Urban greenhouse gas emissions from the Berlin area: A case study using airborne CO_2 and CH_4 in situ observations in summer 2018

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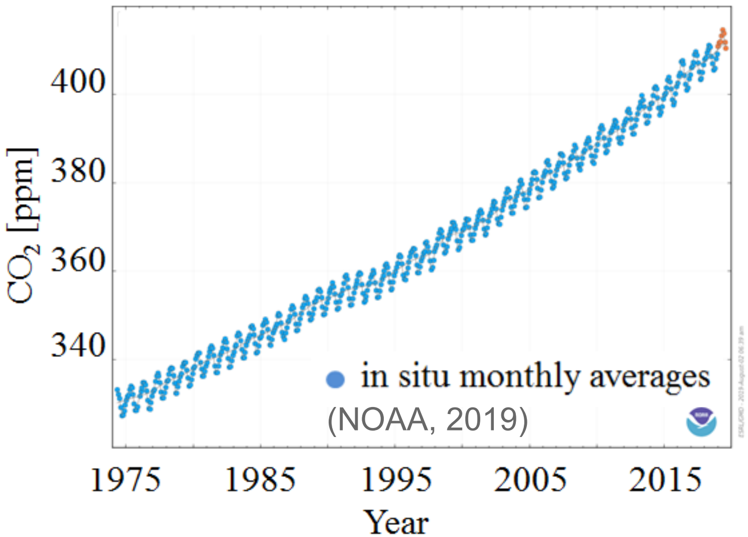
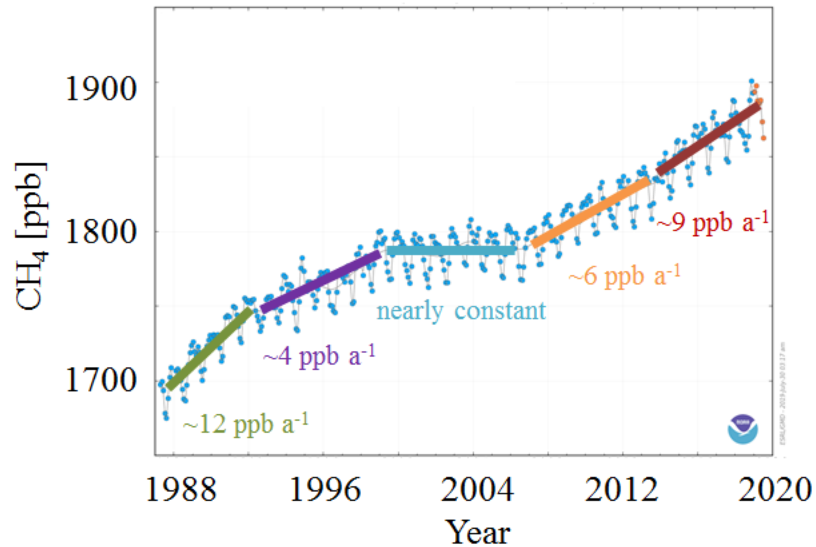
Motivation: Greenhouse Gases (GHG)

- Two **most important anthropogenic GHG:** carbon dioxide (CO_2) and methane (CH_4)
- **Significant increase** in global surface mixing ratios (MR) since pre-industrial times

CO_2 +147 %



CH_4 +259 % (WMO, 2020)



- **Paris Agreement** aims to keep global temperature rise below 2 °C compared to pre-industrial levels (UNFCCC, 2015)

→ efficient mitigation strategies require **accurate knowledge** of the GHG budget

Motivation: Urban Areas

- More than **half of the world's population** (UN, 2018) lives within less than **3 % of the terrestrial earth's surface** (Liu et al., 2014)
- Recognised as **significant hot spot of GHG** emissions (Kennedy et al., 2012; Marcotullio et al., 2013)
- Relatively **sparse GHG studies** on **European cities**, e.g. London (O'Shea et al., 2014; Helfter et al., 2016; Pitt et al., 2019), Rome (Gioli et al., 2014), Paris (Bréon et al., 2015), Cracow (Kuc et al., 2003; Zimnoch et al., 2019), Florence (Gioli et al., 2012)

https://diercke.westermann.de/

The German capital Berlin:

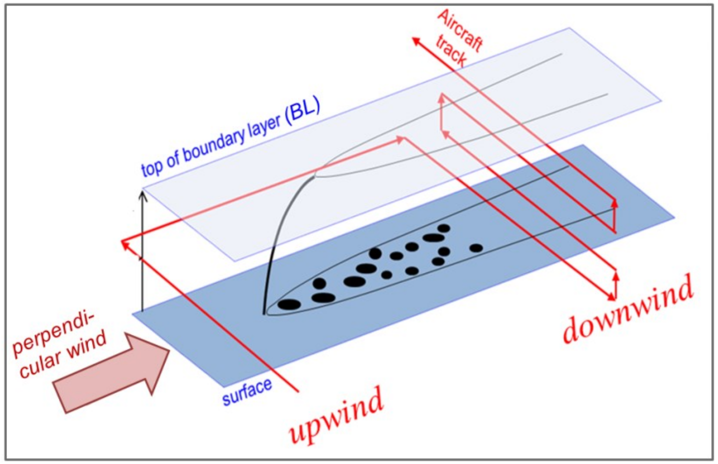
- **Largest city** and 2nd in terms of population density (Statistisches Bundesamt, 2018)
- Expected emissions from CAMS (Kuenen et al., 2014) compared to London (Pitt et al., 2019)
  CO_2: roughly similar, i.e. ~32 Mt a^{-1}
  CH_4: roughly 50 % lower, i.e. ~28 kt a^{-1}
- **Relatively isolated** location and **flat topography** favour the mass balance approach

Strategy: Airborne Top-Down Mass Balance Approach

Used to estimate **emission rates** (e.g. Mays et al., 2009; Karion et al., 2013; Heimburger et al., 2017; Ren et al., 2018) and to independently **validate total bottom-up emissions**

Flight approach within the BL:

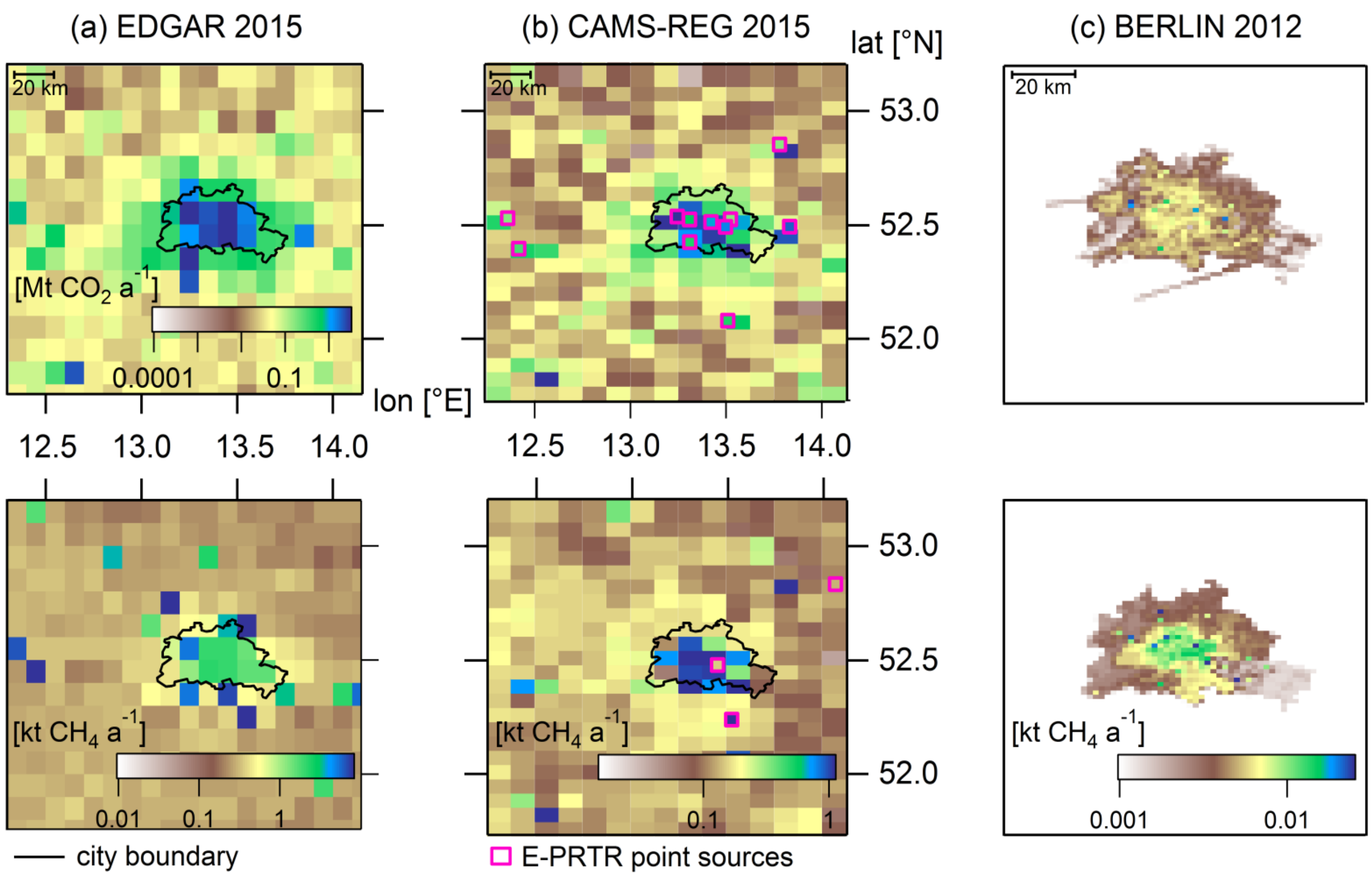
- **Downwind**: multiple transects at stacked altitudes
  → capture urban outflow
- **Upwind**: one centred transect
  → identify possible emission inflow and natural atmospheric variability
- **Vertical profiles**: extend into the free troposphere
  → determine the BL depth
- **Mass flow rate** f [g s^{-1}]



$$f = \int_0^{PBL} \int_{-a}^{a} \left([c]_{ij} - \left[c_{bgr}\right]_{ij} \right) \frac{p_{ij}}{T_{ij} * R} M \; u_{ij} \, dx dz$$

with background MR c_{bgr}, observed MR c, pressure p, temperature T, ideal gas constant R, molar mass M, perpendicular component u of the horizontal wind, horizontal boundaries of the plume $-a$ to a

CO_2 and CH_4 emission maps for the Berlin area



Total emissions within the city boundary

CO_2

16.8 to 24.2 Mt a^{-1}

→ Inventories **agree** by a **factor of ~1.4**

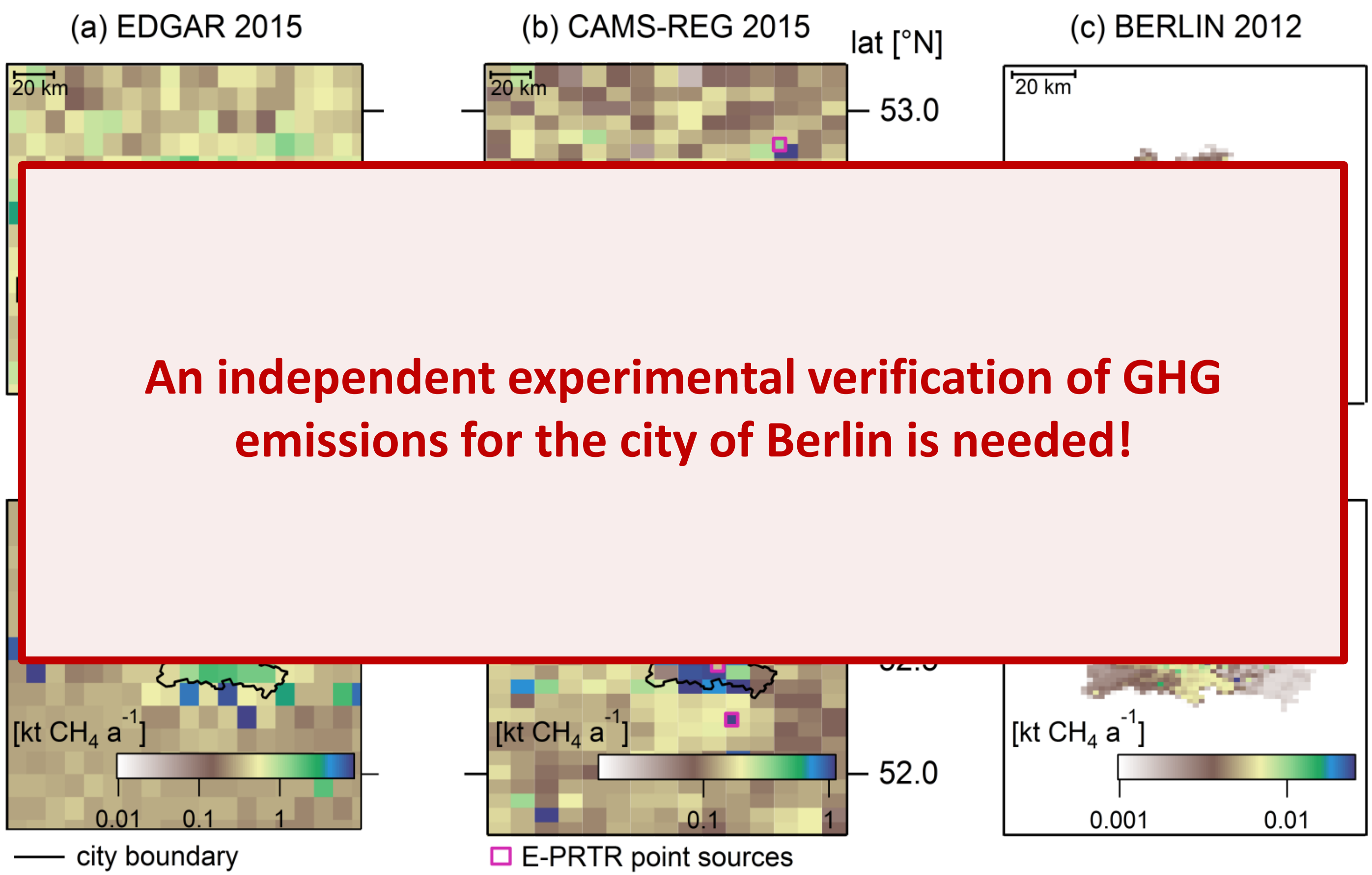
CH_4

3.4 to 25.7 kt a^{-1}

→ Inventories **differ** by a **factor of ~8**

(a) Global inventory EDGAR v5.0 with a resolution of 0.1° x 0.1° (Crippa et al., 2019); (b) European inventory CAMS-REG v1.1 with a resolution of 0.0625° x 0.125° (Kuenen et al., 2014); superimposed are point sources from the European Pollutant Release and Transfer Register (E-PRTR, http://prtr.ec.europa.eu), exceeding a threshold of 0.1 Mt CO_2 a^{-1} and 0.1 kt CH_4 a^{-1}; (c) Local BERLIN inventory of detailed point, line and area sources, which were gridded to a spatial resolution of 0.01° x 0.01° (Berliner Emissionskataster v1.0, AVISO GmbH and IE Leipzig, 2016); horizontal stripes in CO_2 are due to take-off and landing at the two major airports

CO_2 and CH_4 emission maps for the Berlin area



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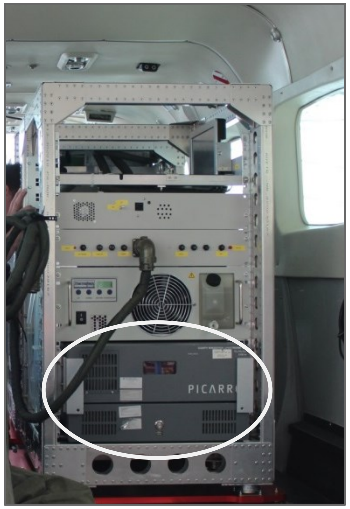
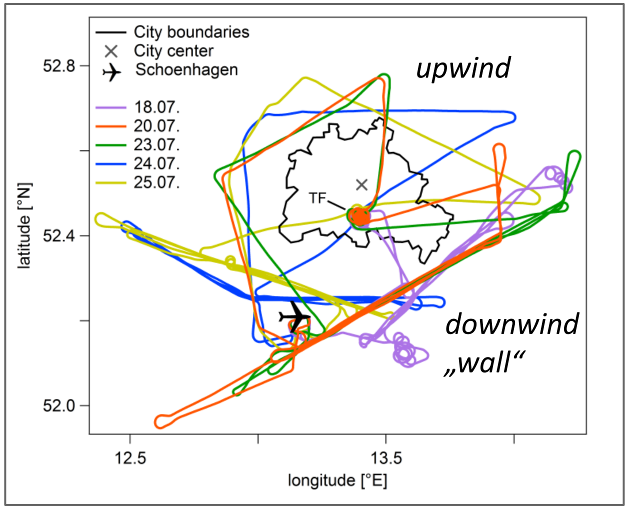
[UC]^2 Urban Climate Under Change
Stadtklima im Wandel

Mission flights were carried out in the framework of the [UC]^2 project, see Scherer et al. (2019)

Mission Flights in July 2018





- **Picarro CRDS analyser** at 0.5 Hz (G1301-m):
  overall measurement uncertainty <0.2 ppm CO_2 and <1.1 ppb CH_4
- Meteorological sensor package:
  T (σ = 0.15 K), p (σ = 0.25 hPa), humidity, wa (σ = 2°), ws (σ = 0.3 m s^{-1}) (Mallaun et al., 2015)
- Upward spiral at the Tempelhofer Feld (TF) from ~300 m to ~3 km
- Stacked flight transects 30 km to 40 km downwind of the city centre

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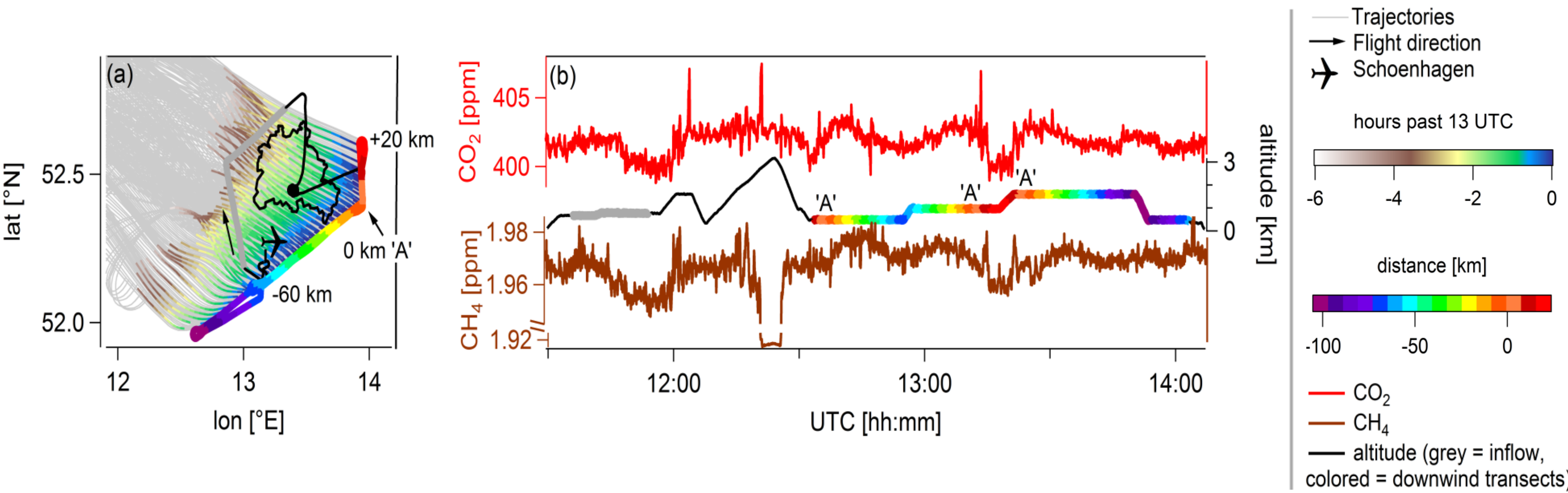
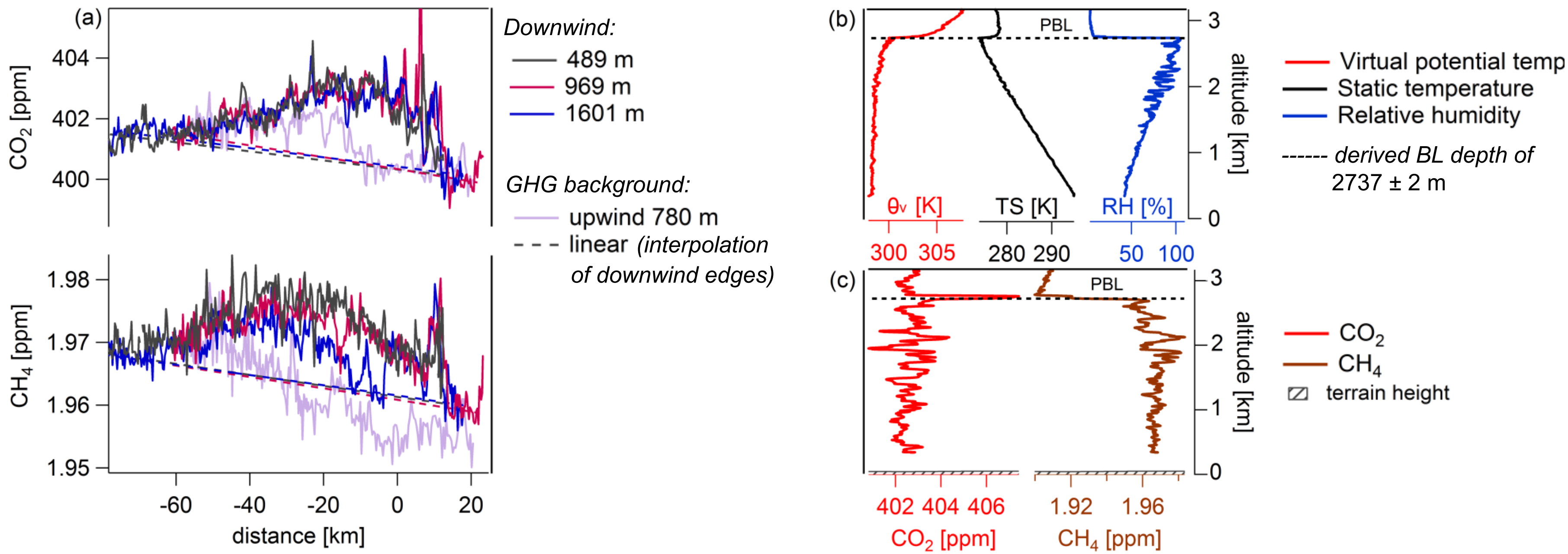
Case Study on July 20th: Flight pattern and time series



- Sampling of the urban plume started at point ‘A’ towards the SW (‘A’ equals 0 km of the flown horizontal distance)
- **HYSPLIT backward trajectories**, started from the downwind wall, indicate a **steady wind flow** within the BL for at least 6 hours prior to the measurements
- Measured average wind speed: 4.8 ± 1.8 m s^{-1}
  Measured average wind direction: 299° ± 27°

GHG mixing ratios and vertical profile



- **CO_2 plume**: **well-mixed** with Δ_{max} = 4 ppm in the northern part of the flight track
- **CH_4 plume**: centre **extends more to the south-west** with consistent MR in the two lower flight legs (Δ_{max} = 21 ppb) and significantly lower MR in the free troposphere (FT)
- **Boundary layer**: well-mixed and **efficiently capped** with strong gradients towards the FT

Instantaneous CO_2 and CH_4 mass flux

(average based on three individual transect emission rates)

	CO_2	CH_4
Mass flux	[t s^{-1}]	[kg s^{-1}]
	1.39 ± 0.76	5.20 ± 1.70
Uncertainties	[%]	[%]
Choice of background	±52	±21
Wind speed and direction	±15	±23
PBL depth variation (by 10 %, i.e. ~270 m)	±9	±10

Choice of background reflects two approaches using:

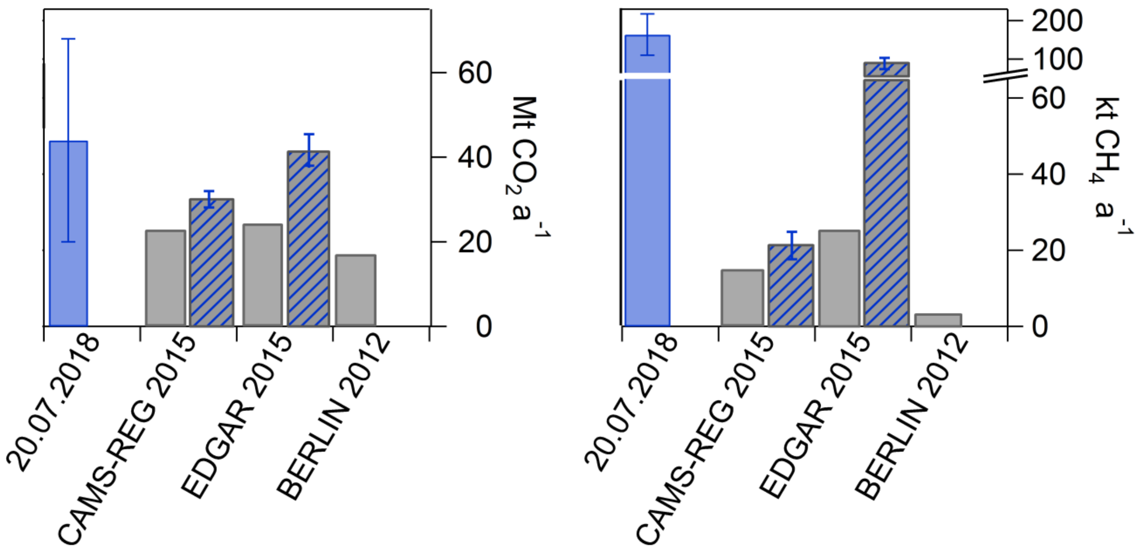
#1) the MR measured during the upwind leg, projected on the downwind wall using HYSPLIT trajectories

#2) the linear interpolation of MR between the downwind plume edges

The **urban plume** needs to be **separated from enhancements** caused by emissions from anthropogenic sources (or natural variability) **upstream of the city**, even in the case of an apparently relatively isolated city as Berlin.

→ approach #1 is used for the final mass flux

Annual CO_2 and CH_4 mass flux

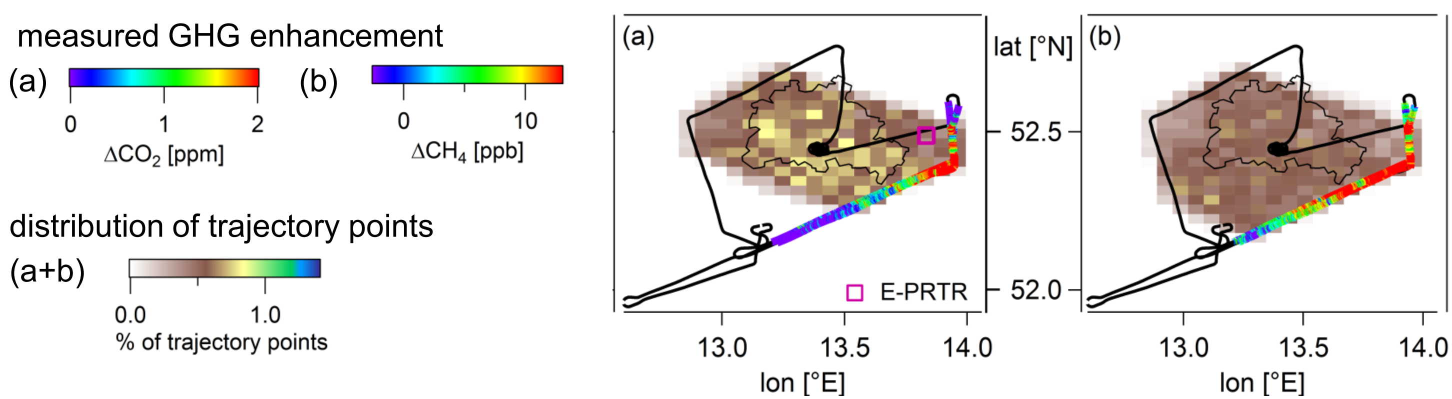


Mass balance flight

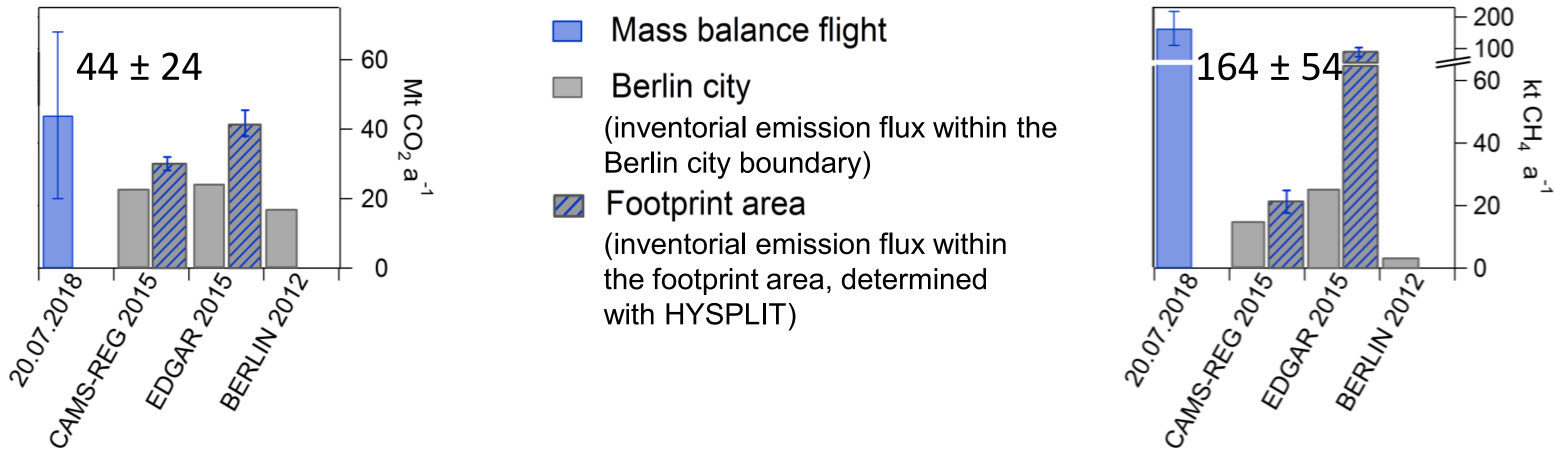
Berlin city
(inventorial emission flux within the Berlin city boundary)

Footprint area
(inventorial emission flux within the footprint area, determined with HYSPLIT)

HYSPLIT footprint area for (a) CO_2 and (b) CH_4



Annual CO_2 and CH_4 mass flux



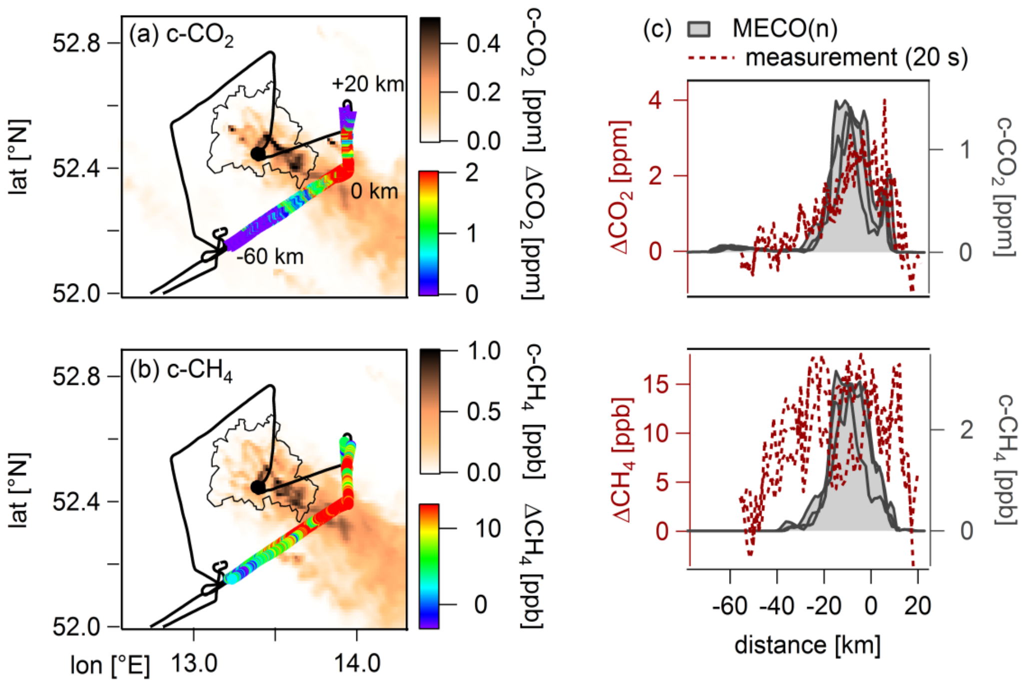
CO_2 flux

- **agrees within error estimates**, but is larger than CAMS-REG and EDGAR
- Overestimation of EDGAR road transport emissions ? similar to e.g. Gately et al., 2013; McDonald et al., 2014; Gately and Hutyra, 2017
- Even larger derived annual flux due to the seasonality of CO_2 emissions ? max. of domestic heating in winter, min. in summer

CH_4 flux

- **agrees better with EDGAR** footprint (factor ~2) than CAMS-REG (factor ~7)
- CAMS-REG claims almost no contribution (~1 %) of waste related emissions compared to EDGAR (~79 %)
- footprint indicates that **sources** in the south-west **outside of Berlin contribute** to the measured CH_4 enhancement

Global/regional nested chemistry climate model MECO(n)



Task: Isolate urban emissions

Input: city-limited BERLIN inventory + E-PRTR point sources (CH_4 emissions of BERLIN are already scaled with a factor of 4.5)

Output: c-CO_2 and c-CH_4 (for „city“) as 2D column-averaged dry air mole fractions (at 13 UTC, a+b) and sampled along the flight (c)

Resolution: ~1 km x 1 km

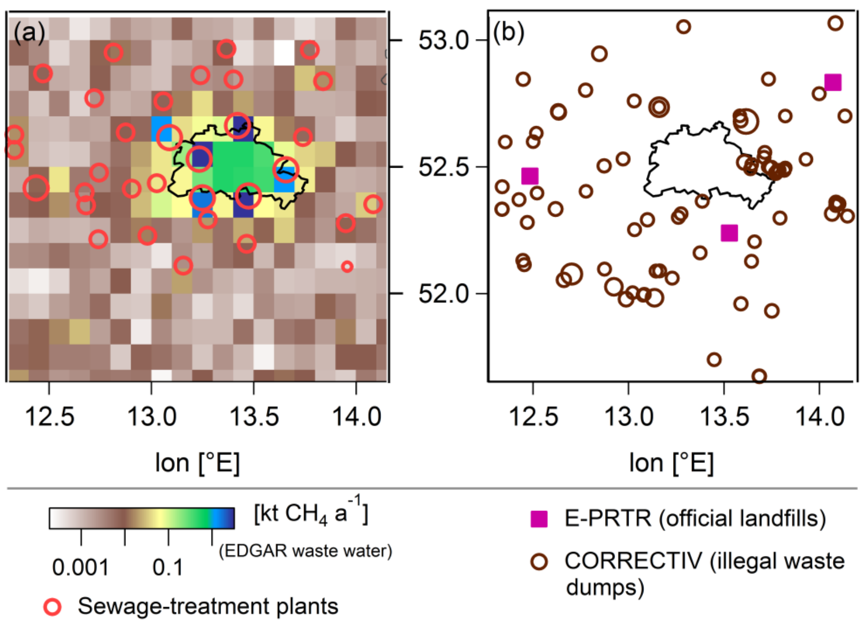
Avg. simulated wind direction: 305° ± 36°

- **CO_2: agreement** of simulated and observed **location** of the CO_2 plume and its **shape**
- **CH_4**: simulated shape is too narrow (→ **missing sources!**) and max. CH_4 enhancements are a factor ~5 too low (→ **significant underestimation of urban emissions!**)

Potential CH_4 sources outside the city boundary

- **CH_4 emissions** show **large discrepancies** between the three different inventories, especially with respect to the **waste sector**

→ Implementation of CH_4 emissions from (a) sewage-treatment plants (MLUL, 2017) and (b) unofficial waste deposits (CORRECTIV, 2016) to investigate the origin of the unexpected missing CH_4 sources



(a) Larger **sewage-treatment plants** agree with pixels of strong EDGAR waste water CH_4 emissions → transfer of emissions (**w-CH_4** = 1 to 7 kt a^{-1})

(b) Estimated CH_4 emissions from **unofficial waste deposits** using Landfill Gas Emission Model (LandGEM) (**l-CH_4** = 0.1 to 32 kt a^{-1})

→ Emissions serve as input for model sensitivity test rather than representing true values

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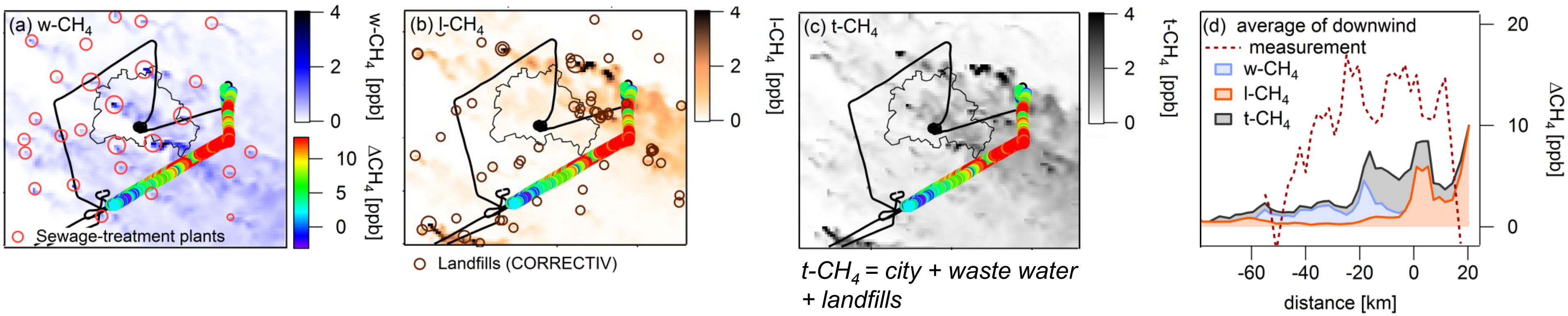
Simulated CH_4 contributions from the waste sector



(a) **w-CH_4** tracer: rather **evenly distributed** CH_4 mole fractions, despite being point sources

(b) **l-CH_4** tracer: more **point-like CH_4 enhancements** either from waste-rich dumps or from a spatial concentration of several dumps

(c) **t-CH_4** tracer: inhomogeneous CH_4 distribution, indicating a **less uniform and more varying background** compared to CO_2

(d) average GHG mixing ratios along the flown horizontal distance: measured CH_4 plume shape is not directly reproduced, but emissions from waste water plants and landfills **broaden and enhance** the simulated **c-CH_4 plume** which considers only city emissions

Achievements

- The **urban GHG plume from Berlin** (Germany) was **detected** and **isolated** in a well-mixed and efficiently capped boundary layer
- GHG **emission rates** were estimated based on sensitive in-situ measurements:
  CO_2: 1.39 ± 0.76 t s^{-1} and CH_4: 5.20 ± 1.70 kg s^{-1}
- **CO_2**
  - estimated flux is **in the same order of magnitude** as given in the inventories
  - simulated citywide MR agree well with observed CO_2 in location and shape
- **CH_4**
  - estimated flux is ~2 times larger than the highest reported inventorial value
  - simulated citywide MR are **substantially lower** than observed and the plume width is too narrow (***missing*** *waste* ***sources*** *outside of Berlin?*)

→ **Large uncertainties**, especially for CH_4, are identified in bottom-up inventories at the **city scale** even in a highly developed country like Germany

→ The **inflow and background MR**, especially for CO_2, need to be **precisely determined** when applying the mass balance approach (although Berlin is a relatively isolated city)

→ **Top-down** emission estimate is an important tool to **verify inventorial emissions** and to **reveal missing sources**

Outlook

Subsequent ground-based measurements and/or further airborne in-situ **observations are needed**

- in the **greater Berlin area** with a special focus on emission sources located outside the city boundaries
  → would improve the knowledge on the regional CH_4 budget with a clear attribution of waste related CH_4 emission sources and their quantification
- in **different seasons**
  → would reflect the seasonal cycle of the CO_2 emissions
- in a **Lagrangian** flight track pattern
  → would improve the estimation of the background variability

Thanks and feel free to contact me!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The paper “Urban greenhouse gas emissions from the Berlin area: A case study using airborne CO_2 and CH_4 in situ observations in summer 2018” is also published:

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