Munich Column Carbon Monitoring network (MUCCnet)

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Environmental Sensing and Modeling

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IAS TUM Institute for Advanced Study

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Munich Greenhouse Gas Observation Landscape in 2015

Munich Greenhouse Gas and Air Quality Landscape Today

- Integrated observation approach
  - MUCCnet
  - Air quality sensor network
  - OCO2 target modes, OCO3 SAM mode

MUCCnet: Differential Column Measurements

(Chen et al., 2016)

- **Approach**: $Emission \propto C_{downwind} - C_{upwind}$
- **Species:**
  - Carbon dioxide: CO_2
  - Methane: CH_4
- **Advantages**:
  - Insensitive to boundary layer height dynamics
  - Representative for regional emissions
- **Application**:
  - Monitoring urban GHG emissions over long-term
  - Validating satellites

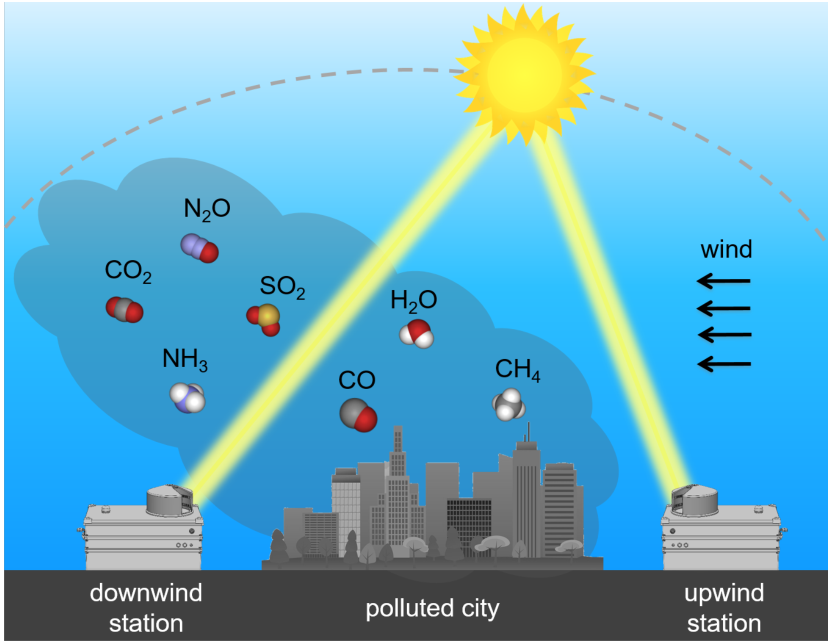


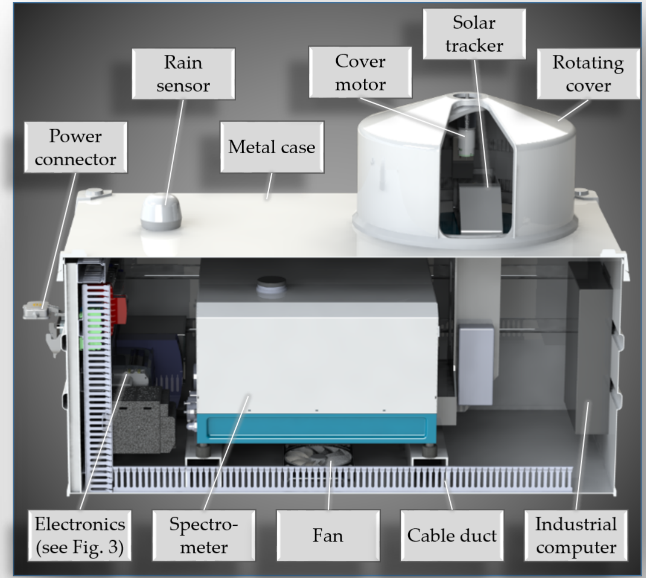
Fig. 1: Principle of the differential column measurements

Chen et al.: *Differential column measurements using compact solar-tracking spectrometers. Atmospheric Chemistry and Physics, 2016*

Patented Sensor System

(Heinle and Chen, 2018; Dietrich et al. 2021)

- Fully-automated sensor systems:
  - Fourier transform spectrometer + sun tracker
  - Smart system protect the spectrometer: Sunny → measure, Rainy → cover close
- Easy to transport, mobile deployable
- Deployed in Munich (5 stations), Finland and Uganda



→ Our system reduces the personnel costs to a minimum and increases the amount of measurement data to a maximum

Heinle and Chen: *Automated Enclosure and Protection System for Compact Solar-Tracking Spectrometers. Atmos. Meas. Tech., 2018*
Dietrich et al.: *MUCCnet: Munich Urban Carbon Column network, Atmos. Meas. Tech., 2021.*

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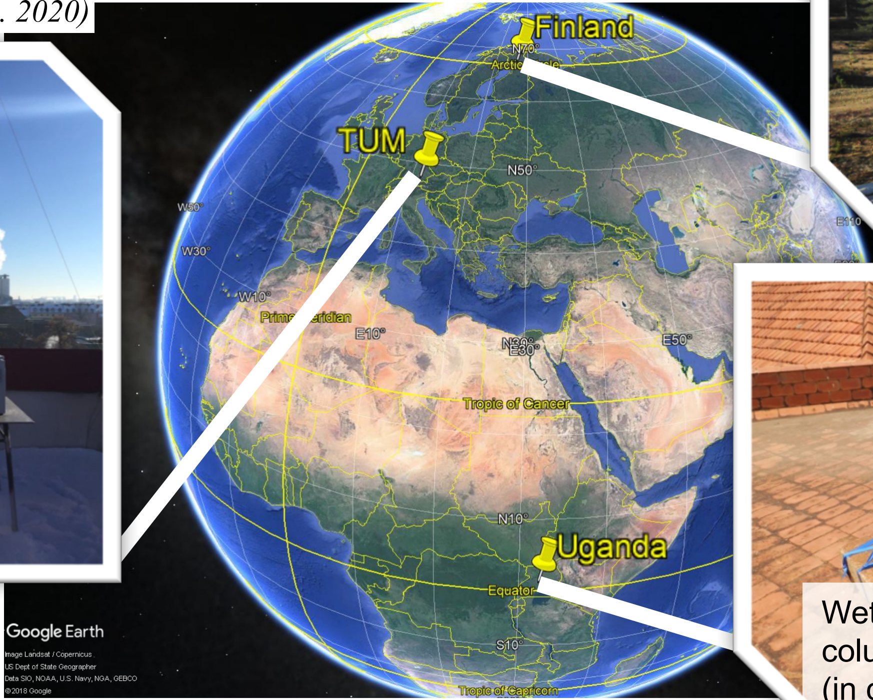
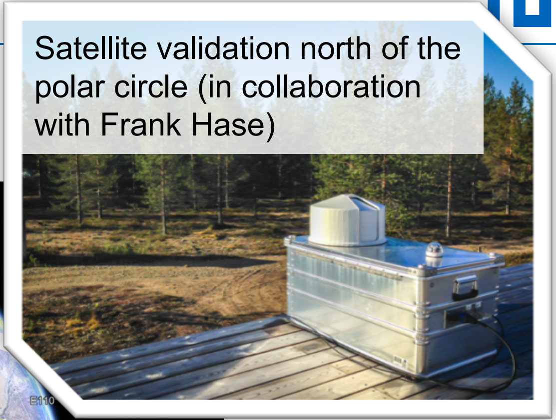
International Sites of our System

(Dietrich et al. 2021; Tu et al. 2020)





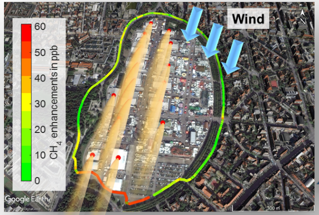
Satellite validation north of the polar circle (in collaboration with Frank Hase)

Wetland CH_4 emissions. First column measurement in East-Africa (in collaboration with Hartmut Bösch).

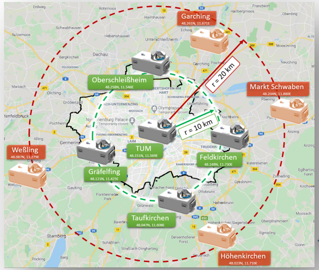
Tu et al.: *Intercomparison of atmospheric CO2 and CH4 abundances on regional scales in boreal areas using CAMS analysis, COCCON spectrometers, and Sentinel-5 Precursor satellite observations. Atmos. Meas. Tech., 2020*

GHG Monitoring – A Multiscale Approach

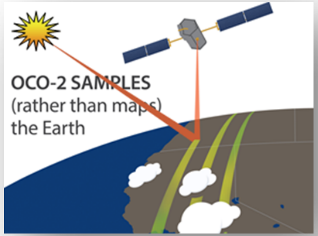
Point sources
(power plant study)



Area sources
(Oktoberfest)



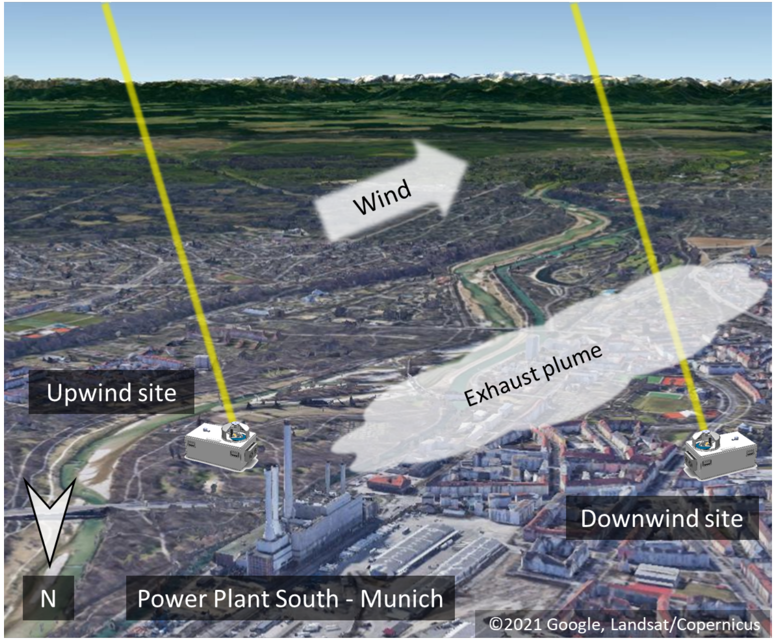
City sources
(MUCCnet)

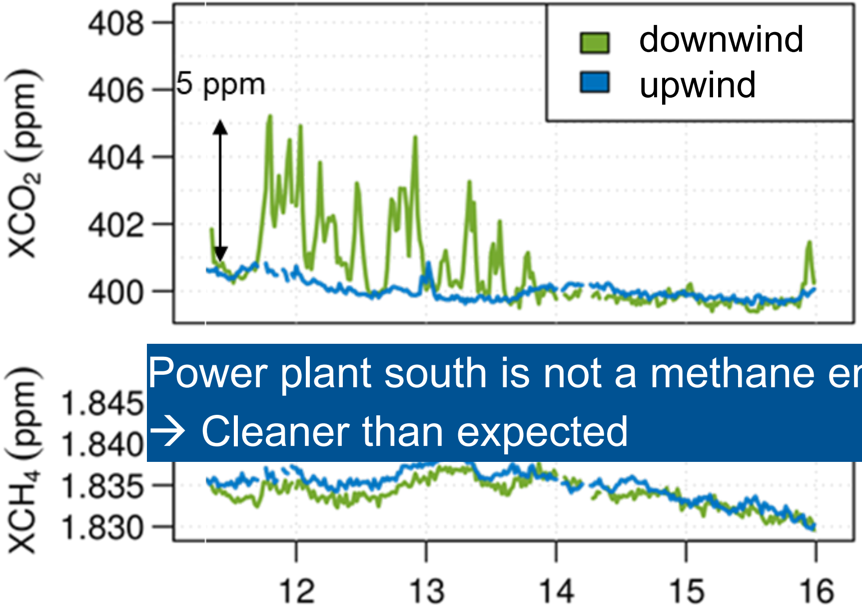


Global scale
(satellite studies)

Power Plant South Study (Natural Gas-fired → Potential methane source)

Toja-Silva, Chen et al. (2017)



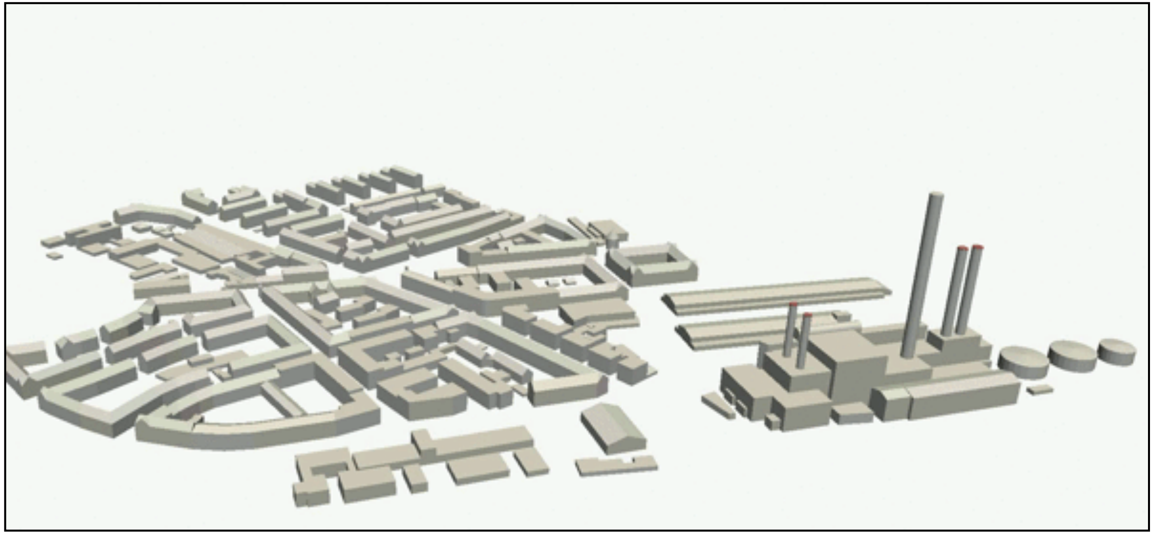


Power plant south is not a methane emitter
→ Cleaner than expected

Toja-Silva et al.: *CFD simulation of CO2 dispersion from urban thermal power plant: Analysis of turbulent Schmidt number and comparison with Gaussian plume model and measurements., 2017*

Gas-Fired Power Plant – CFD Simulation (OpenFoam)

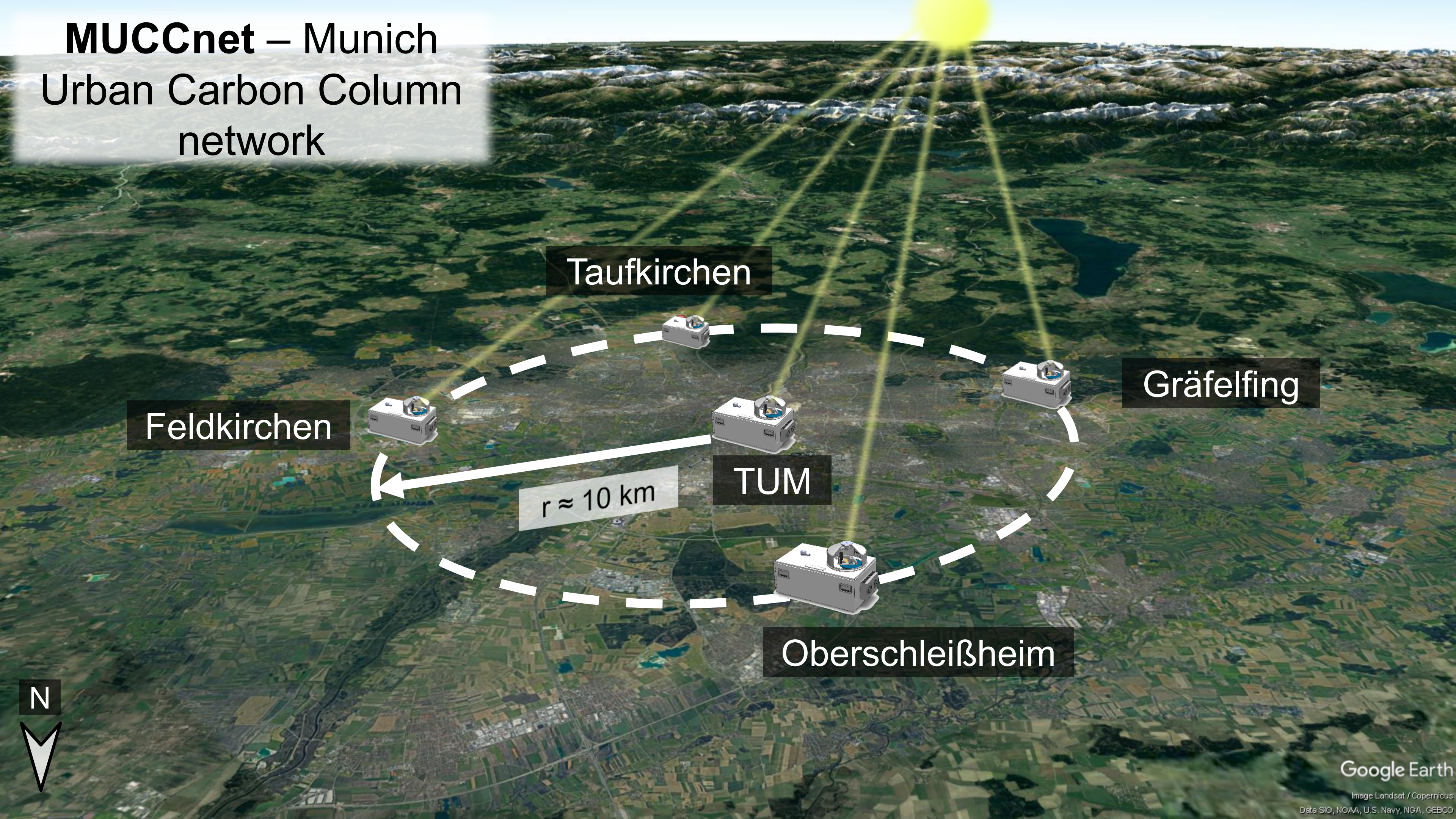
Toja-Silva, Chen et al. (2017)



- Wind field: Navier-Stokes equations (meter scale)
- Concentration field: convection-diffusion equations

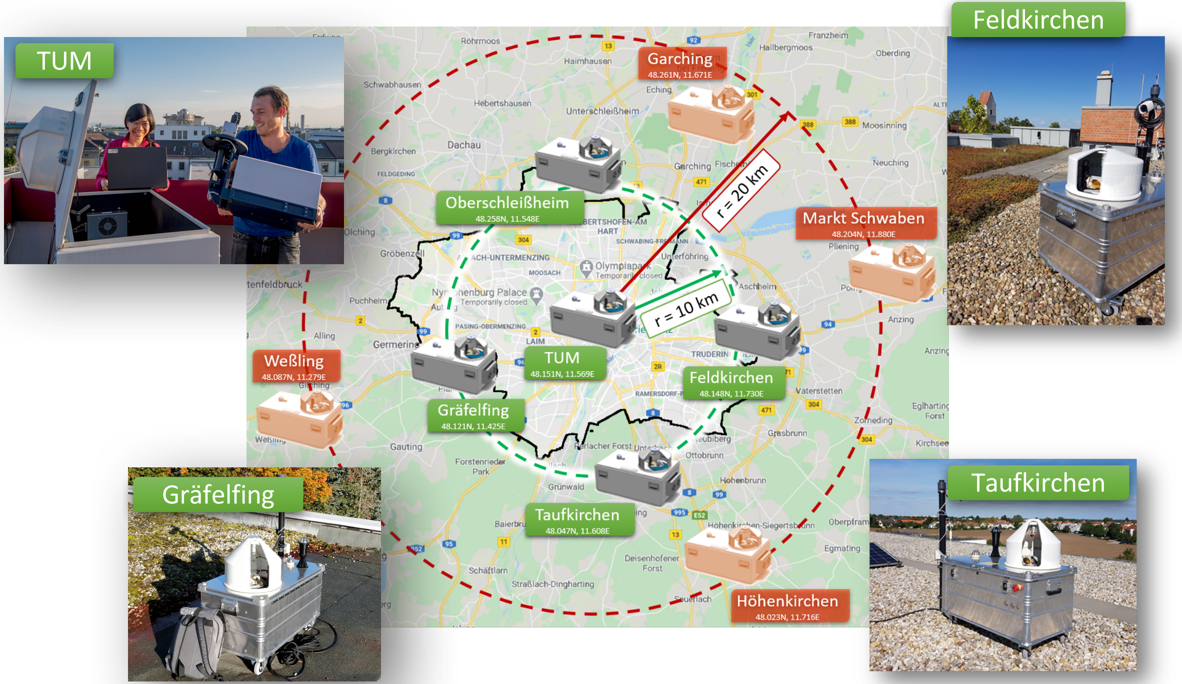
→ Microscale CFD model to convert measured concentration to emission strength

Toja-Silva et al.: *CFD simulation of CO2 dispersion from urban thermal power plant: Analysis of turbulent Schmidt number and comparison with Gaussian plume model and measurements., 2017*


MUCCnet – Munich Urban Carbon Column network
Taufkirchen
Gräfelfing
Feldkirchen
TUM
r ≈ 10 km
Oberschleißheim
N
Google Earth
Image Landsat / Copernicus
Data SIO, NOAA, U.S. Navy, NGA, GEBCO

Munich Carbon Column Network (MUCCnet)

(Dietrich et al., 2021)

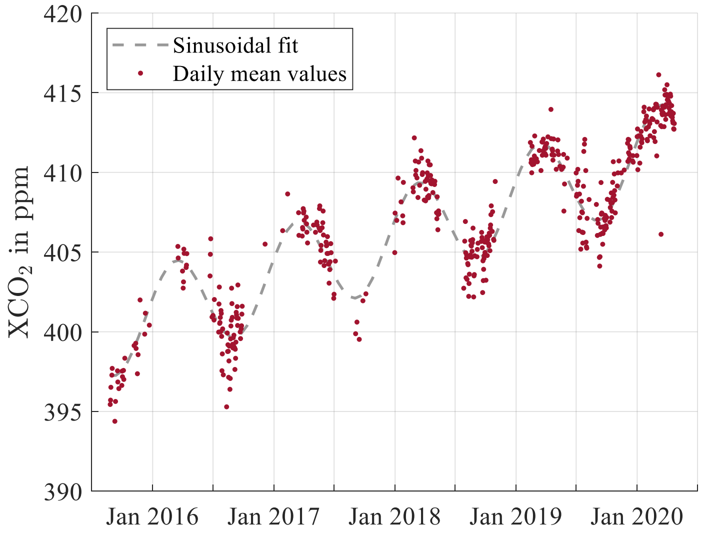


- 5 sensor systems distributed in and around Munich:
  - Always at least one upwind/downwind station for arbitrary wind conditions
  - Center station is the downwind of half the city
- Fully automation important for permanent monitoring
- Application: unknown sources discovery, emission monitoring, satellite validation

Dietrich et al.: *MUCCnet: Munich Urban Carbon Column network, Atmos. Meas. Tech., 2021.*

Measurement Results – Seasonal Cycle

(Dietrich et al., 2021)



- Center station is operating since summer 2015
- Capturing the seasonal cycle and increasing trend of CO_2 (≈2.4 ppm per year)
- No measurement gap in winter 2019/2020 thanks to the full automation.

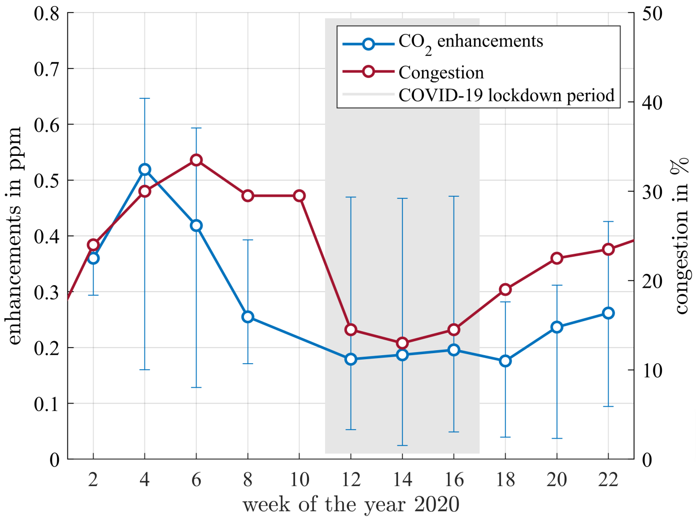
→ Inner-city station captures the seasonal cycle of CO_2 for the last 4.5 years very well

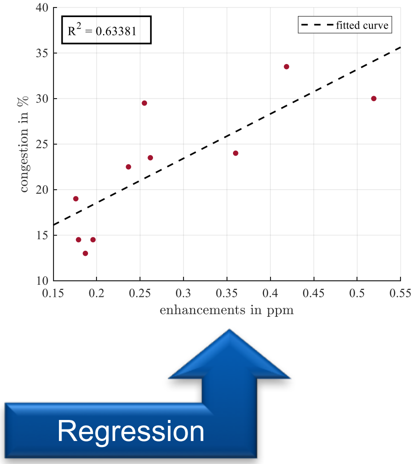
Dietrich et al.: *MUCCnet: Munich Urban Carbon Column network, Atmos. Meas. Tech., 2021.*

Measurement Results – CO_2 Concentration Enhancements

(Dietrich et al., 2021)

COVID-19 influences



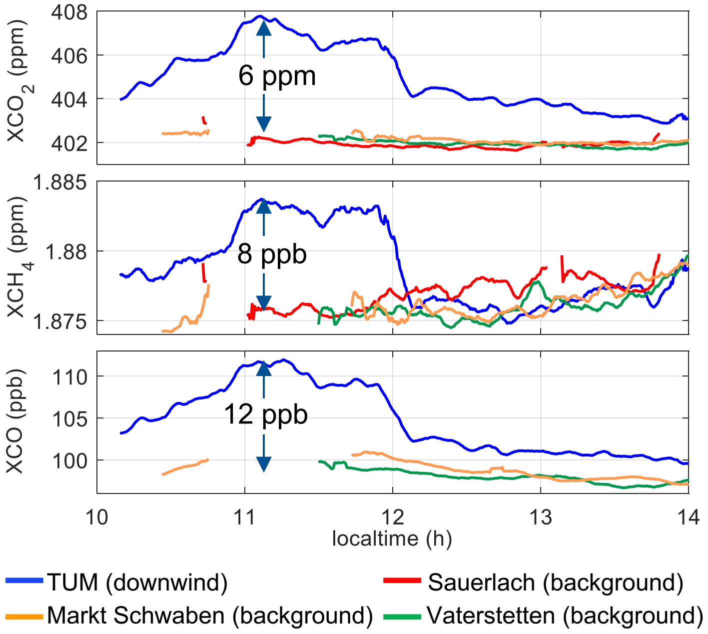


→ Sensor network can sense the GHG concentration gradients to quantify the emissions

Dietrich et al.: *MUCCnet: Munich Urban Carbon Column network, Atmos. Meas. Tech., 2021.*

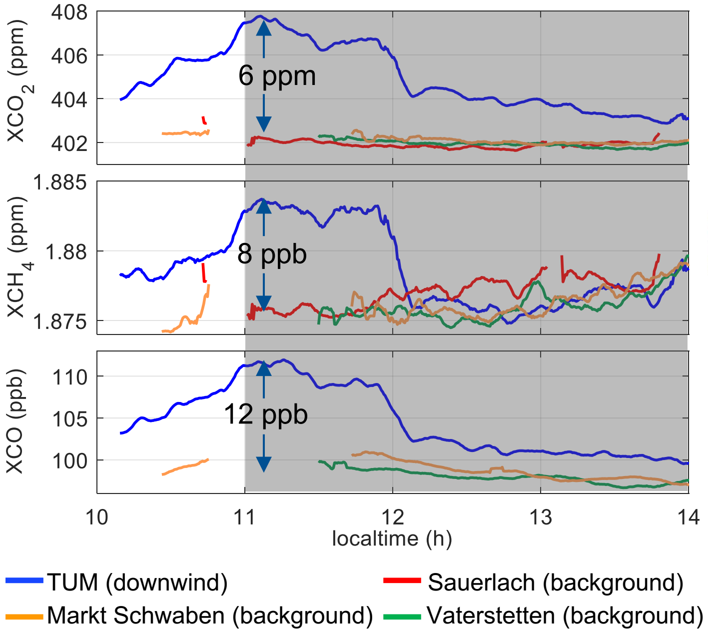
Unknown emission sources

1 day during Oktoberfest

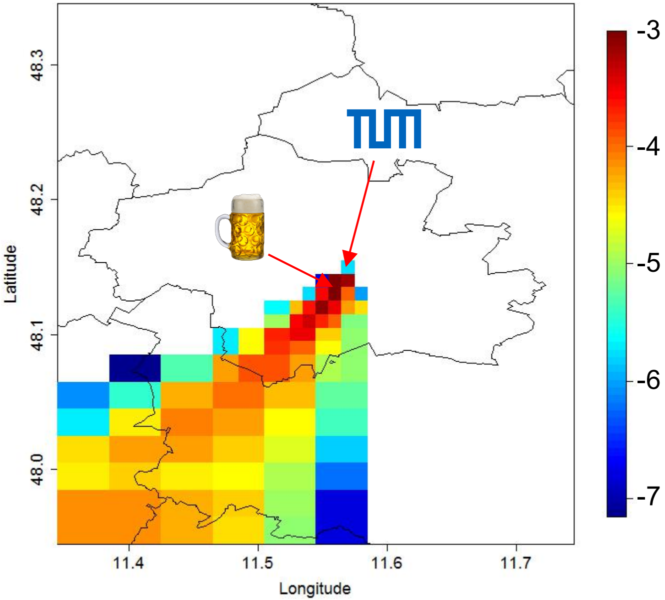


Unknown emission sources - Origin

1 day during Oktoberfest

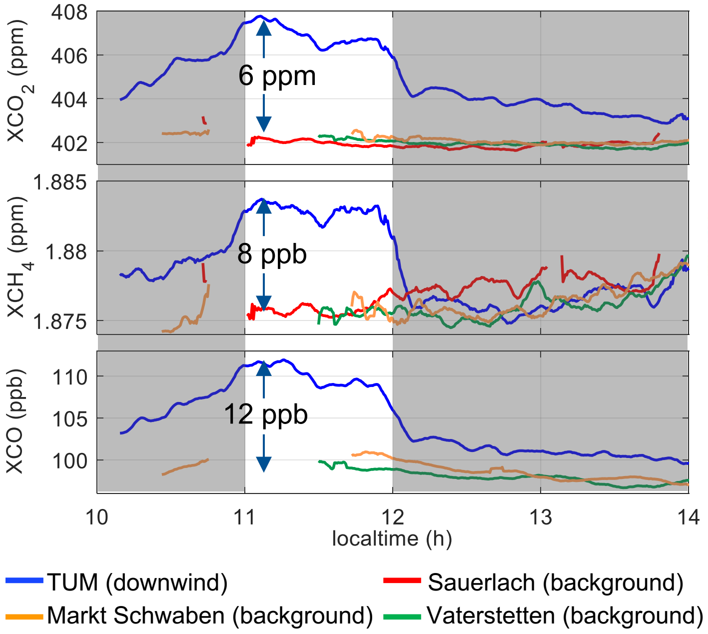


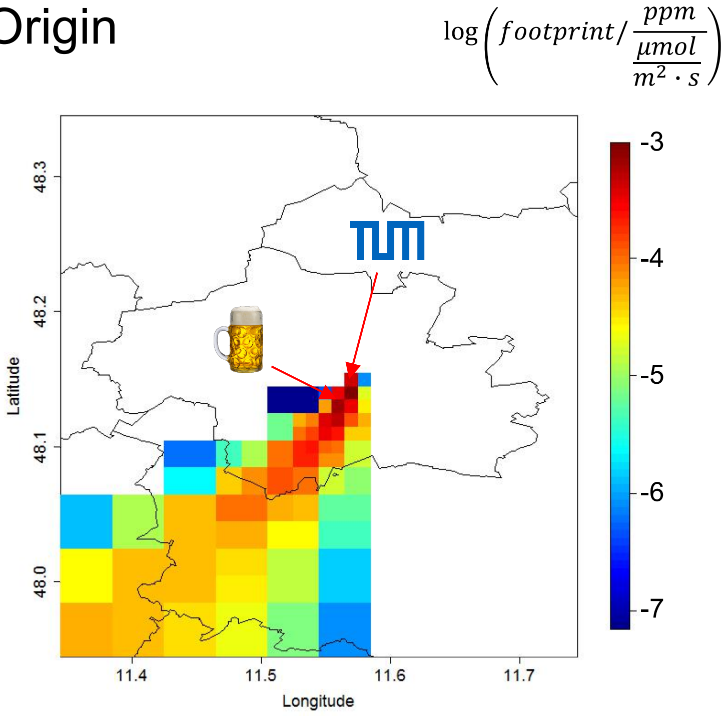
$$\log\left(footprint/\frac{ppm}{\frac{\mu mol}{m^2\cdot s}}\right)$$



Unknown emission sources - Origin

1 day during Oktoberfest





Unknown emission sources - Origin

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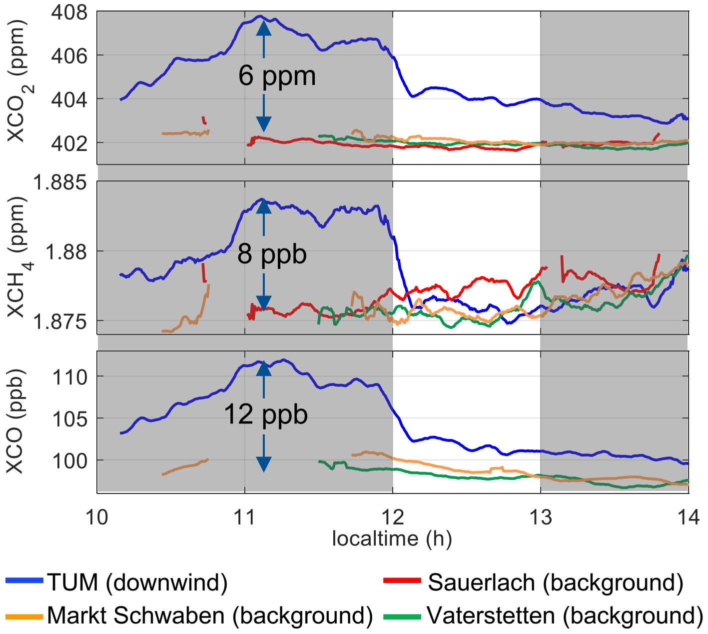

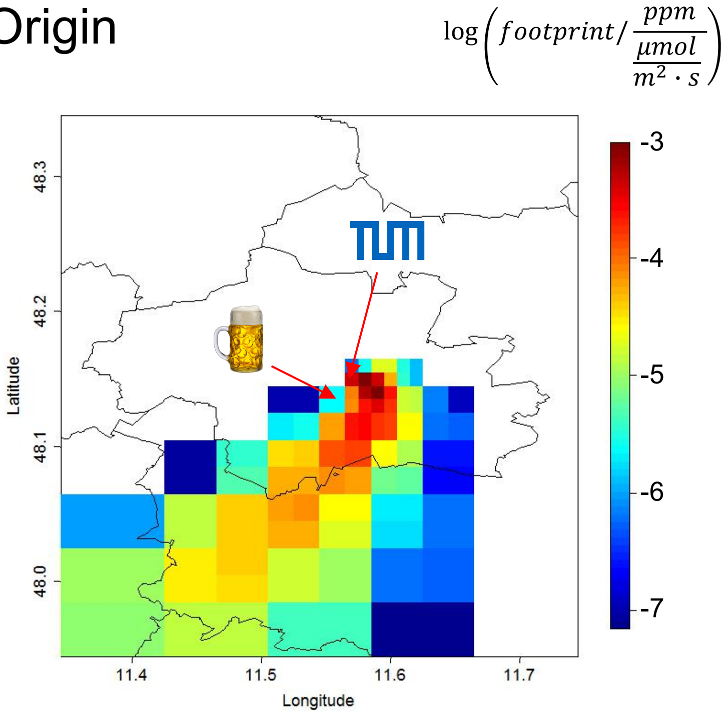

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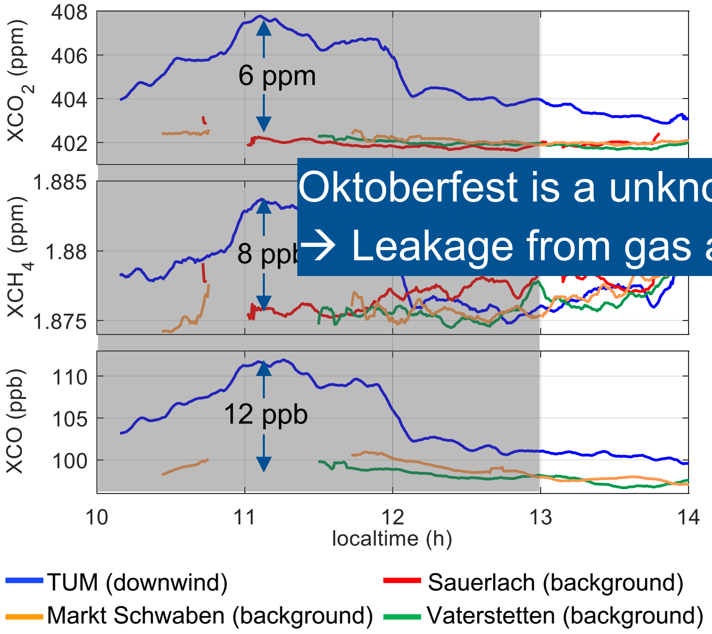
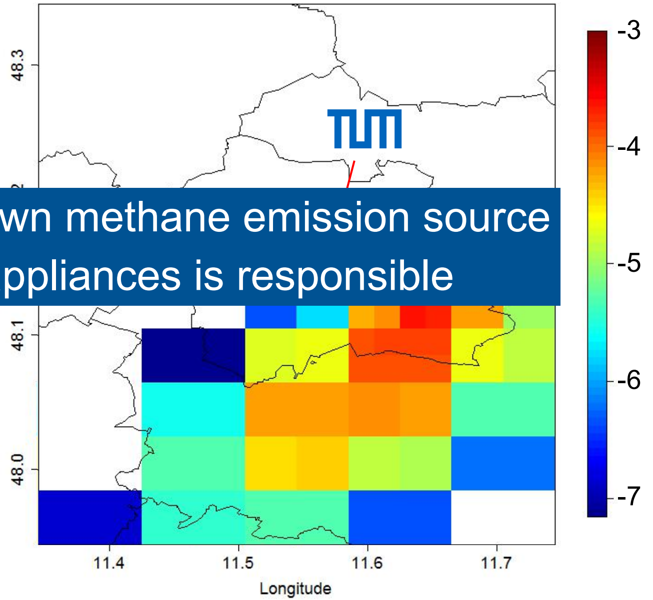
Unknown emission sources - Origin

1 day during Oktoberfest

$$\log\left(footprint/\frac{ppm}{\frac{\mu mol}{m^2 \cdot s}}\right)$$

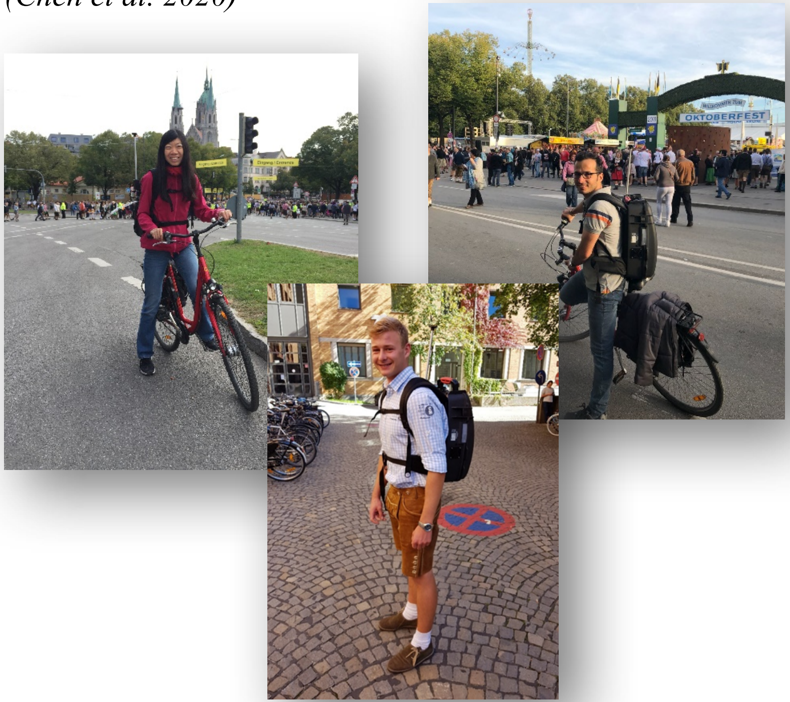


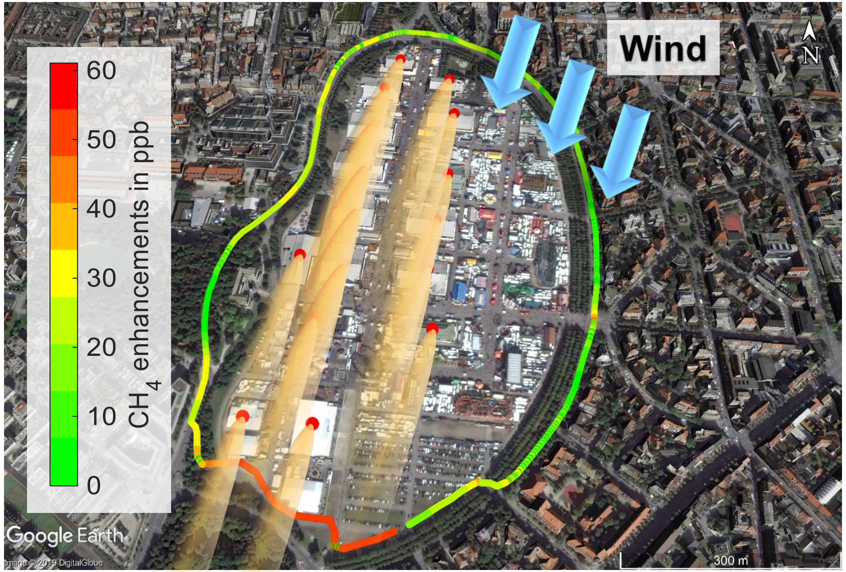


Oktoberfest is a unknown methane emission source
→ Leakage from gas appliances is responsible

Oktoberfest Investigation 2018

(Chen et al. 2020)



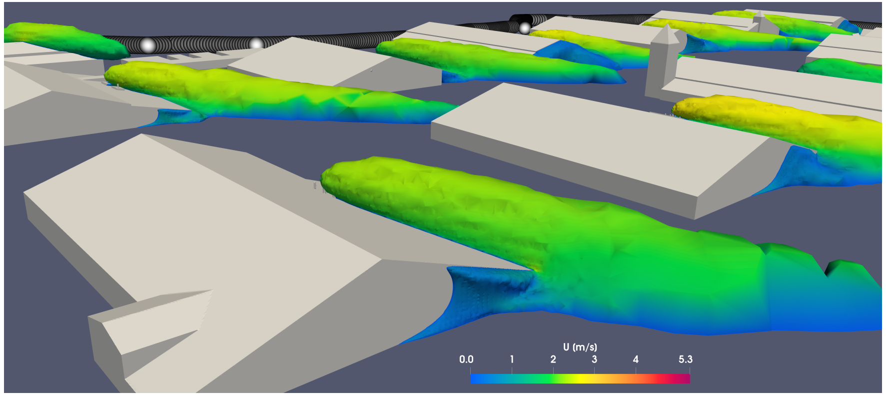


Chen et al.: *Methane emissions from the Munich Oktoberfest. Atmospheric Chemistry and Physics, 2020*

Results – emission and leakage rate

(Chen et al. 2020, Lober et al. 2021)

CFD simulation



- Total emission: 6.7 μg/m²/s
  (vs. city of Munich: 0.3 μg/m²/s)
- 90% CH_4 emission from gas appliances
- Total gas consumption: ~201 000 m^3
- Loss rate: ~ 1.1%

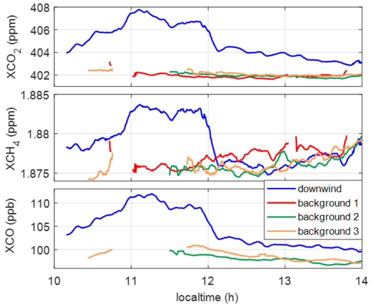
→ Leakage rate might change the climate balance of different energy sources

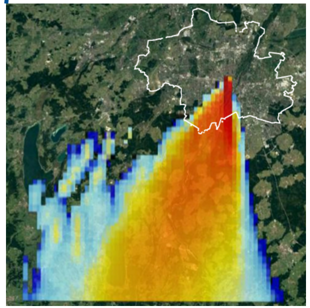
Chen et al.2020: *Methane emissions from the Munich Oktoberfest. Atmospheric Chemistry and Physics, 2020*
Lober et al. 2021: *Computational Fluid Dynamics Model to Simulate Methane Dispersion at Oktoberfest, Earth and Space Science Open Archive, 2021*

Framework for Estimating Emission (Bayesian Inversion)

(Jones et al. 2021)

$$\min_{x,\,b}[(Hx + Bb - y)^T S_\epsilon^{-1}(Hx + Bb - y) + (x_a - x)^T S_a^{-1}(x_a - x)]$$





y: *observations*

H: *footprint matrix*

x: *emissions*

x_a: *prior emissions*

B: *background influence matrix*

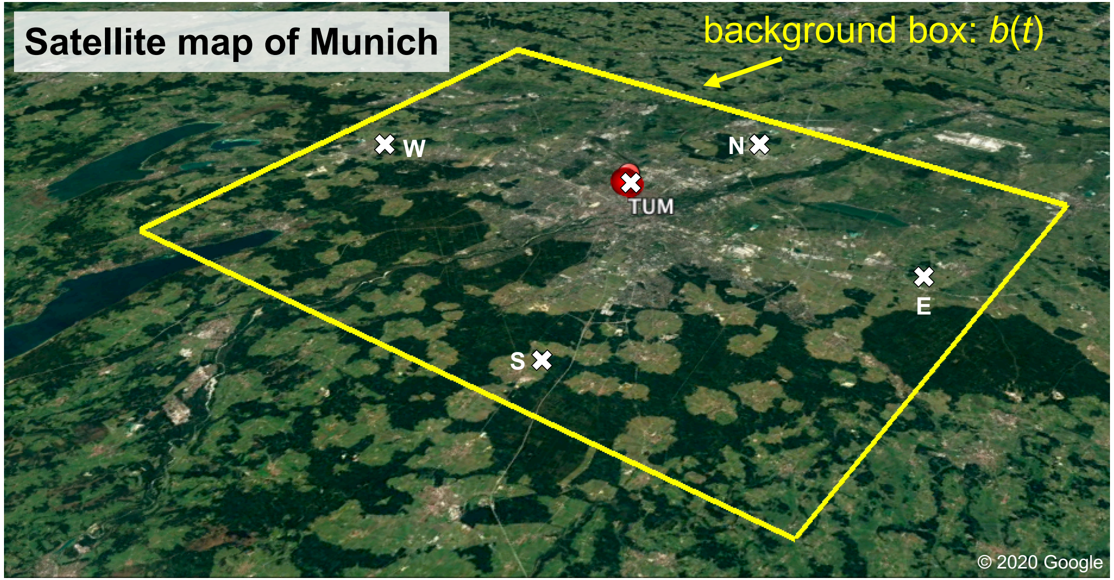
b: *background concentration*

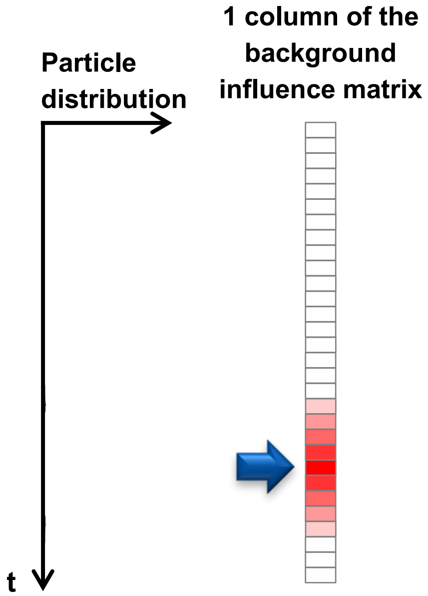
S: *error covariance matrix*

→ Approach: Minimizing a cost function to determine the emissions and the background influence

Jones et al.: *Assessing Urban Methane Emissions using Column Observing Portable FTIR Spectrometers and a Novel Bayesian Inversion Framework, Atmos. Chem. Phys., 2021*

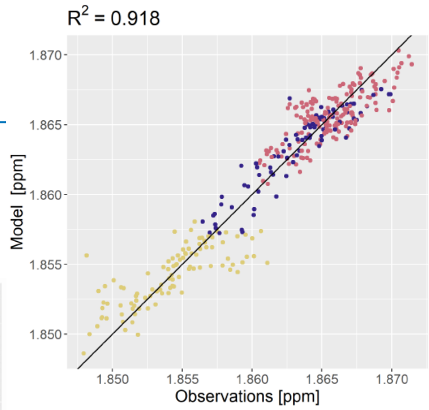
Backward Particle Simulation

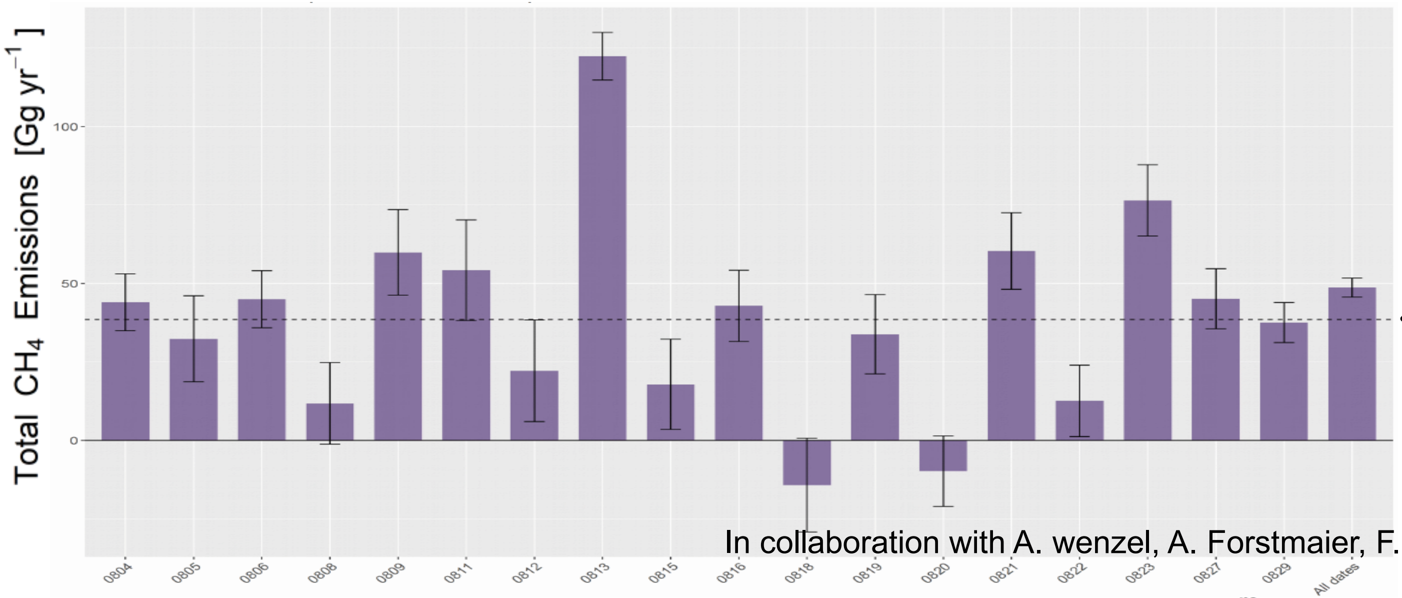




→ Particle backwards trajectory simulation (STILT) produces the footprints and background influence matrix for the inversion

Emission Results of Munich





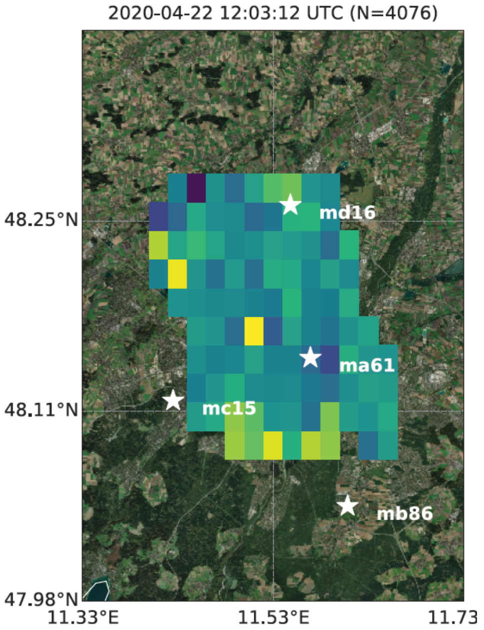
Bottom-up
emission inventory

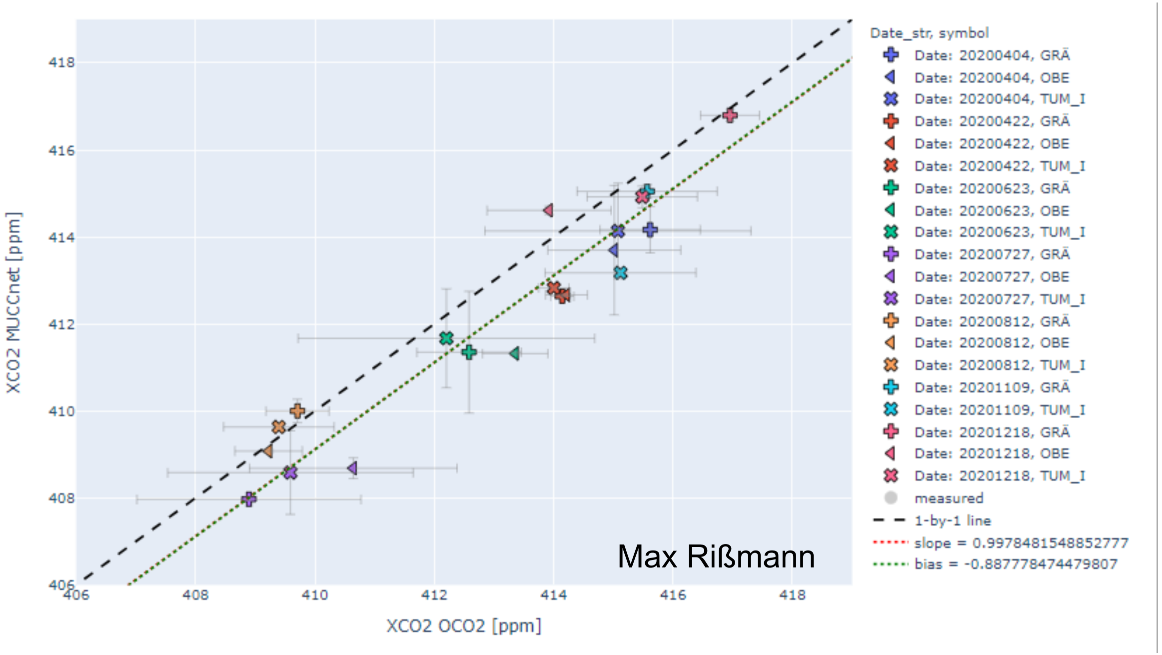
In collaboration with A. wenzel, A. Forstmaier, F. Klappenbach, X. Zhao et al.

→ Emission number about 1.2 times higher than the emission inventory (using long-term dataset)
→ Good correlation between measured and modelled concentrations

Munich CH4 emission assessment using a Bayesian inverse modeling approach, in preparation

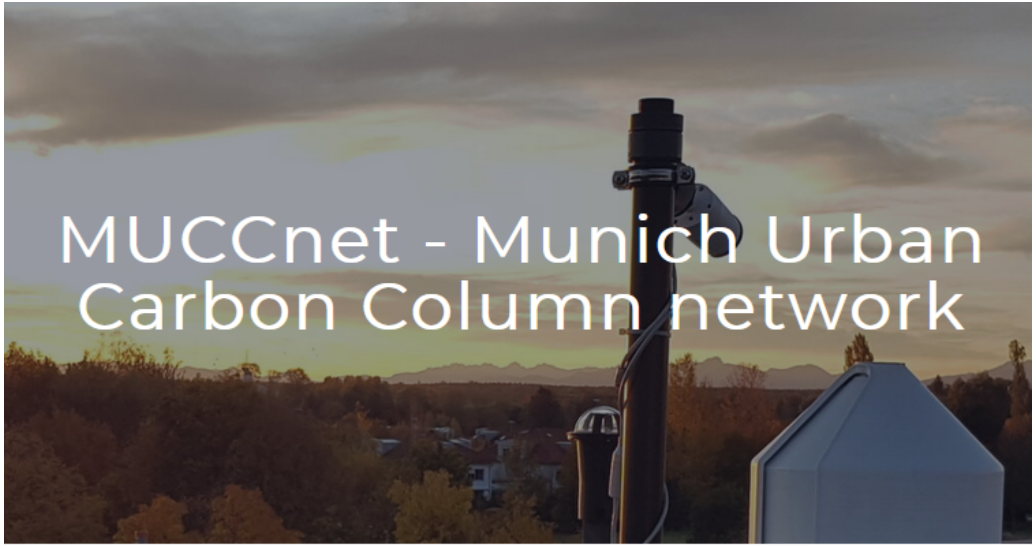
Satellite validation using MUCCnet (in collaboration with M. Kiel and G. Osterman)



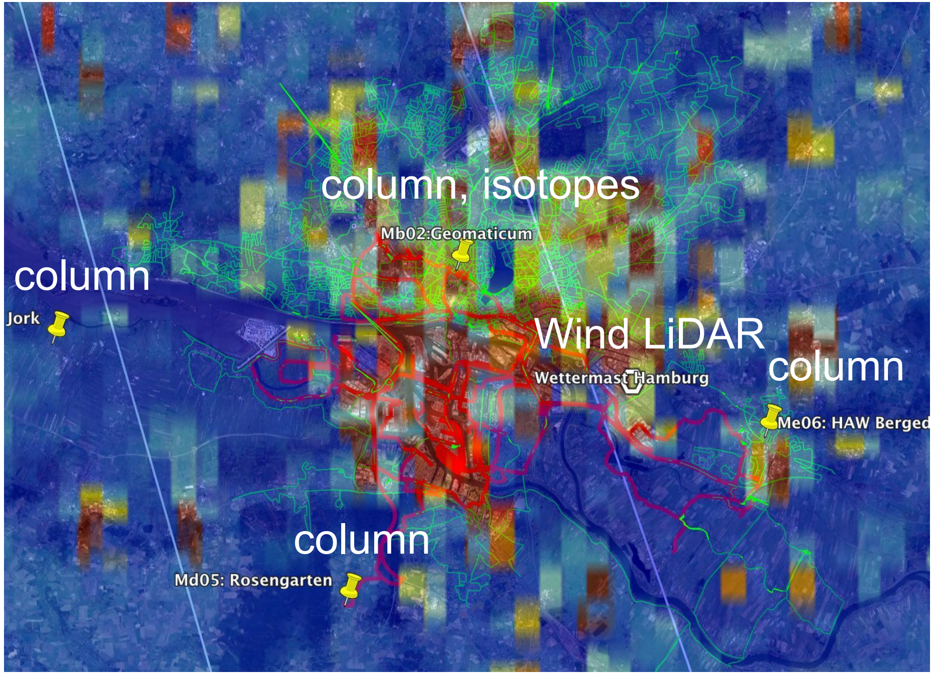


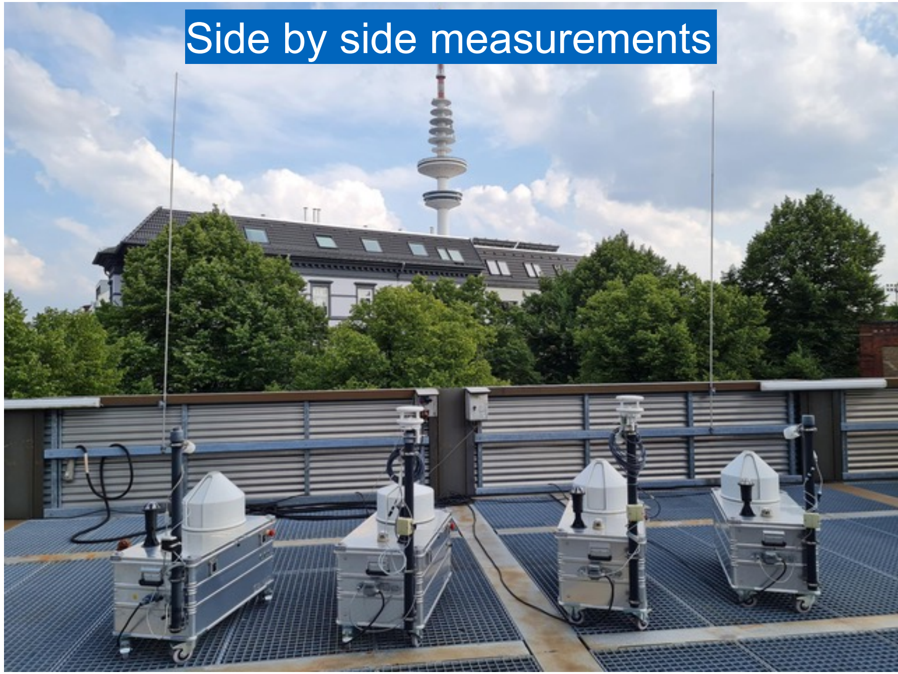
Measurement data accessible online

https://atmosphere.ei.tum.de/



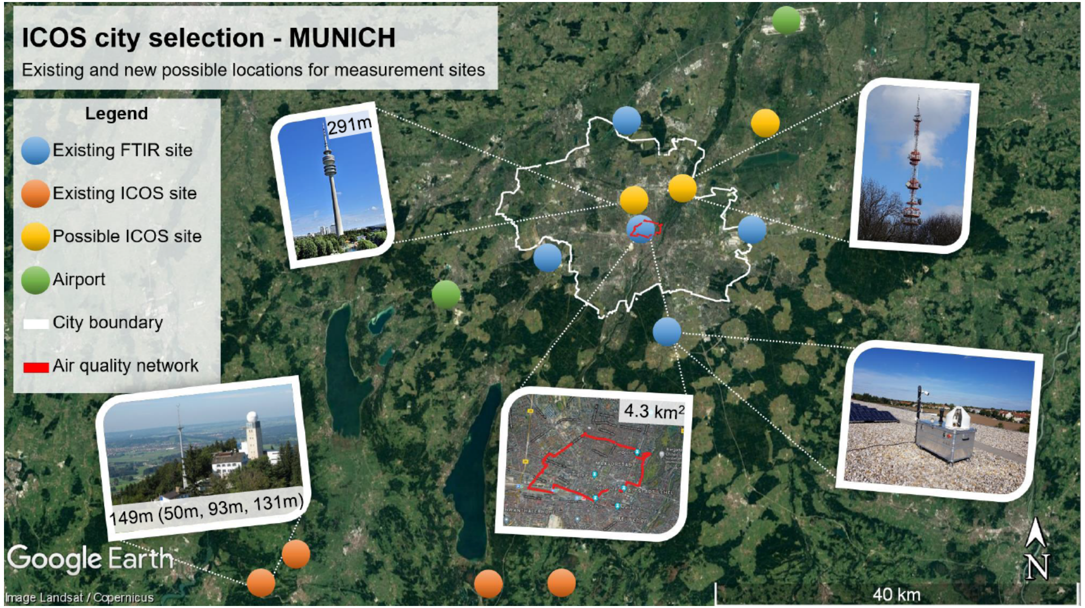
Hamburg Campaign (supported by the UN)





Munich → Pilot city of European Green Deal

- Munich was selected to be one of the three pilot city (+ Paris and Zurich) of the European Green deal (TUM: Science lead Munich)
- Measurements to be established:
  - Ground-based remote sensing system
  - Street level sensors
  - Roof level sensors
  - Co-species
  - 1 tall tower eddy covariance station
  - Airborne measurements (on board Lufthansa)



Thank You!

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