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Urban carbon dioxide flux monitoring using Eddy Covariance and Earth Observation: An introduction to diFUME project

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Introduction

Monitoring urban CO_2 emissions has become a necessity to support sustainable urban planning strategies and climate change mitigation efforts. Integrative decision support, where net effects of various emission/sink components are considered and compared, is an increasingly relevant part of urban planning processes (Grazi & van den Bergh, 2008). The current emission inventories rely on indirect approaches that use fuel and electricity consumption statistics for determining CO_2 emissions (Kennedy et al., 2010). The consistency of such approaches is questionable (Ramaswami et al. 2008) and they usually neglect the contribution of the biogenic components of the urban carbon cycle. Moreover, their spatiotemporal resolution is restricted and are usually scaled down using proxy data (e.g. population density) to city-scale annual estimates.

The diFUME project is developing a methodology for mapping and monitoring the urban CO_2 flux at optimum spatial and temporal scales, meaningful for urban design decisions. The goal is to develop, apply and evaluate independent models, capable to estimate the components of the urban carbon cycle (Fig. 1). The net CO_2 flux (F_C) of an urban area can be budgeted as:

$$F_C = E_V + E_B + R_H + R_S + (R_V - P_V) \quad (1)$$

E_V concerns emissions from fossil fuel combustion by motor vehicles, E_B is emissions from combustion within buildings (e.g. natural gas, oil, wood), R_H is the metabolic release of CO_2 by human respiration, R_S is the below-ground soil, root, and waste microbial respiration, R_V is the above-ground vegetation respiration, and P_V is the CO_2 assimilation by photosynthesis. P_V is the only component acting as a carbon sink. The sequestered carbon by vegetation is stored locally in tree biomass and soil.

diFUME approach combines mainly Eddy Covariance (EC) with Earth Observation (EO) data to achieve comprehensive F_C monitoring and modelling. EC provides continuous *in-situ* measurements of CO_2 flux at the local scale, whereas EO offers synoptic and continuous monitoring of the urban areas in multiple spatial scales (local to microscale) that aid to a complete characterization of the urban environment.

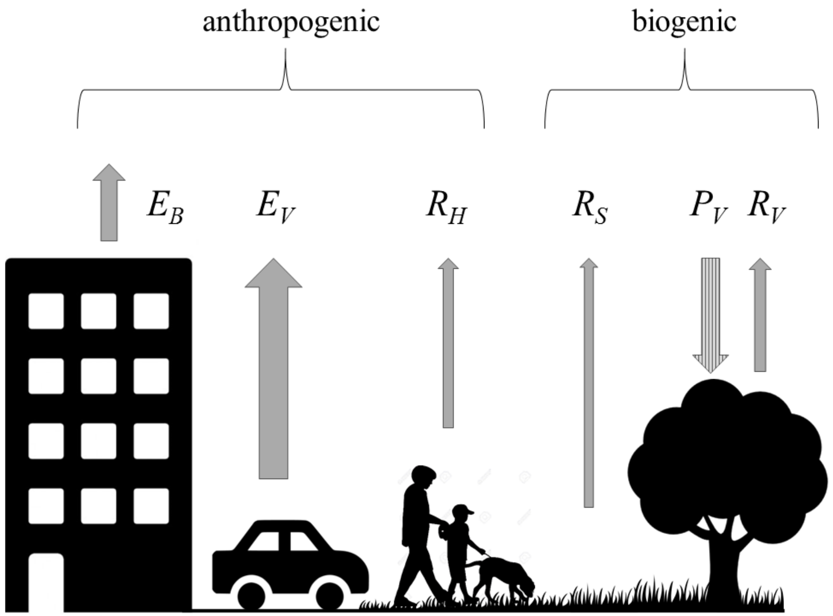

Figure 1. Schematic representation of the main components of the vertical CO_2 flux in an urban area.

Overview – the diFUME approach

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A particular challenge of diFUME is to combine EC with EO-derived datasets, to develop innovative modelling techniques of the individual source and sink processes (Fig. 2). Specifically, long-term EC-measured F_C time-series from the study area, characterized by diverse urban typologies, is used to develop statistical modelling approaches combining analytic source area modelling, EO-based land cover/morphology and auxiliary predictors for describing E_B and E_V temporal patterns (e.g. Crawford & Christen, 2015). Auxiliary predictors include air temperature and population density for E_B and traffic counts/profiles for E_V. An indirect method will be applied for R_H modelling based on disaggregated census data (e.g. population density, workforce, age, time use), combined with spatial-morphological data for the estimation of dynamic spatiotemporal distribution of the population.

The biogenic CO_2 exchange (R_S, R_V, P_V) is estimated by developing mechanistic models that use meteorological observations and EO monitoring. The 3D structure of the city morphology and the multiple radiation interactions between buildings and urban vegetation are considered in a multi-layer modelling approach. Air temperature variability across the urban space is modelled adopting the methodology of Wicki et al. (2018). The biogenic flux models will be calibrated during an upcoming extended field campaign of microscale *in-situ* CO_2 flux measurements on urban trees and soils.

This current study presents the first results from the EC data analysis and the source area modelling, and investigates the relationships between traffic profiles and the EC-derived F_C.

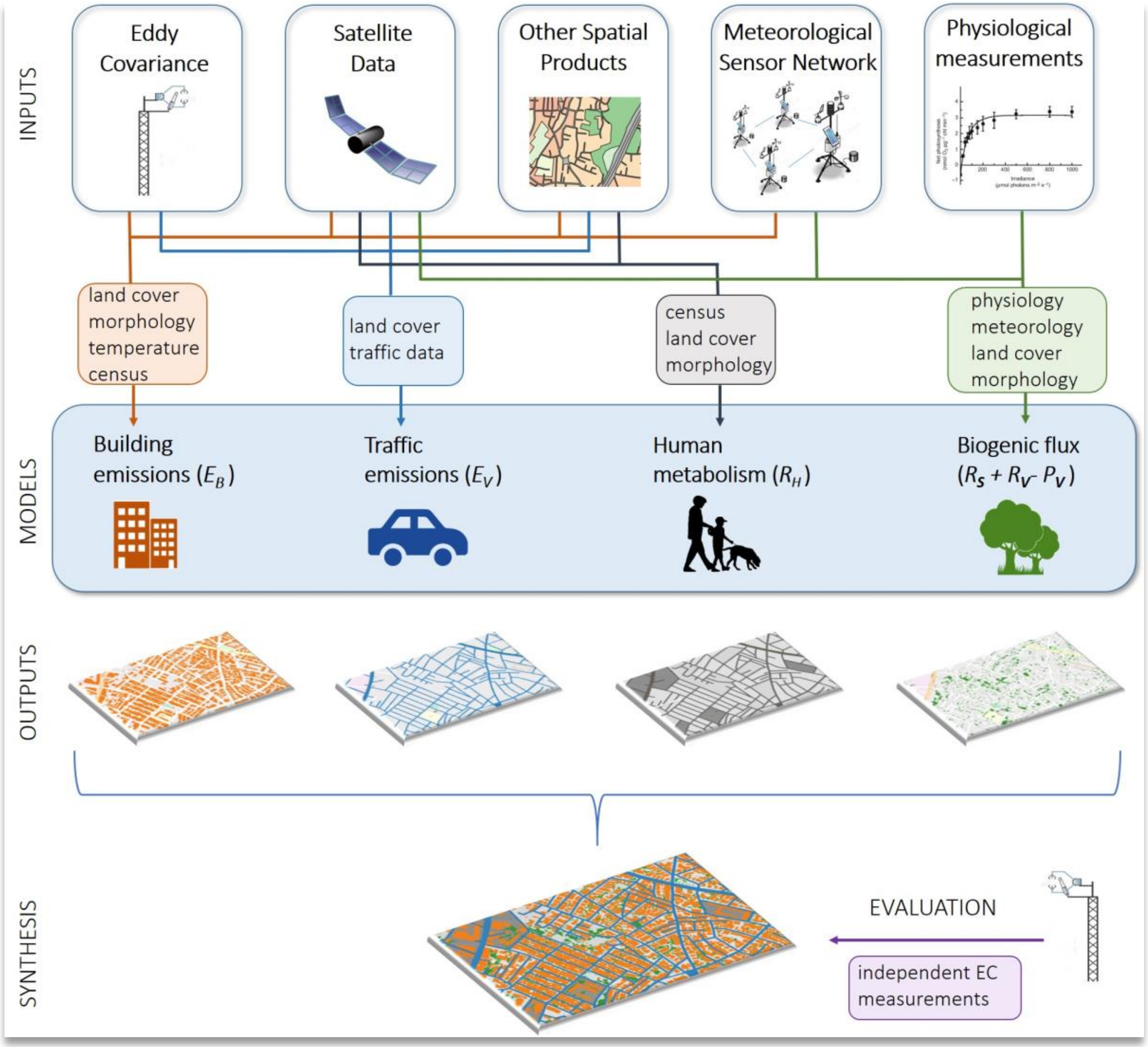

Figure 2. Diagrammatic representation of the diFUME methodology including the main data sources.

Methods

Study Area

diFUME methodology is being developed in the city of Basel (Fig. 3), exploiting the available long-term database (> 15 years) of urban EC measurements, the extended urban meteorological sensor network and the spatial products and know-how developed in past H2020 projects (e.g. URBANFLUXES)

Earth Observation and other geospatial data

The diFUME methodology is using multiple EO and other auxiliary datasets to achieve multi-scale monitoring of urban cover and morphology. Detailed (1 m) urban cover is achieved by combining spatial information from the Official survey of Basel-Stadt, the road network and an airborne Lidar dataset. High resolution (1 m) Digital Surface and Terrain Models (DSMs, DTM) to characterize building and tree heights are derived by airborne Lidar and the 3D city model.

Eddy Covariance

F_C measurements from the 2 urban and 1 rural EC stations (Fig. 3) are calculated at 30 min time-step and flagged according to statistical thresholds on raw data (Crawford et al., 2013; Vickers and Mahrt, 1997), the steady state test and the developed turbulent conditions test (Foken et al., 2004; Göckede et al., 2008). All flagged values were omitted from further analysis. The temporal aggregation of 30-min F_C measurements to seasonal averages followed the approach of Stagakis et al. (2019).

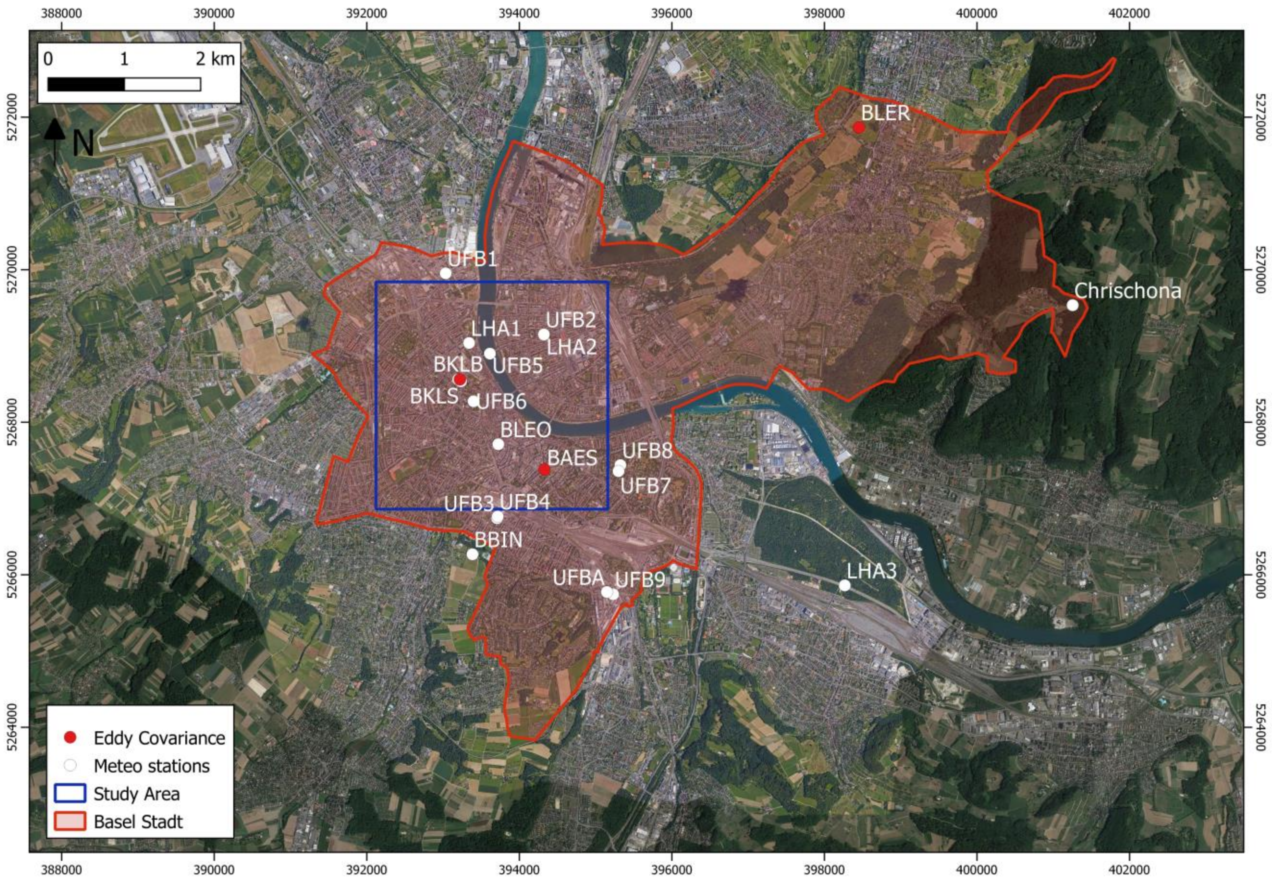

Figure 3. Locations of the 21 meteorological and 3 Eddy Covariance stations. The blue square defines the study area, while the red polygon is the area of Basel-Stadt.

Methods

Source area modelling

DSM and DTM products were used to estimate morphology and roughness (Kanda et al., 2013) parameters of the study area. The Urban Multi-scale Environmental Predictor (UMEP) tool (Lindberg et al., 2018) was used for multi-direction parameter estimation at 5° wind sectors around the two urban EC towers to a radius of 400 m. The parameters were used in the parametrization of the Flux Footprint Prediction (FFP) model (Kljun et al., 2015), along with EC-derived indicators of atmospheric conditions.

Land Cover weighting

The measured F_C for each 30-min period were attributed to the basic F_C components (Fig. 1) by weighting the land cover fractions of each 30-min footprint (Stagakis et al., 2019). The relative contribution of each class to the measured F_C (w_{if}) was determined by multiplying the gridded products of normalized footprint function values (φ) by the land cover fraction of each surface component (λ_i) for each grid cell (x,y) and summing over the entire domain area:

$$w_{if} = \sum_{x=0\,m}^{2000\,m} \sum_{y=0\,m}^{2000\,m} \varphi\,(x,y)\lambda_i(x,y) \qquad (2)$$

Traffic data

Traffic counts from several stations across the study area were derived from the local authorities for the period 2011 – 2018. The data were categorized per street type and area to extract the traffic profiles.

Figure 4. Building, tree and terrain height maps of the study area. The average turbulent flux source area isopleths for 2017-2018 are displayed for the two urban EC stations.

Results

Land cover fractions

Analysing the complex source/sink configuration of the areas around each EC tower is the first prerequisite to unravel the measured F_C signal. The typical land cover analysis of an area around the tower (e.g. 400 m radius) is not providing as accurate information as the source area weighted fractions, since the turbulent flux source areas are not equally distributed to all directions and vary logarithmically with the distance from the tower location (Fig. 5).

Table 1. Land cover fractions (%) of the study area, the areas around each EC station (circle with 400 m radius) and the source area weighted land cover fractions according to the long-term footprints (Fig. 5).

	Study area	BKLI 400 m radius	BKLI Source area	BAES 400 m radius	BAES Source area
Buildings	31.9	38.0	36.3	35.8	34.4
Paved	21.6	20.8	18.0	20.5	23.0
Trees	12.2	14.2	16.5	15.2	7.1
Grass-Soil	22.8	24.4	28.7	27.0	14.7
Water	6.5	0.1	0.8	0.0	0.2
Main roads	4.3	4.7	6.9	5.3	20.8
Tempo 30 km/h	6.6	7.1	6.6	6.7	2.2
Other road types	3.4	1.4	1.6	1.5	1.9

** LC fractions do not sum to 100 % because the area of roads, grass and soil below trees are also taken into account.*

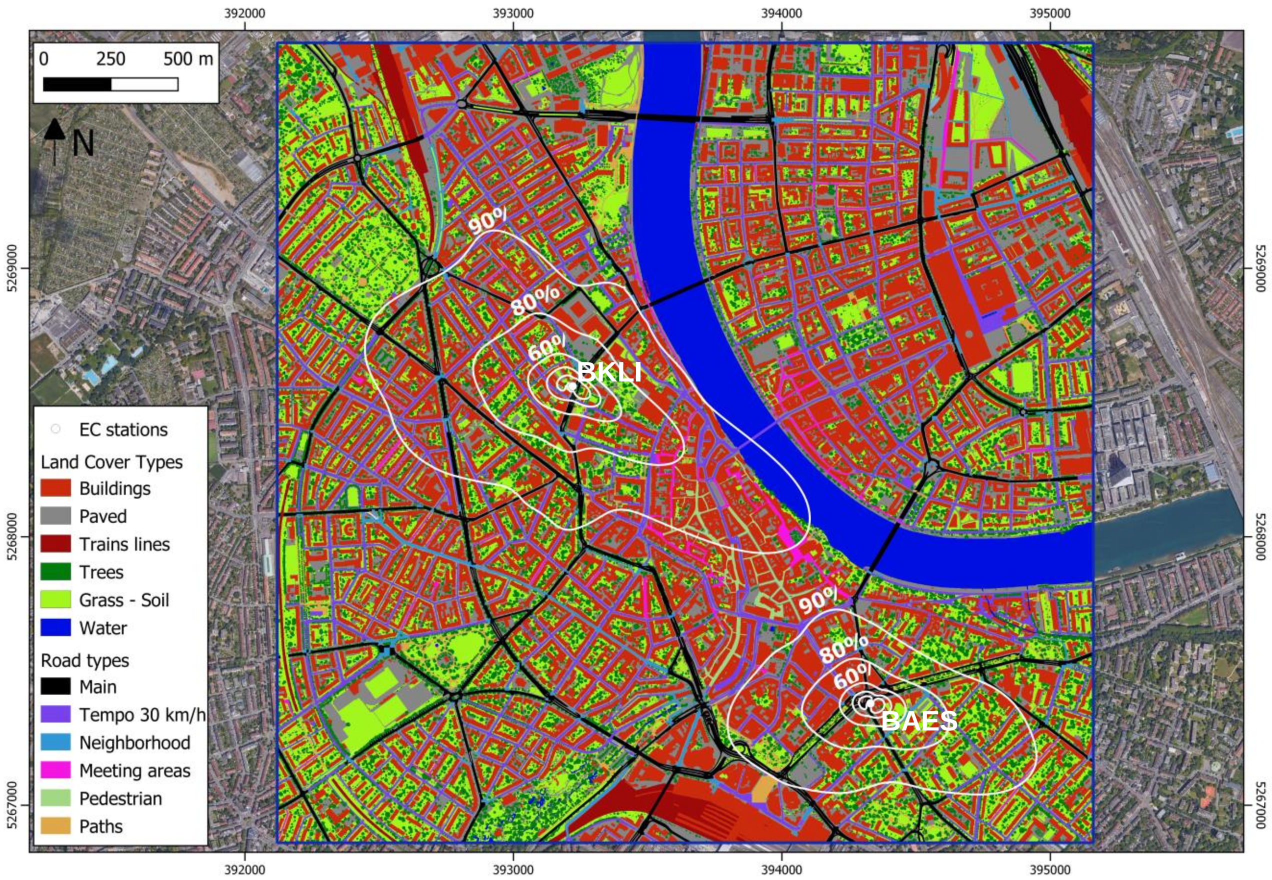

Figure 5. Land cover map of the study area at 1 m resolution (WGS84, UTM 32N; EPSG: 32632). The average turbulent flux source area isopleths for 2017-2018 are displayed in white for the two urban EC stations.

Results

Diurnal F_C patterns

The diurnal variability of measured F_C in BKLI shows that CO_2 emissions typically occur during weekdays in the morning and decline during afternoon (Fig. 6a). F_C is much lower during weekends and does not present a clear diurnal pattern (Fig. 6c). The analysis of source area weighted land cover fractions shows that the emissions are dominated by traffic, since the F_C pattern is considerably higher when main road fraction is > 5 % (Fig. 6b). However, the diurnal F_C pattern is not exactly similar to the traffic pattern, indicating that the rest of the sources and sinks are also significant.

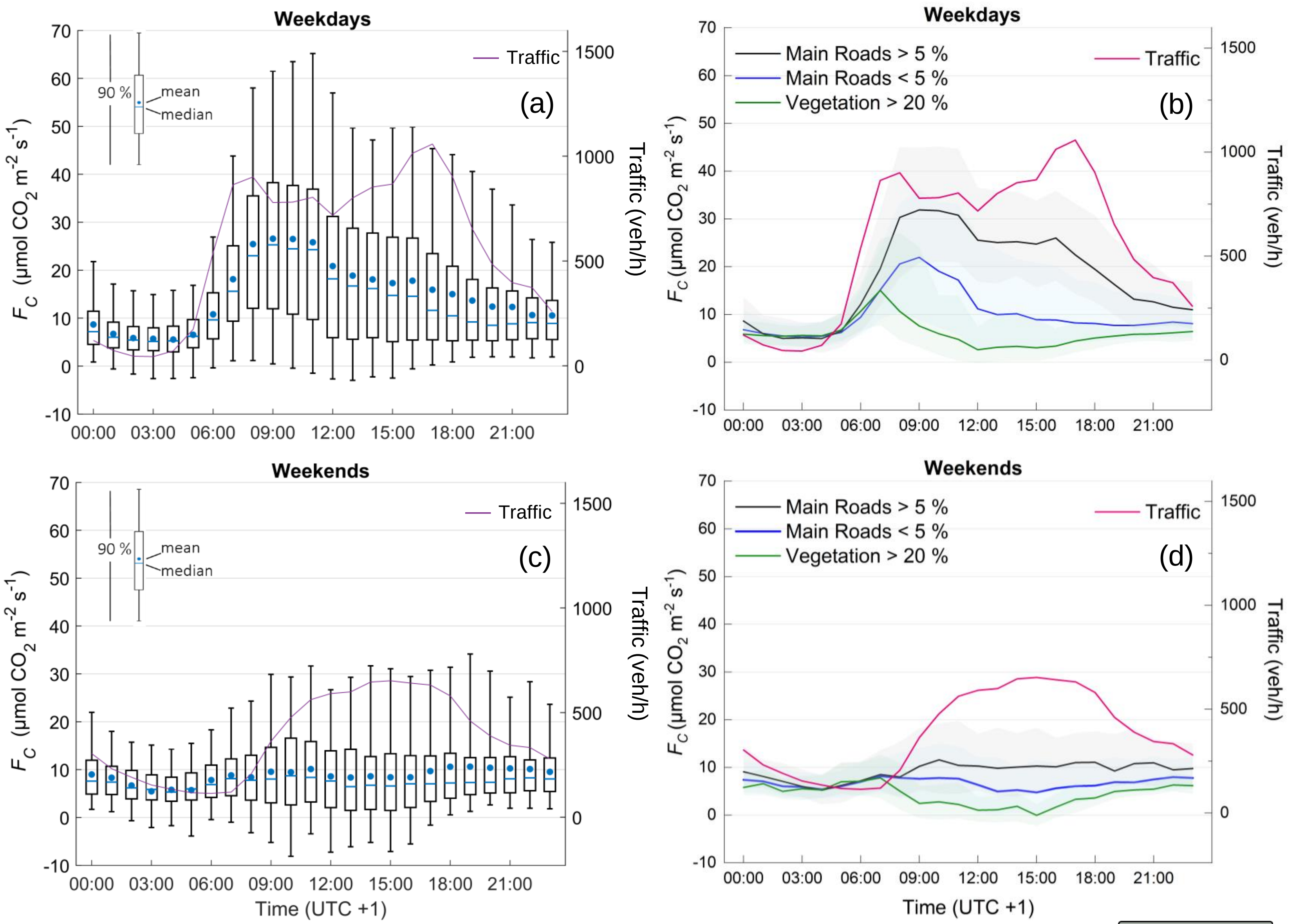

Figure 6. Diurnal F_C patterns for (a,b) weekdays and (c,d) weekends in the BKLI station. Boxplots (a,c) show the 5th, 25th, 75th, 95th percentiles, the median (dash) and the mean hourly F_C for the whole study period. The hourly median F_C patterns are decomposed according to source area weighted fractions for (b) weekdays and (c) weekends. Traffic patterns of the main roads for weekdays (a,b) and weekends (c,d) are also plotted for comparison.

Results

Emission patterns in BAES station (Fig. 7) are higher than BKLI (Fig. 6). A significant difference between the two sites is the high contribution of main roads and the low contribution of vegetation to the BAES F_C signal (Table 1). As a result, traffic pattern is more obvious in BAES emissions both during weekdays and weekends (Fig. 7). The F_C is much higher when the fraction of main roads in the footprint is > 20 % during weekdays and its diurnal pattern is similar to traffic volume (Fig. 7b). The morning traffic peak is not clear in the F_C pattern, which could be the result of low turbulence development in early morning hours. The F_C is lower when vegetation fraction is high, but it still preserves the typical rise during daytime at workdays (Fig. 7b). During weekends, the F_C with high vegetation fraction presents a slight reduction during daytime, indicating the small effect of photosynthetic uptake in the urban setting. The photosynthetic signal is more obvious in BKLI station (Fig. 6b,d) where the vegetation fraction is higher (Table 1).

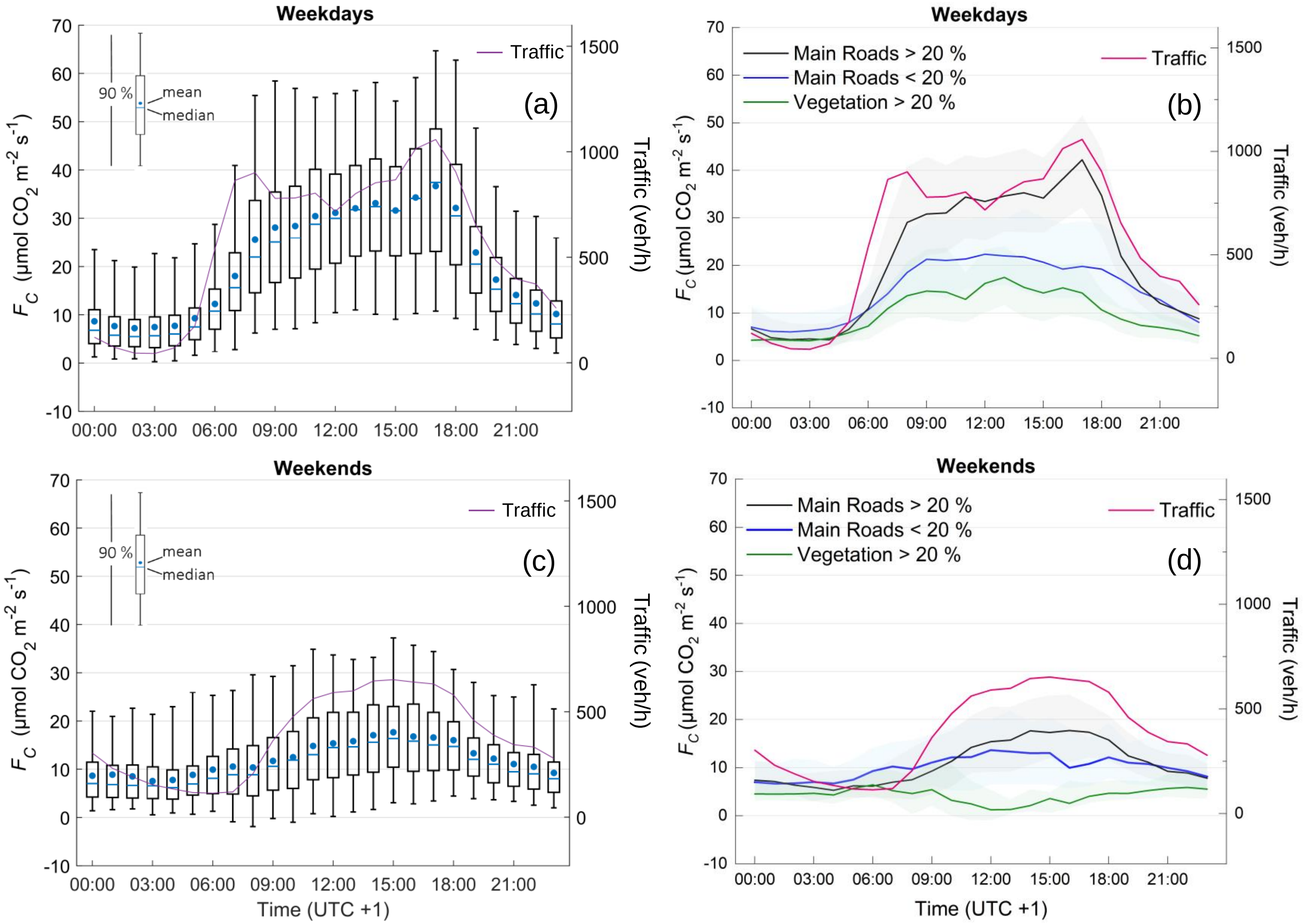

Figure 7. Same as Fig. 6, for BAES station.

Results

Seasonal F_C patterns

The seasonal emissions for both stations follow the same pattern of lower emissions during summer and higher during winter (Fig. 8). This indicates the contribution of building heating emissions that occur only during winter. The monthly F_C totals are significantly different between the two sites. BKLI emissions are lower than BAES, which can in part be explained by the lower main roads signal in BKLI source area (Table 1). The lower contribution of traffic in BKLI measurements would not be recognized without weighting land cover fractions according to the source area modelling. The simple land cover fraction analysis of the area around each tower indicates similar percentages of road types for the two towers (Table 1), however, this changes dramatically when the source area weighting is applied, revealing that the driving factor of the emission differences between the two sites is the measured traffic signal.

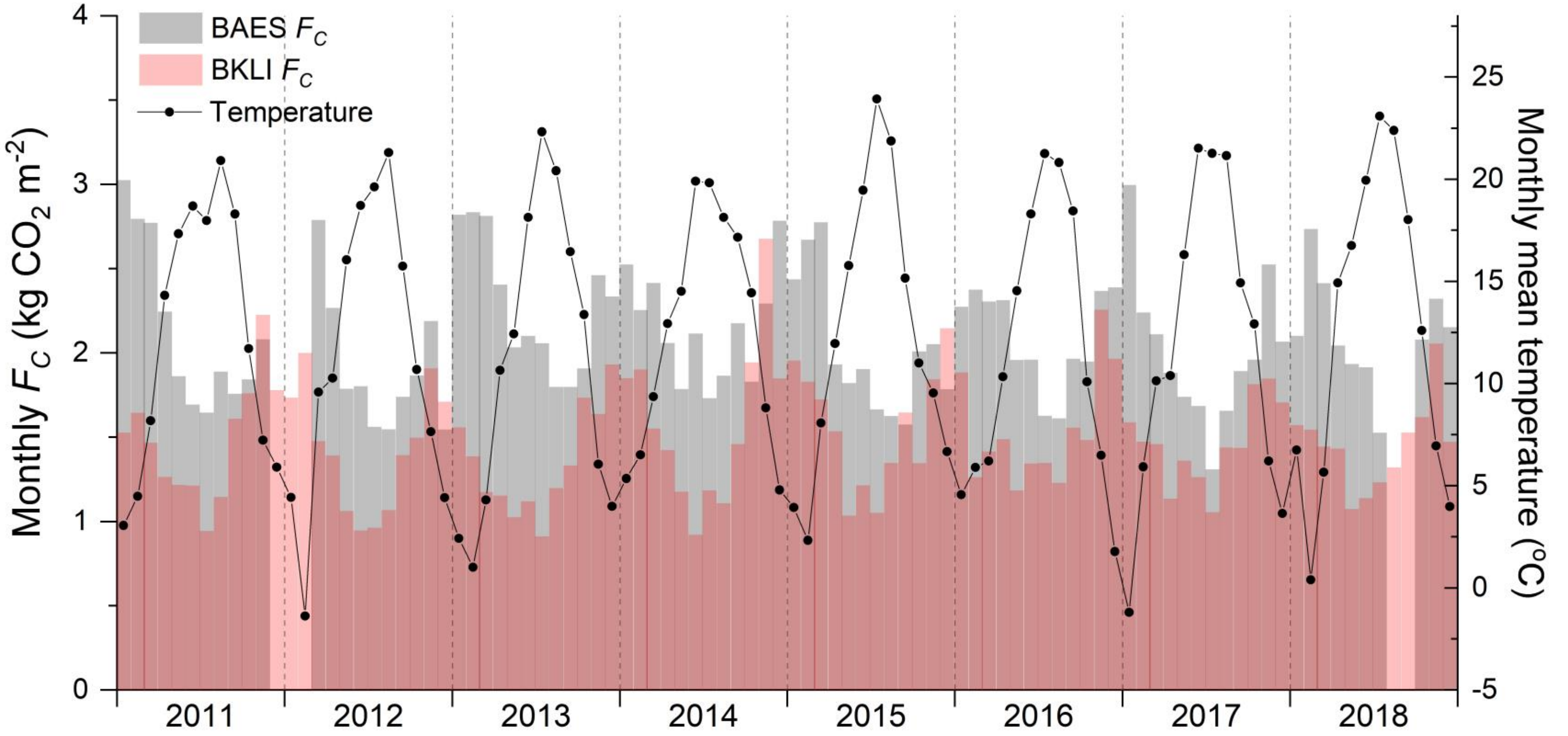

Figure 8. Monthly mean ambient air temperature (°C) time-series along with total monthly CO_2 emissions (kg m^{-2} month^{-1}) for the two EC sites during the study period.

Conclusions

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- The complexity in the spatiotemporal configuration of the urban CO_2 sources and sinks makes the urban Eddy Covariance F_C measurement interpretation a very challenging task.
- High resolution EO-derived and other auxiliary geospatial data describing the urban form are very useful to (a) parameterize turbulent flux source area models and (b) interpret the EC-derived F_C measurements.
- Source area weighted land cover fractions provide more accurate and detailed information regarding the F_C controlling factors compared to simple analyses of the land cover type distribution around each tower.
- The source area modelling and land cover fraction weighting revealed that vehicle traffic emissions is a very significant controlling factor of F_C at both urban Basel sites and also the reason of the higher emissions measured in BAES station.
- Seasonal F_C variability indicates the contribution of building heating emissions during winter at both sites. The relationship between monthly temperature (or Heating Degree Days) and F_C is confounded by the traffic emissions and the directionality of the F_C measurements and needs further investigation. Previous studies at the same sites (Lietzke et al., 2015; Schmutz et al., 2016) have revealed such relationships and seasonal F_C trends.
- The contribution of photosynthetic uptake is not clearly discerned in the measured F_C due to the coincident anthropogenic emissions, however some effects of photosynthetic uptake are visible during weekends and at the BKLI site where vegetation fraction is higher.
- The next steps of diFUME project will focus on investigating clear relationships between traffic count measurements and EC-measured F_C, the contribution of building heating emissions during winter according to air temperature, building volume and building type spatial data, the modelling of emissions from human metabolism and the development of models for the biogenic CO_2 flux according to climatic and vegetation phenology parameters.

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