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Atmospheric measurement techniques to quantify greenhouse gas emissions from cities

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Introduction

- Cities are hot-spots of anthropogenic greenhouse gas (GHG) emissions and hence considered a focus area for emission reduction efforts.
- The majority of energy-related GHG emissions from cities are caused by fuel combustion for space heating, transportation, industry, and power generation.
- The Greenhouse gases at micro-scale by capturing GHG plumes of individual sources using mobile platforms and measuring vertical profiles of GHGs in the urban canopy layer; at the local-scale by direct eddy-covariance flux measurements of GHGs on towers ; at the meso-scale by measurements of mixing ratios and isotopologues of GHGs in the urban and rural boundary layer combined with box and inverse models.

Need and limitations of GHG emission inventories at urban scales

- GHG EMISSION inventories are based on nationally or regionally aggregated fuel consumption data that is distributed by spatial and temporal allocation tables into location- and time-specific emissions at regional and urban scales
- Another approach is the use of bottom-up estimates to scale GHG emissions from a limited set of detailed model-runs or measurements to aggregate scales
- The challenges are the upscaling algorithms, i.e., whether the number of samples taken is representative for an entire urban system and whether all technological, environmental, and behavioral aspects are properly reflected. Small errors emission factors will propagate into larger uncertainties when scaling-up

Need for emission measurements in urban systems

Scale (systems studied)	Spatial dimension	Atmospheric layer studied	Temporal resolution	Common measurement approaches
Micro-scale (buildings, roads, industry, greenspace)	~1–100 m	Urban canopy layer, roughness sublayer	One-time measurements at specific locations or along transects, in some cases long-term observations (5 min to years)	Traverse and vertical profile measurements in canyons, ecophysiological measurements using closed-chambers (vegetation, soils)
Local-scale (neighborhoods, land-use zones)	~100 m–10 km	Inertial sublayer	Continuous measurements that resolve diurnal and seasonal dynamics (30 min to years)	Direct, relaxed or disjunct eddy-covariance flux measurements on towers above the city
Meso-scale (cities, urbanized regions)	~10–100 km	Urban boundary layer	Short-term campaigns or continuous measurements at selected sites that resolve day-to-day variations and seasonal differences	Boundary-layer budgets, upwind-downwind mixing ratio differences, regional inverse modeling, isotopic ratios

Table1. Summary of measurement approaches to quantify GHG emissions and uptake in urban ecosystems separated by scales of interest and reporting.

Land-atmosphere exchange of greenhouse gases in urban systems

➤ Carbon-dioxide

➤ Methane

➤ Nitrous oxide

Carbon-dioxide

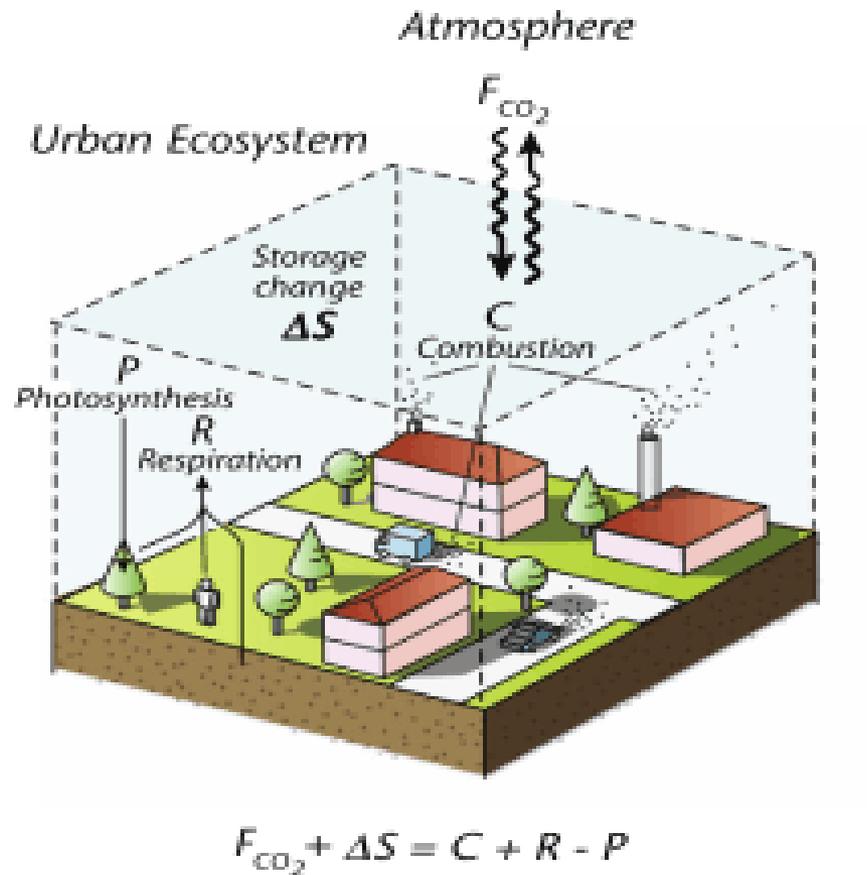


Fig. 1 Conceptual representation of the mass fluxes of carbon dioxide

Methane

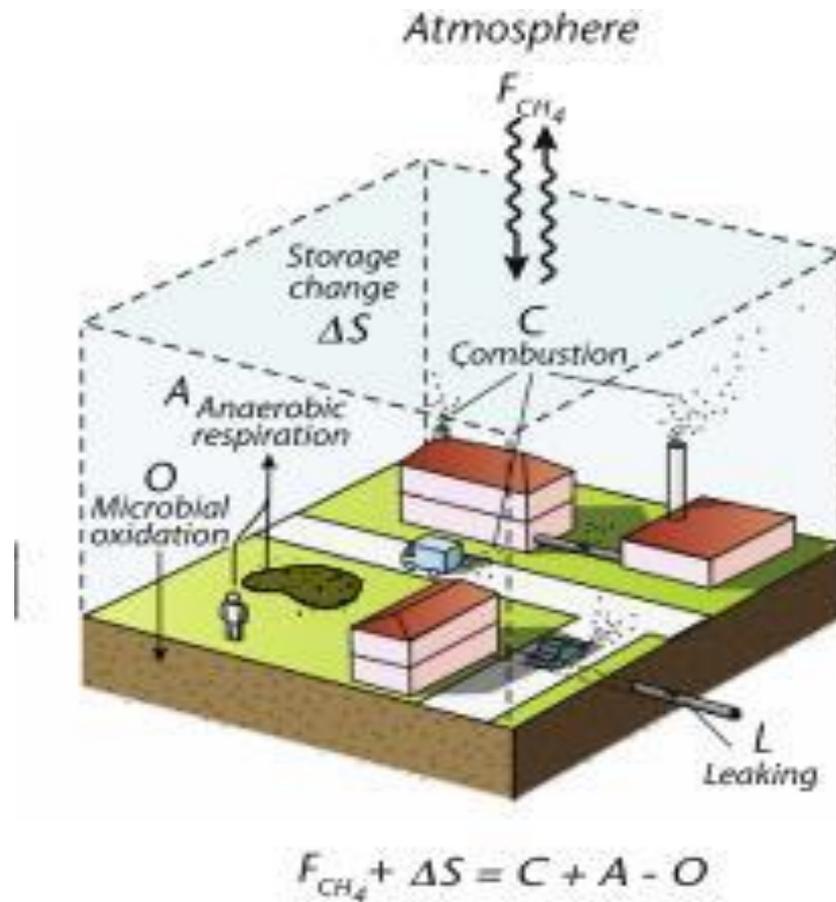
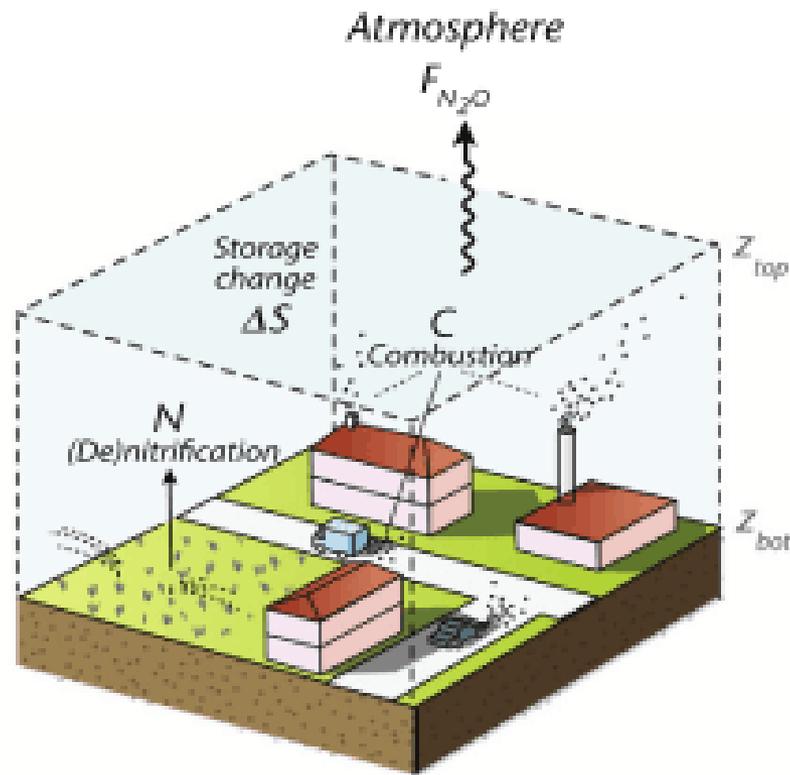


Fig. 2 Conceptual representation of the mass fluxes of methane

Nitrous oxide



$$F_{N_2O} + \Delta S = C + N$$

Fig. 3 Conceptual representation of the mass fluxes of Nitrous oxide

Emission monitoring at the micro-scale

- Most efforts to quantify emissions at the micro-scale have focused on isolating a particular emission process (combustion, leaks, photosynthesis, microbial activity).
- Micro-scale measurements of GHGs reported in the literature are either transect measurements on mobile platforms, where GHG mixing ratios or concentrations are measured with gas analyzers while driving on a car across cities, or measurements along fixed vertical profiles on towers located within street canyons.
- Another approach, measurements of CO_2 mixing ratios are made quasi-simultaneously at several heights within and above street canyons by using a gas-multiplexer with inlets at various heights.

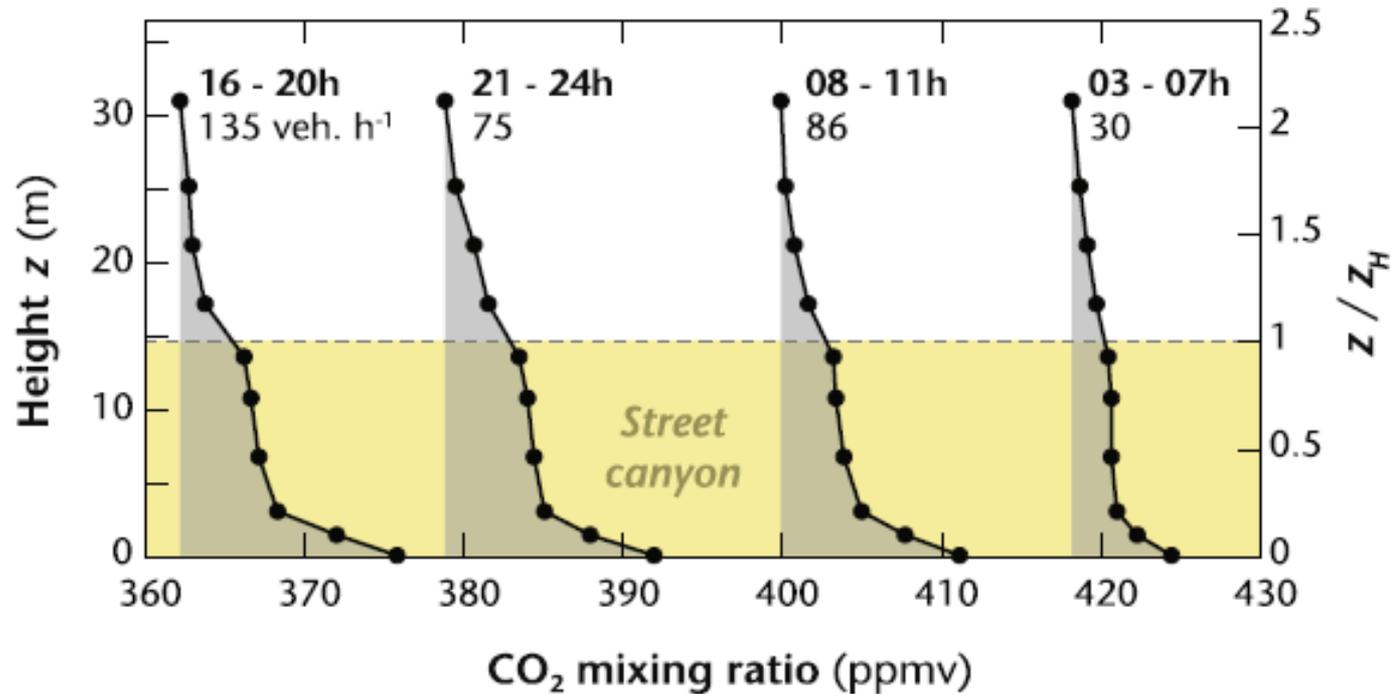


Fig. 4 Ensemble vertical profiles of CO₂ mixing ratios measured at different heights z along a tower in a 15 m deep street canyon in Basel, Switzerland. The area of yellow shading refers to measurement heights inside the street canyon while the white area above is the atmosphere above roofs. z_H is the mean building height, and the numbers below the local time indicators are average measured vehicles per hour (adapted and modified from Vogt et al., 2006. With kind permission from Springer Science and Business Media).

Emission monitoring at the local-scale

Flux measurements on towers above cities allow us to quantify the emissions (and uptake) of GHGs by means of eddy covariance (EC).

◆ The composition of the EC system

- Fast anemometer



Recording fluctuations of the vertical wind component w'

- A co-located fast gas analyzer



Providing the concentration fluctuations of the GHG of interest, c' .

◆ computing method

By multiplying the instantaneous fluctuations of the vertical wind w' (in m s^{-1}) and GHG concentration c' (usually in mol m^{-3}) and then averaging their products over a longer time (usually ≈ 30 min), we get the covariance $\overline{w'c'}$ which is equal to the mass flux density F of the GHG at the given height

◆ Quite rigid site requirements of the EC method

- the tower site must be located in flat terrain
- the urban roughness elements (buildings, trees) need to impose a homogeneous drag on the flow in all upwind directions – this means that the urban density and height should be horizontally homogeneous around the tower
- the EC system needs to be located high enough in the inertial sublayer, i.e., at a height where the turbulent flow is independent of location and avoids individual building wakes

Relating land-cover and built density in tower source areas to fluxes

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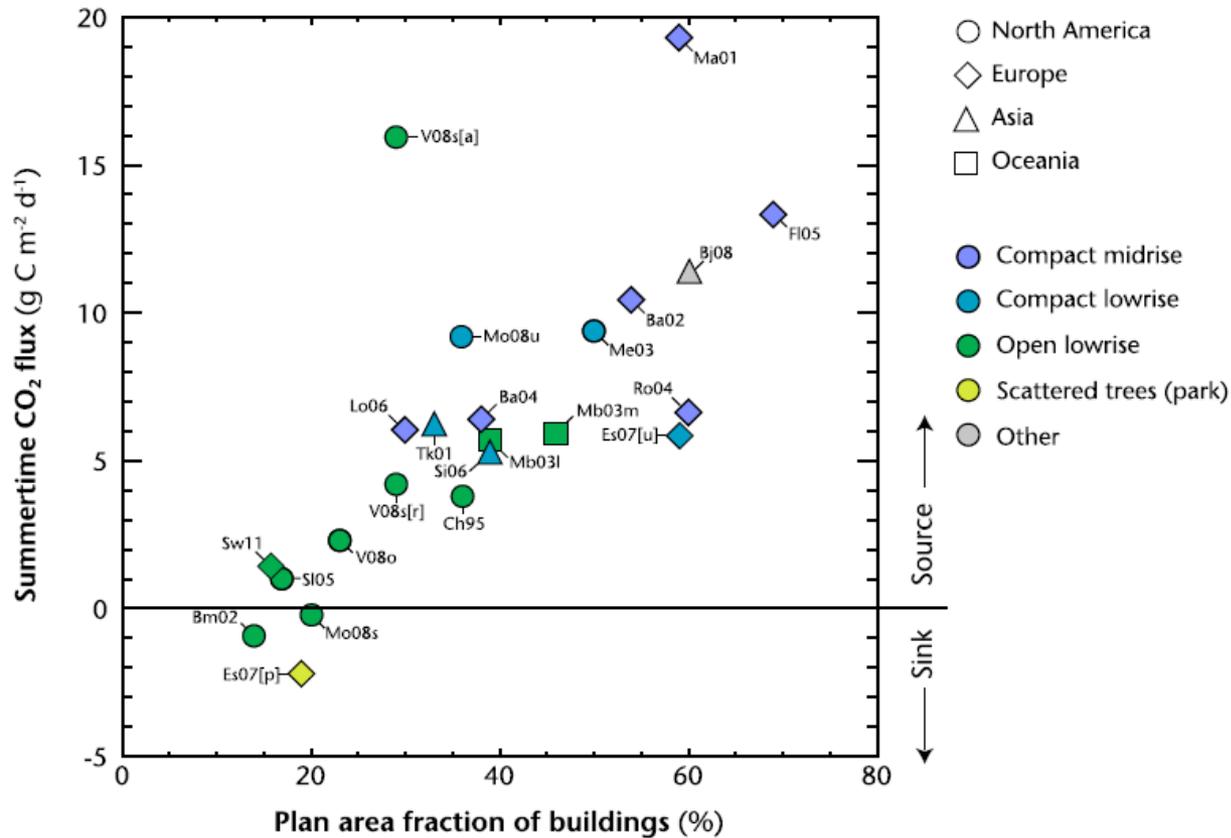


Fig. 5. Summertime carbon-dioxide fluxes (F_{CO_2}) measured by eddy covariance (EC) on different urban flux towers as a function of building density in the source area of the tower (expressed as plan area of buildings per total ground area).

Diurnal, weekly and seasonal variations of fluxes

Site	LCZ	λ_b	Daily F_{CO_2} (g C m ⁻² day ⁻¹)	Daily F_{CO_2} (g C m ⁻² day ⁻¹)	Annual F_{CO_2} (kg C m ⁻² yr ⁻¹)	References
Mid-latitude cities			Summer	Winter	Year	
Baltimore-Cub Hill, USA (39°N)	Open lowrise	14%	-0.9	+3.8	+0.35	Crawford et al. (2011)
Montréal-Roxboro, Canada (46°N)	Open lowrise	12%	+0.5	+8.2	+1.48	Bergeron and Strachan (2011)
Swindon UK (52°N)	Open lowrise	44%	+0.6	+9.5	+1.84	Ward et al. (2013)
Melbourne-Preston, Australia (38°S)	Open lowrise	46%	+5.9	+7.6	+2.31	Coutts et al. (2007)
Łódź-Lipowa, Poland (52°N)	Compact midrise	30%	+6.0	+9.9	+2.94	Pawlak et al. (2011)
Tokyo-Kugahara, Japan (36°N)	Compact lowrise	33%	+6.1	+13.6	+3.35	Moriwaki and Kanda (2004)
Basel-Klingelbergstrasse, Switzerland (48°N)	Compact midrise	38%	+6.8	+10.6	+3.63	Lietzke and Vogt (2013)
Essen-Grugapark, Germany (51°N)	Compact lowrise	59%	+5.9	+19.5	+3.94	Kordowski and Kuttler (2010)
Montréal-Rue des Écores, Canada (46°N)	Compact lowrise	27%	+9.8	+23.4	+5.64	Bergeron and Strachan (2011)
Vancouver-Sunset, Canada (49°N)	Open lowrise	29%	+16.4	+21.4	+6.71	Christen et al. (2011)
Subtropical and tropical cities			Wet season	Drier season	Year	
Singapore-Telok Kurau, Singapore (1°N)	Compact lowrise	39%	+5.10	+4.31	+1.79	Velasco et al. (2013)

Table 1: Seasonal and annual measured mass fluxes of carbon dioxide (F_{CO_2}) at selected urban eddy covariance flux towers sorted by increasing annual F_{CO_2} .

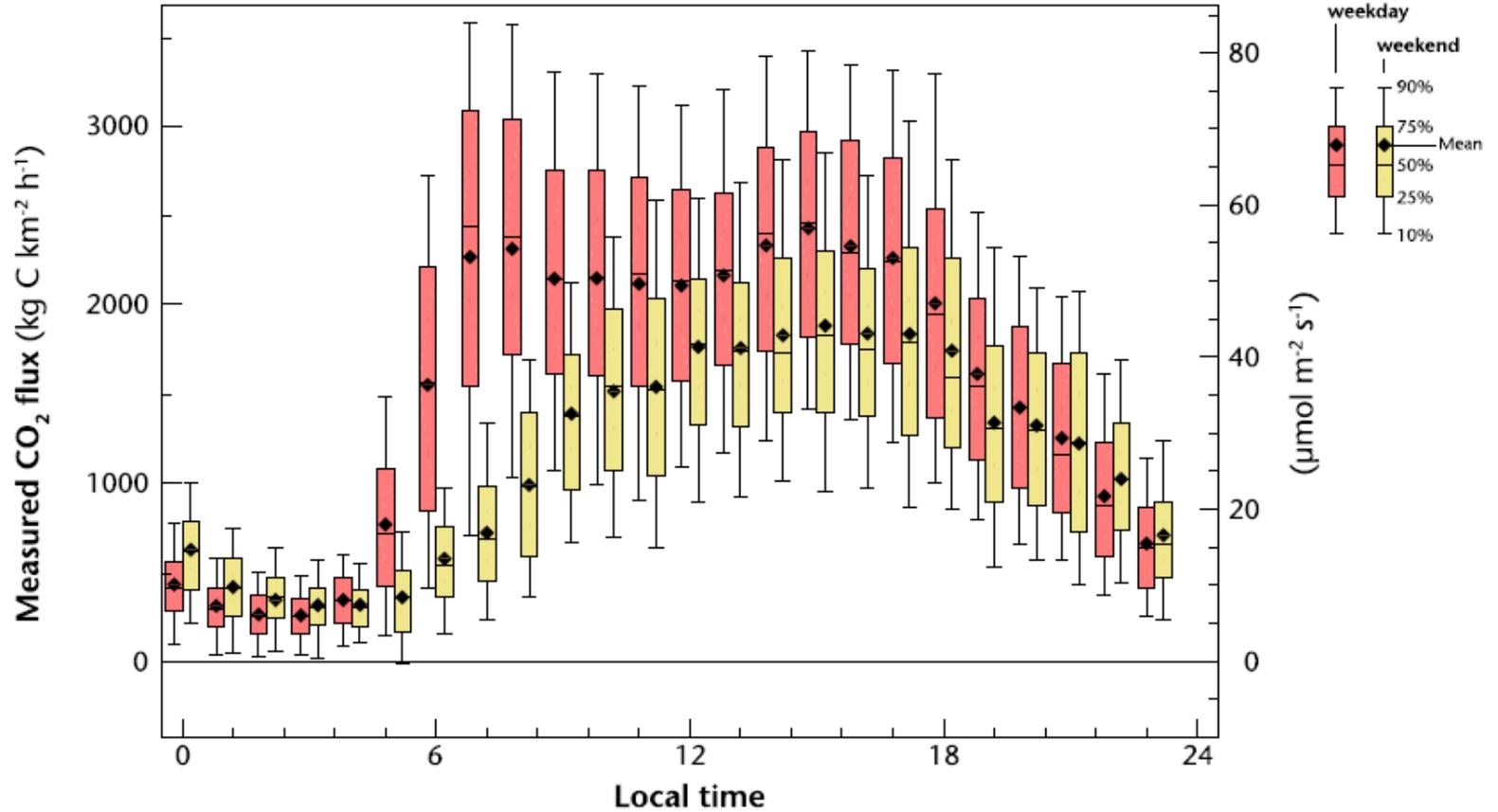
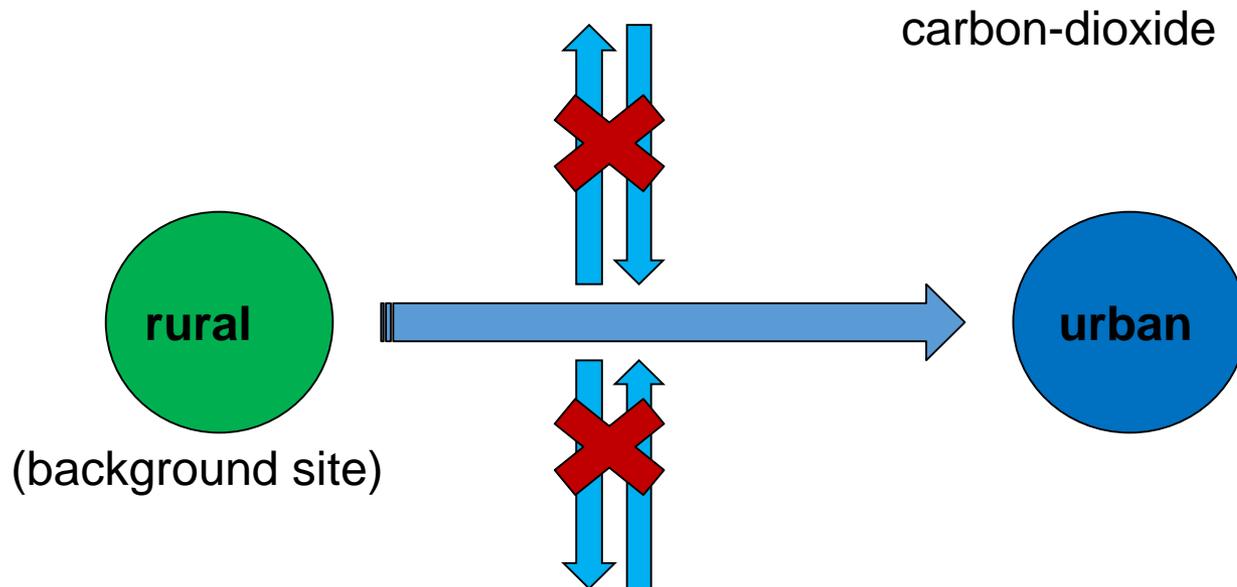


Fig. 6. Ensemble diurnal course of F_{CO_2} measured by EC on the flux tower Vancouver-Sunset, BC, Canada under conditions with wind from the sector 90–180° where a busy traffic intersection is located. Data is separated into weekday and weekend and ensemble fluxes for the period May 2008–April 2012 are shown.

Emission monitoring at the meso-scale

- mix-ing ratios of GHGs measured at rural (background) vs. urban sites and measurements downwind and upwind of metropolitan areas
- mixing ratios measured at a single or multiple points in an urban region combined with boundary-layer mass conservation models or regional inverse models
- the study of stable isotopologues of GHGs to distinguish between various anthropogenic and biogenic sources that elevate mixing ratios in the UBL.

- ◆ ***mix-ing ratios of GHGs measured at rural (background) vs. urban sites and measurements downwind and upwind of metropolitan areas***



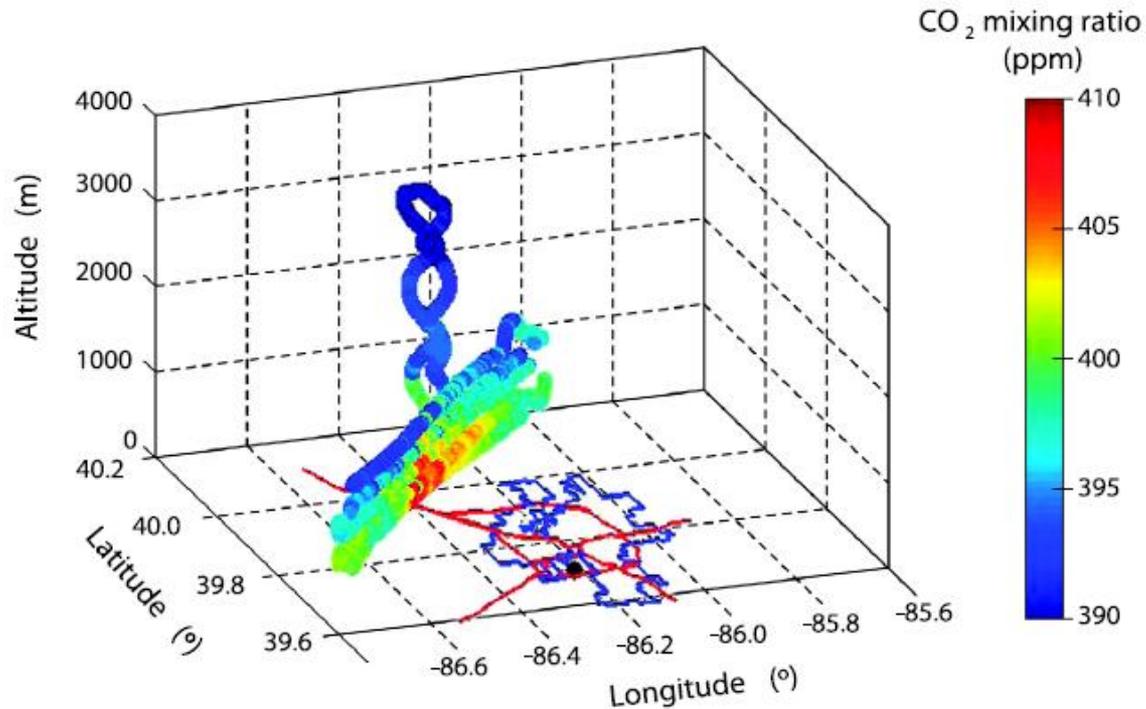
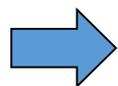


Fig. 7. Aircraft-based measurements of carbon-dioxide mixing ratios downwind of Indianapolis, IN, USA (blue: outline of builtup area, red: highways, back dot: power plant). The visualizations shows the urban plume as captured by aircraft transects perpendicular to the mean wind (140) in the urban plume (adapted with permission from [Mays et al. 2009](#), Copyright 2009 American Chemical Society). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

◆ ***mixing ratios measured at a single or multiple points in an urban region combined with boundary-layer mass conservation models or regional inverse models***



temporally varying capping inversion height?

- aerosol-backscatter
- Sodars
- using additional tracers such as Radon



◆ Emission source attribution using isotopologues

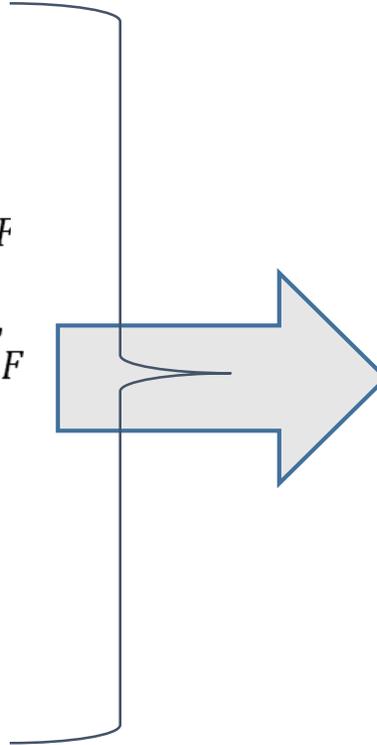
$$C = C_A + C_R + C_F$$

$$\delta^{13}C_{\tau}C = \delta^{13}C_A C_A + \delta^{13}C_R C_R + \delta^{13}C_F C_F$$

$$\delta^{18}O_{\tau}C = \delta^{18}O_A C_A + \delta^{18}O_R C + \delta^{18}O_F C_F$$

$$\delta = \left(\frac{R_{\text{sample}}}{R_{\text{criterion}}} - 1 \right) \times 1000\text{‰}$$

$$R = \frac{\text{heavy isotope abundance}}{\text{light isotope abundance}}$$



C_A

C_R

C_F

?



Summary and conclusions

- This paper reviewed methods to directly or indirectly identify, quantify and attribute emissions (and uptake) of the major GHGs at urban scales using in-situ measurements in the atmosphere.
- At the micro-scale, current possibilities to measure GHG fluxes based on measurements in the urban canopy layer (UCL) are quite limited due to the complexity of source configurations and the wind field in the UCL.
- On the local-scale, a major limitation is the simplicity of current source area models that link between fluxes measured by EC systems on towers and the urban surface.
- The box-models used in many meso-scale studies lack the incorporation of urban effects and the horizontally non-homogeneous nature on the boundary layer, which limits the accuracy of determining emissions.
- A general challenge, inherent to all scales of atmospheric in-situ measurements, is that the functional 'footprint' of the urban metabolism and the resulting geographic location of GHG emissions within the built-up area do not overlap.



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Thank you