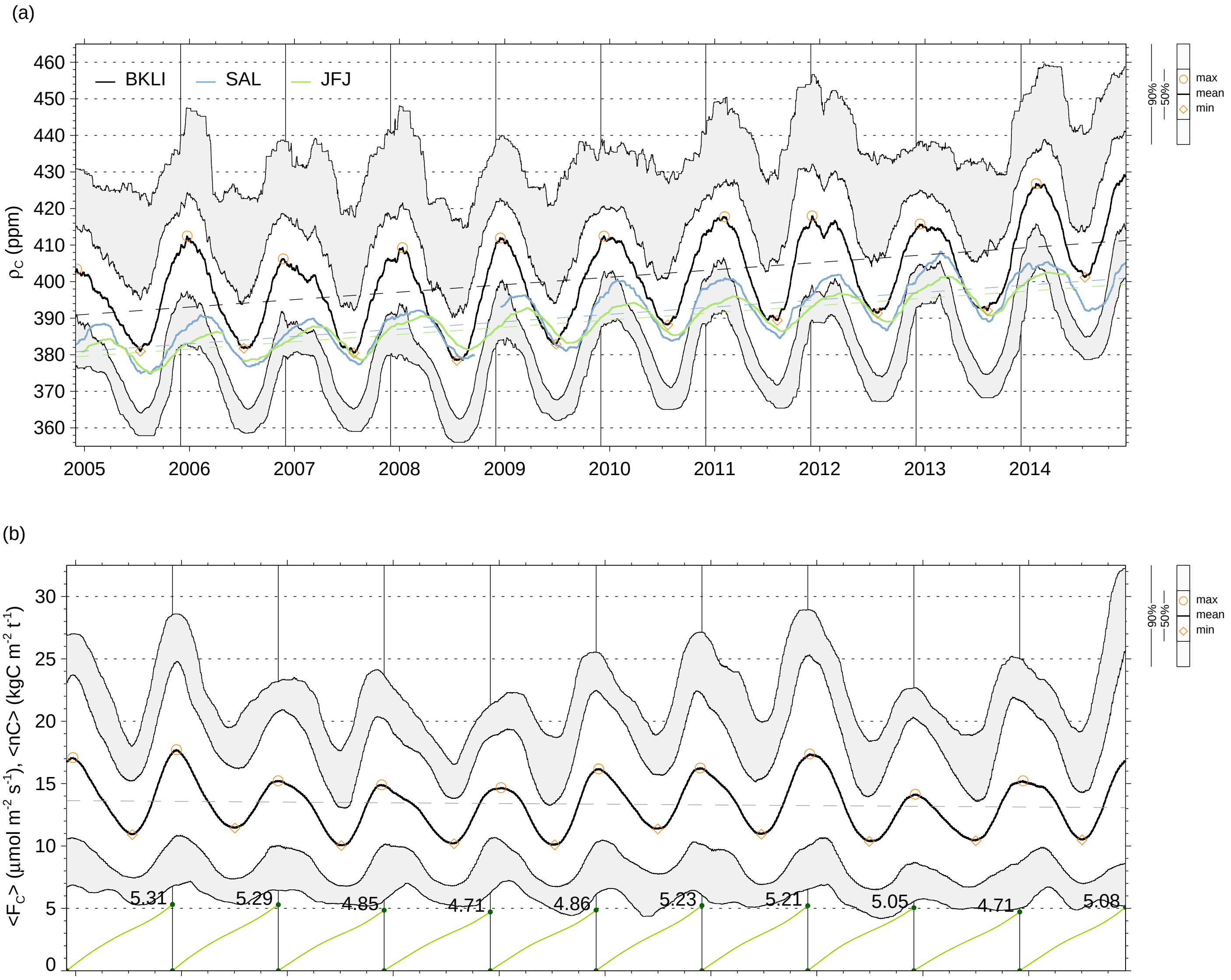

Figure 8. (a) Time series of CO_2 concentration at BKLI, Schauinsland (SAL), and Jungfraujoch (JFJ) and (b) time series of <F_C> (horizontally averaged F_C) and yearly cumulative <n_C> (green lines from 2005 until 2014). The solid lines are 90 days running means of half hourly data. Statistics for BKLI are indicated by grey shaded areas. The dashed lines show the linear regression for each time series. Additionally, winter maxima (circles) and summer minima (diamonds) are drawn (adapted from Schmutz et al. 2016).

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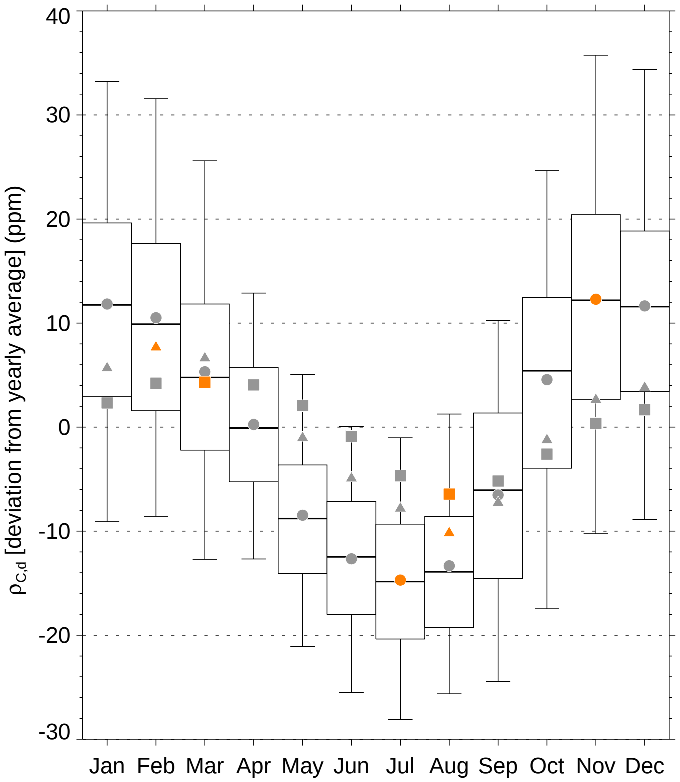

Figure 9. Average seasonal amplitude (deviation from yearly mean) of CO_2 concentration ($\rho_{C,d}$) for BKLI (circle), SAL (triangles), and JFJ (squares). Depicted are average monthly values of $\rho_{C,d}$ calculated from daily averages corrected for long-term trend of each station. Winter and summer peak values are marked in orange (adapted from Schmutz et al. 2016).

Christian Feigenwinter
christian.feigenwinter@unibas.ch

Michael Schmutz
mi.schmutz@unibas.ch

Roland Vogt
roland.vogt@unibas.ch

Eberhard Parlow
eberhard.parlow@unibas.ch

Meteorology, Climatology and Remote Sensing (MCR), Department of Environmental Sciences
University of Basel, Switzerland

This article is a basically a summary of three recent papers representative for the research on urban CO_2 fluxes and concentrations based on the Basel flux tower data: Lietzke & Vogt (2013), Lietzke et al. (2015) and Schmutz et al. (2016), but also shortly recapitulates the 25 years of flux measurements in the city of Basel, Switzerland. For more detailed information please refer to the full papers.