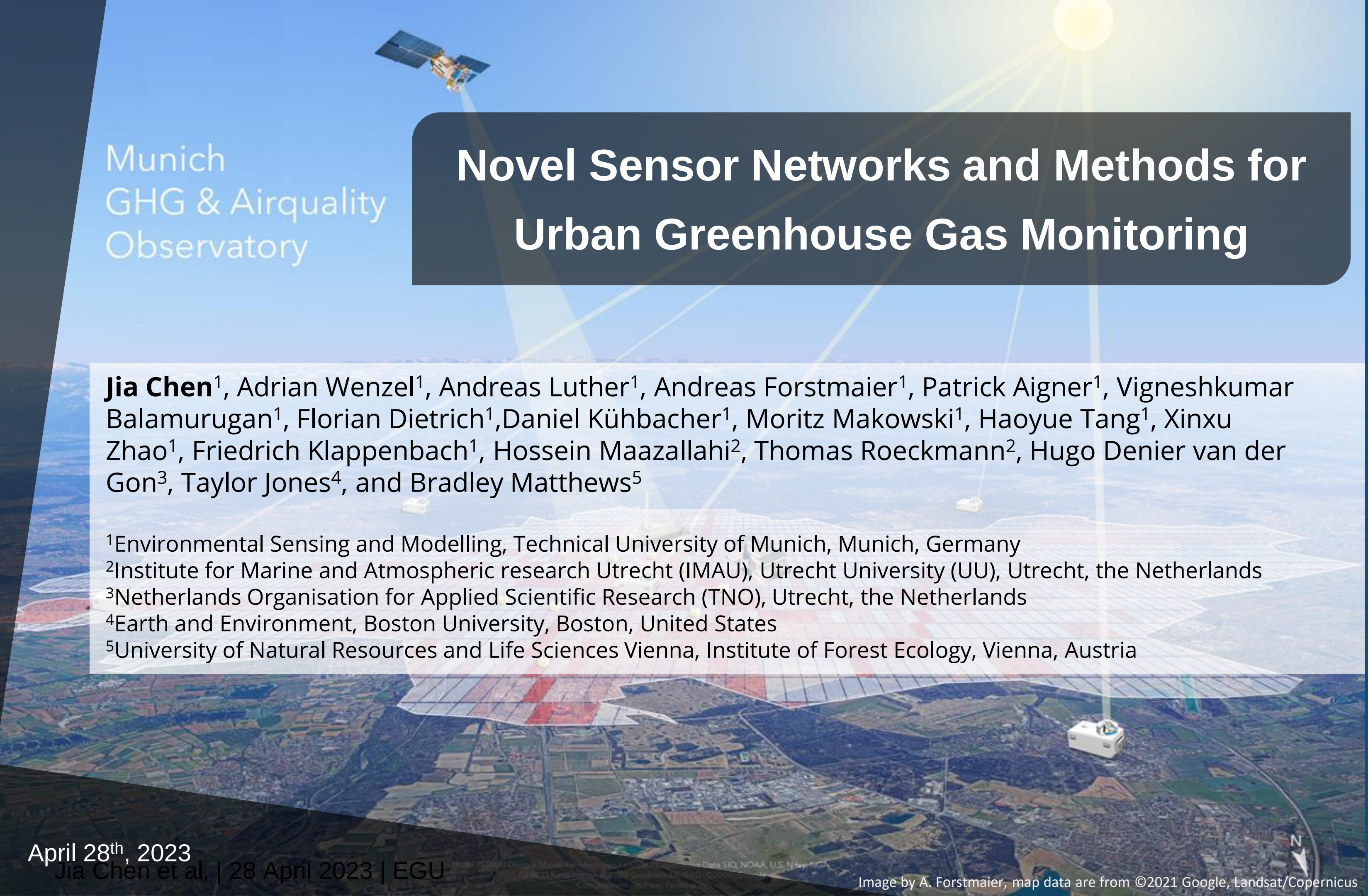


Novel Sensor Networks and Methods for Urban Greenhouse Gas Monitoring

Jia Chen
TU Munich
Environmental Sensing & Modeling
jia.chen@tum.de

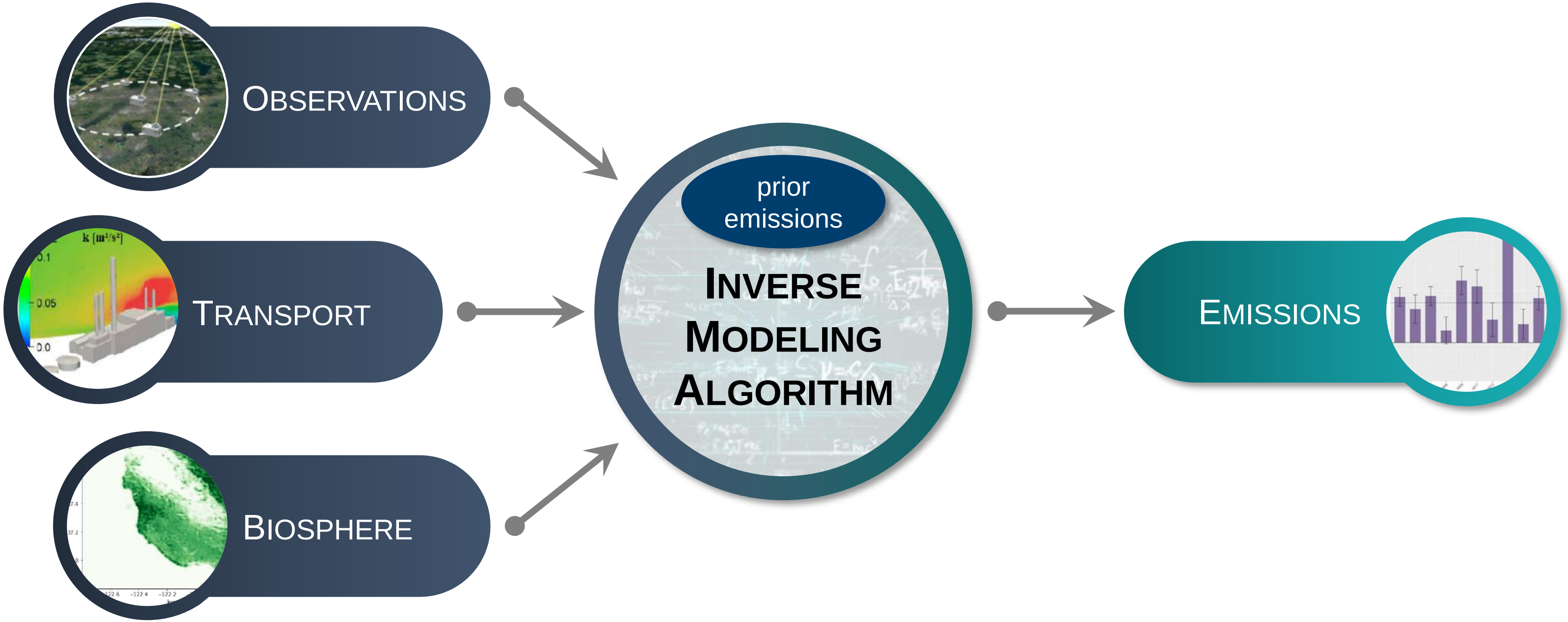
Jia Chen[1], Adrian Wenzel[1], Andreas Luther[1], Andreas Forstmaier[1], Patrick Aigner[1], Vigneshkumar Balamurugan[1], Florian Dietrich[1],Daniel Kühbacher[1], Moritz Makowski[1], Haoyue Tang[1], Xinxu Zhao[1], Friedrich Klappenbach[1], Hossein Maazallahi[2], Thomas Roeckmann[2], Hugo Denier van der Gon[3], Taylor Jones[4], and Bradley Matthews[5]

[1]Environmental Sensing and Modelling, Technical University of Munich, Munich, Germany
[2]Institute for Marine and Atmospheric research Utrecht (IMAU), Utrecht University (UU), Utrecht, the Netherlands
[3]Netherlands Organisation for Applied Scientific Research (TNO), Utrecht, the Netherlands
[4]Earth and Environment, Boston University, Boston, United States
[5]University of Natural Resources and Life Sciences Vienna, Institute of Forest Ecology, Vienna, Austria

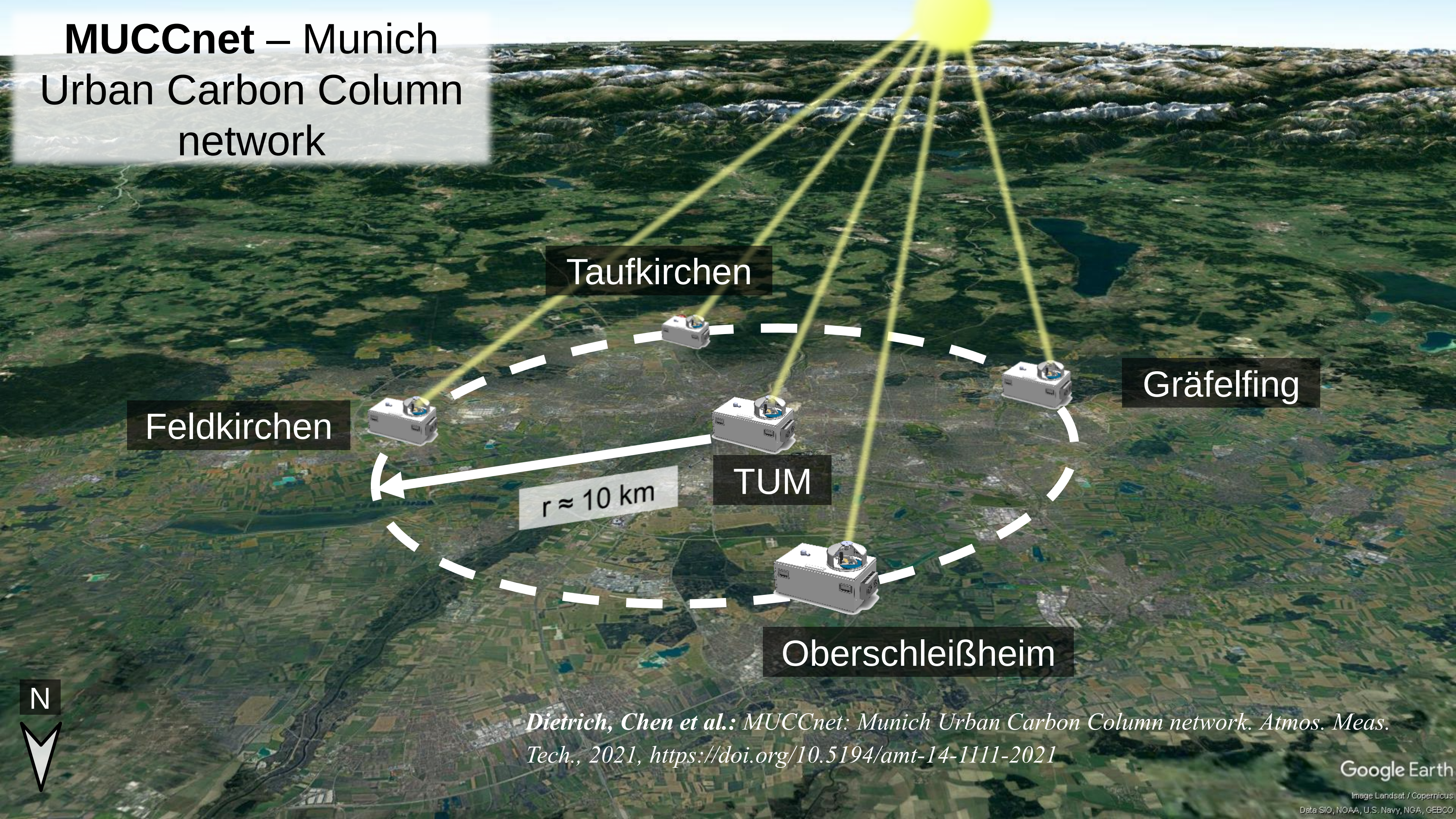
April 28th, 2023

Image by A. Forstmaier, map data are from ©2021 Google, Landsat/Copernicus

Emission Monitoring



MUCCnet – Munich Urban Carbon Column network



Dietrich, Chen et al.: *MUCCnet: Munich Urban Carbon Column network. Atmos. Meas. Tech., 2021, https://doi.org/10.5194/amt-14-1111-2021*

Differential Column Measurements

(Chen et al., 2016, Dietrich et al. 2021)

- **Approach**: $Emission \propto C_{downwind} - C_{upwind}$
- **Species**: CO_2, CH_4 and CO
- **Advantages**:
  - Insensitive to boundary layer height dynamics
  - Representative for regional emissions
- **Precision**: 0.01% @10 min integration time
- **Application**:
  - Monitoring urban GHG emissions over long-term
  - Validating satellites
- Included the **WMO IG3IS** Guideline for Urban GHG Emission Monitoring

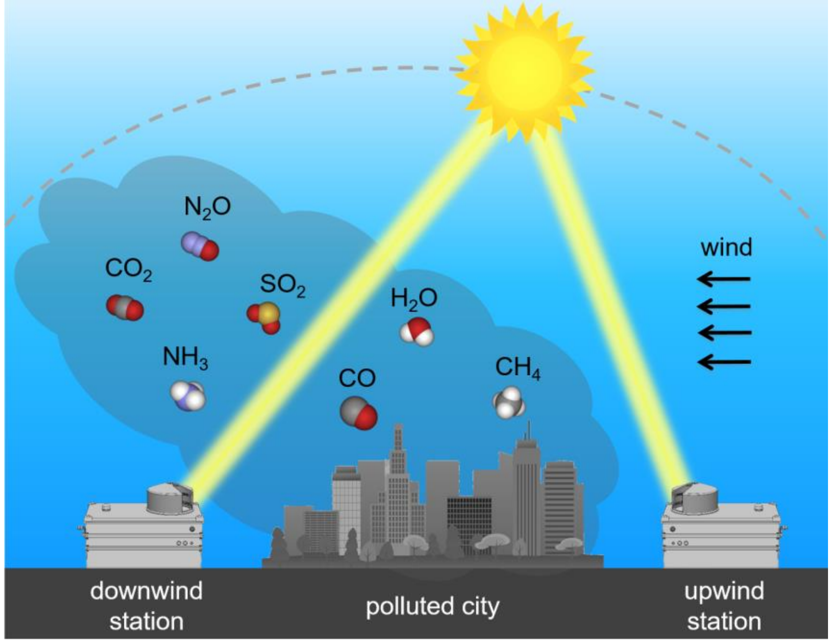


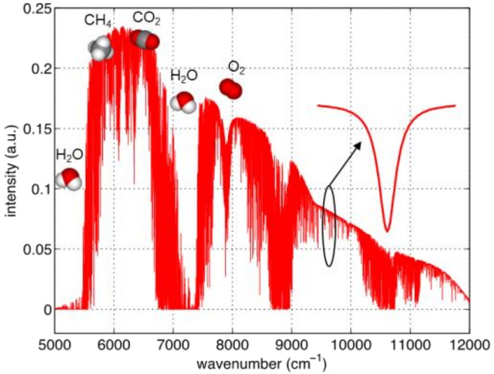
Fig. 1: Principle of the differential column measurements

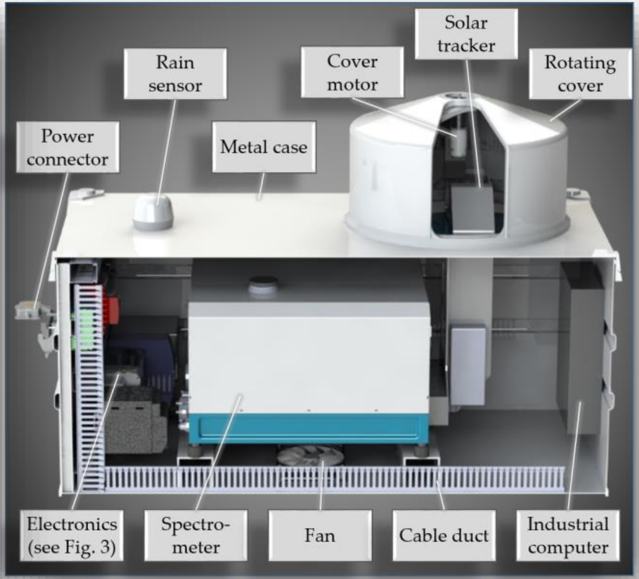
Chen et al.: *Differential column measurements using compact solar-tracking spectrometers. Atmospheric Chemistry and Physics, 2016, https://doi.org/10.5194/acp-16-8479-2016*

MUCCnet Sensor System

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

- Fully-automated sensor systems:
  - Solar-tracking Fourier transform spectrometer (Bruker EM27/SUN)
  - Patented enclosure system



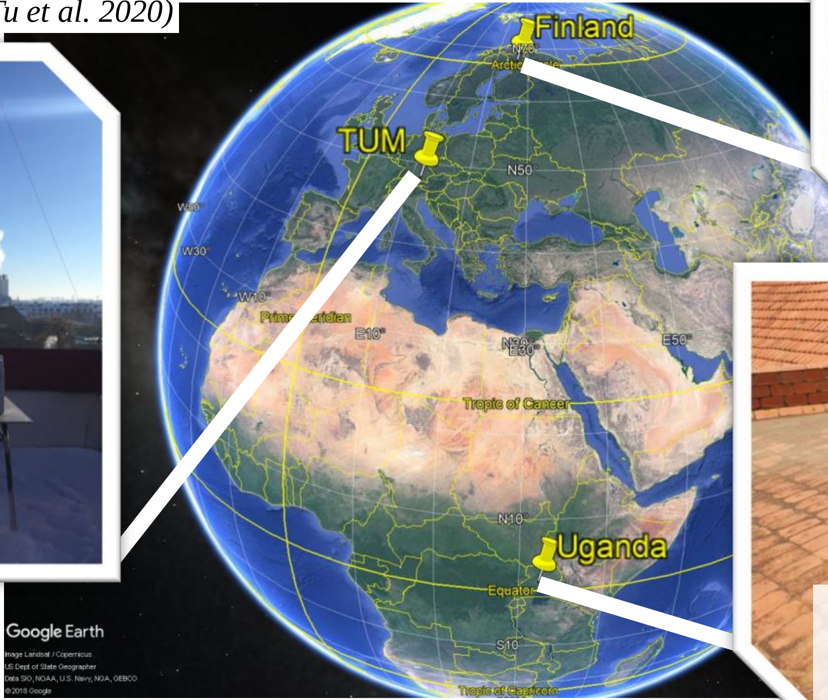


→ Our system reduces the personnel costs to a minimum and increases the amount of measurement data to a maximum

Heinle and Chen: *Automated Enclosure and Protection System for Compact Solar-Tracking Spectrometers. Atmos. Meas. Tech., 2018, https://doi.org/10.5194/amt-11-2173-2018*
Dietrich, Chen et al.: *MUCCnet: Munich Urban Carbon Column network. Atmos. Meas. Tech., 2021, https://doi.org/10.5194/amt-14-1111-2021*

International Sites of Our Automated System

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

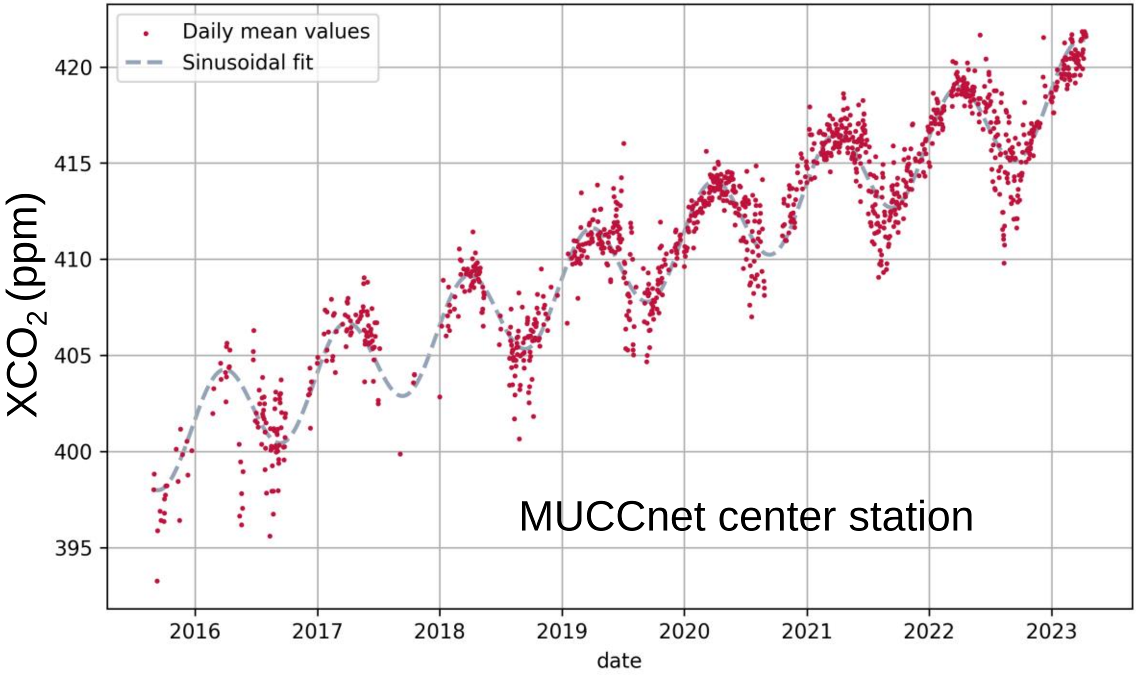


Satellite validation north of the polar circle (in collaboration with team **Frank Hase**)

Wetland CH_4 emissions. **First** column measurement in East-Africa (In collaboration with team **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*

Measurements (2015 – now)



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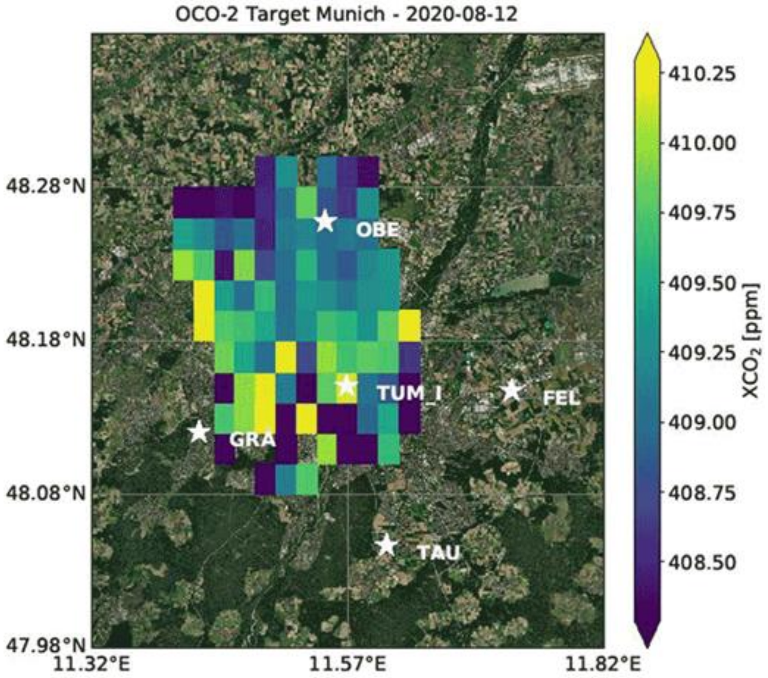
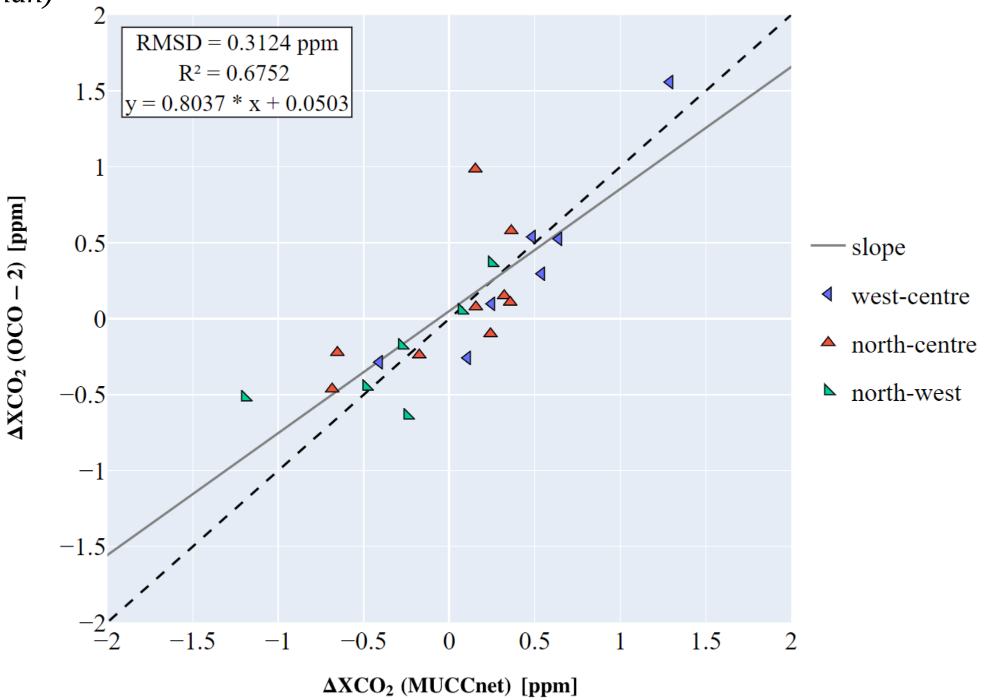
Satellite **Gradient** Validation using MUCCnet

(Rißmann et al. 2022 - in collaboration with M. Kiel and G. Osterman)

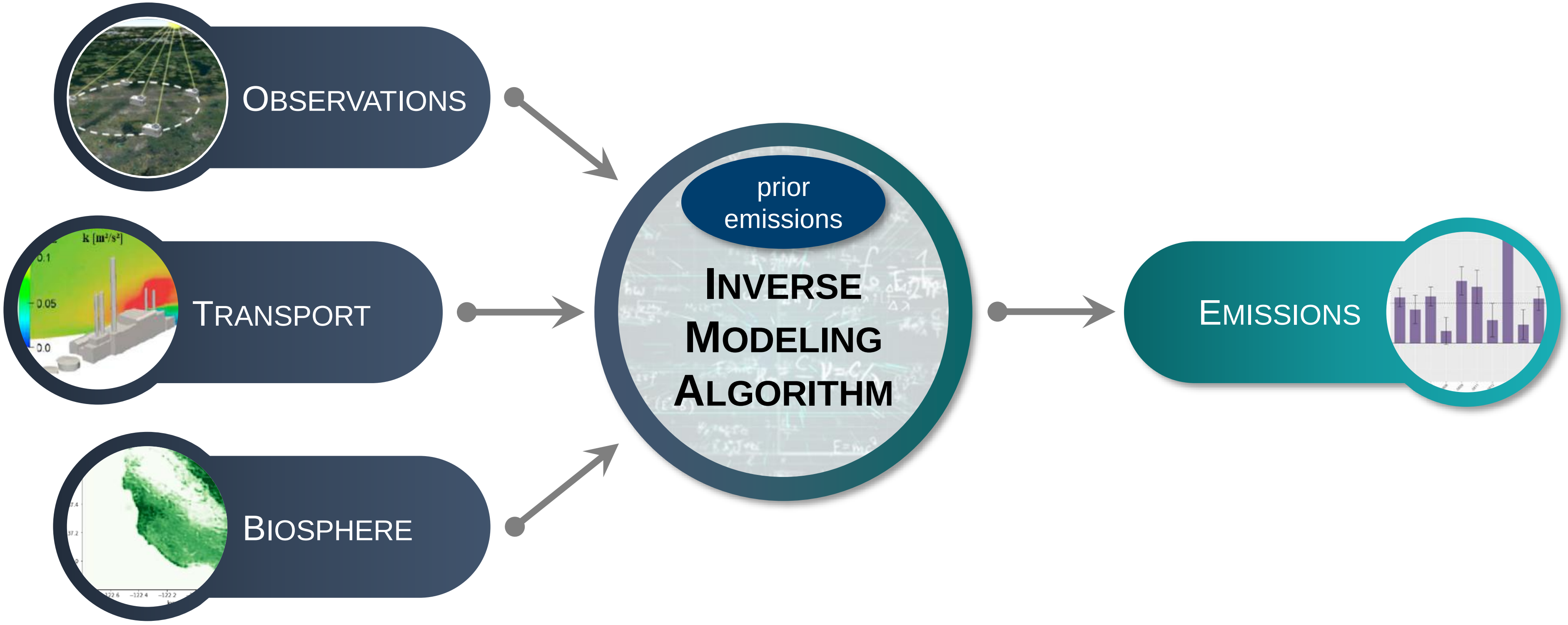




→ Strong correlation between gradient measured by MUCCnet and by satellite

Rißmann, Chen et al*: Comparison of OCO-2 target observations to MUCCnet - Is it possible to capture urban XCO2 gradients from space?, AMT, 2022*

Emission Monitoring



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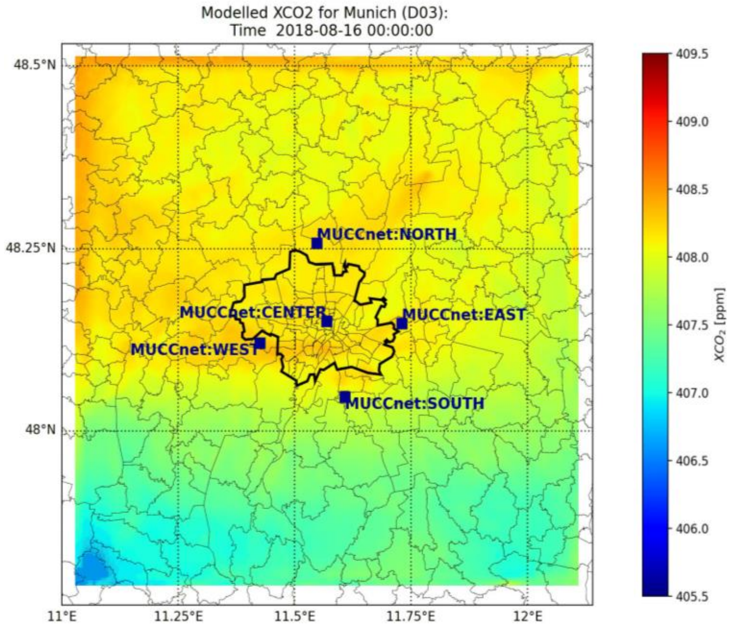
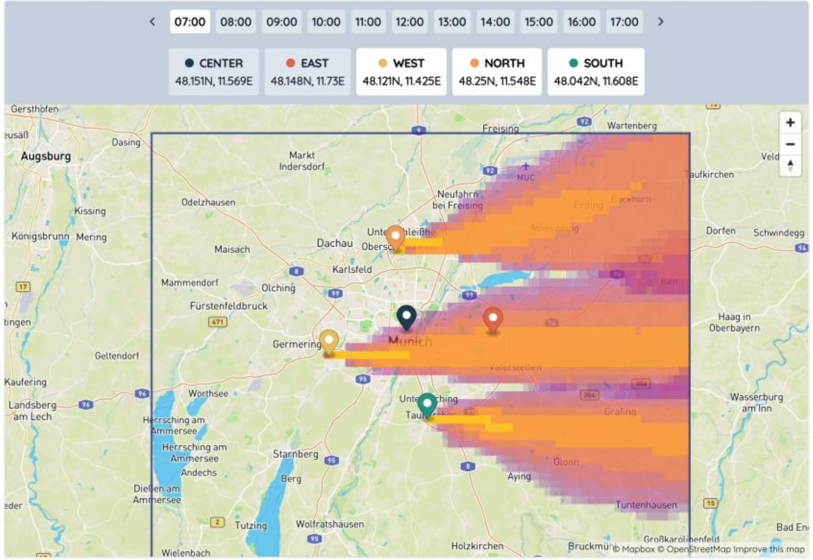
Automated Transport Modeling

(**WRF-GHG**, 400m)



Footprint simulation



Zhao, Chen et al.: *Understanding greenhouse gas (GHG) column concentrations in Munich using WRF, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2022-281, 2022.*

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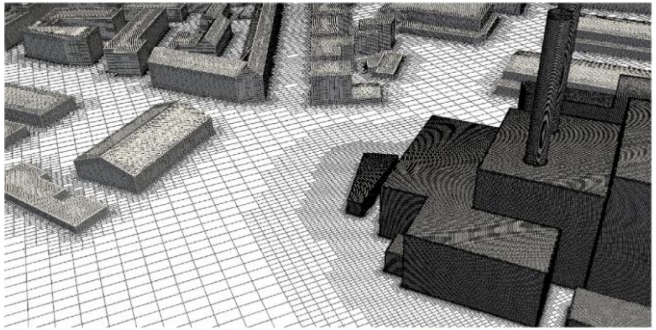
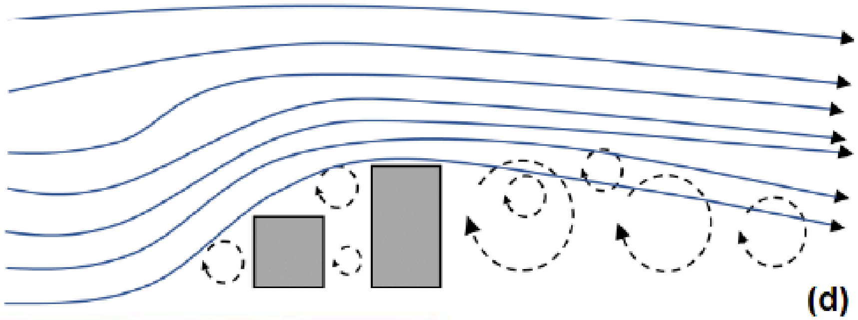
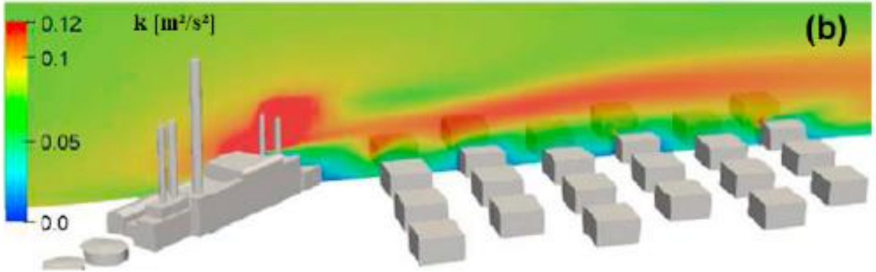
Computational Fluid Dynamics and Urban Geometry Generalization

Toja-Silva et al. (2017, 2018)







Optimizing:
Building density
Distribution
Height

→ Smart geometry building generalization to decrease computational costs while preserving accuracy

Toja-Silva et al.: *On the urban geometry generalization for CFD simulation of gas dispersion from chimneys: Comparison with Gaussian plume model. Journal of Wind Engineering and Industrial Aerodynamics (177), 2018, 1-18*

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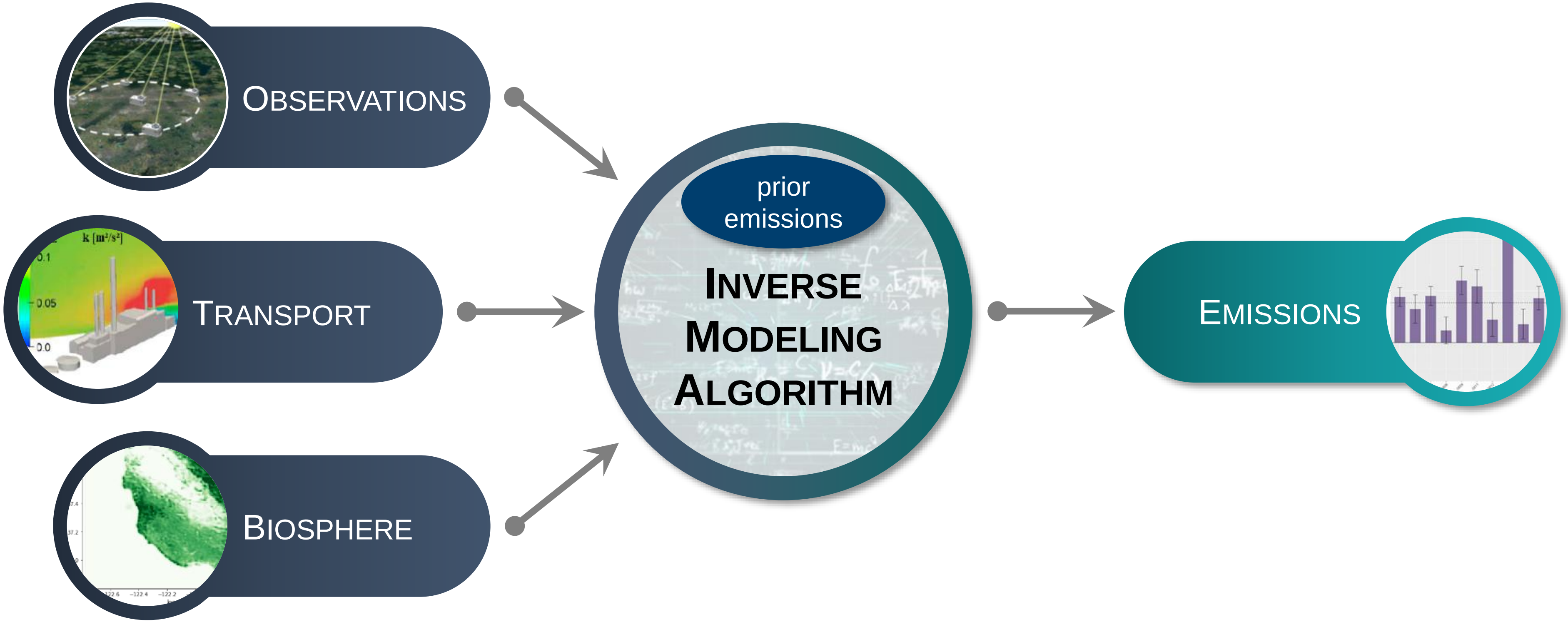
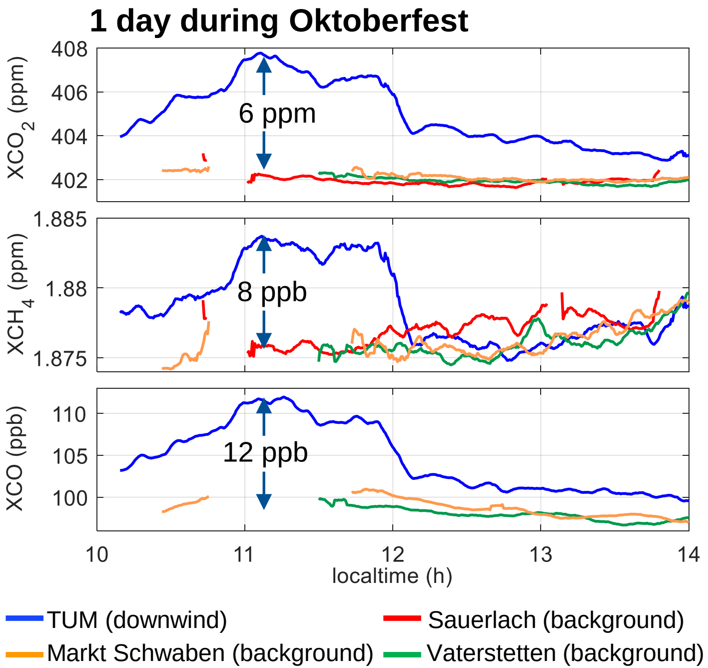
Emission Monitoring



Unknown Emission Sources



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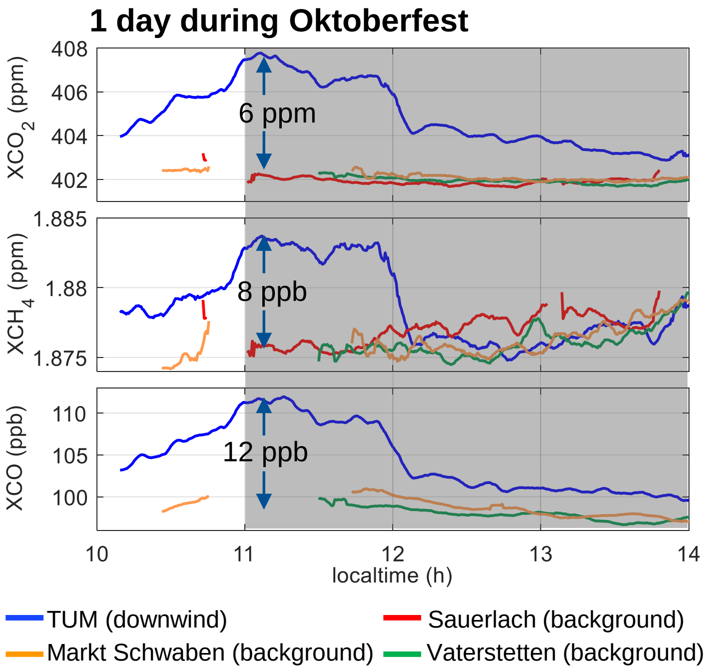
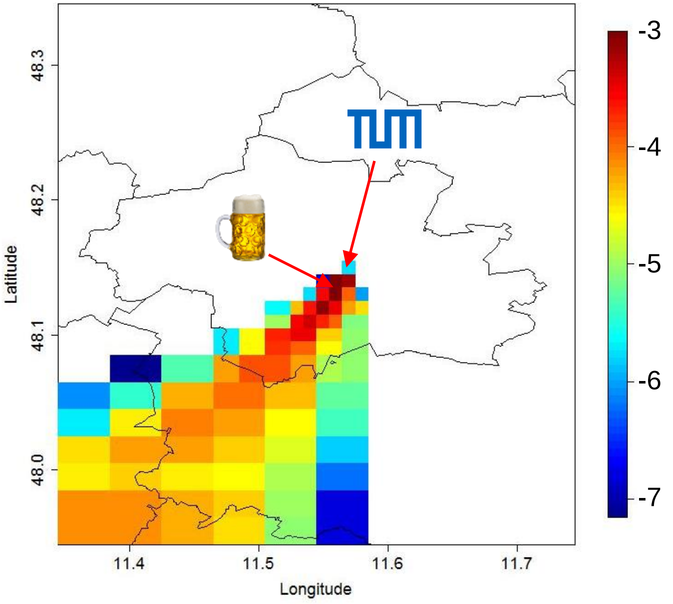


$$\log\left(footprint/\frac{ppm}{\frac{\mu mol}{m^2 \cdot s}}\right)$$



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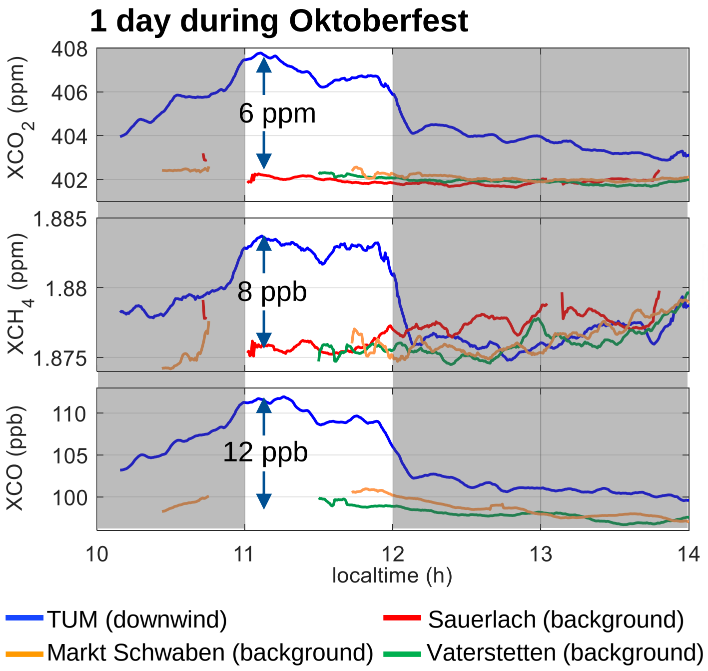
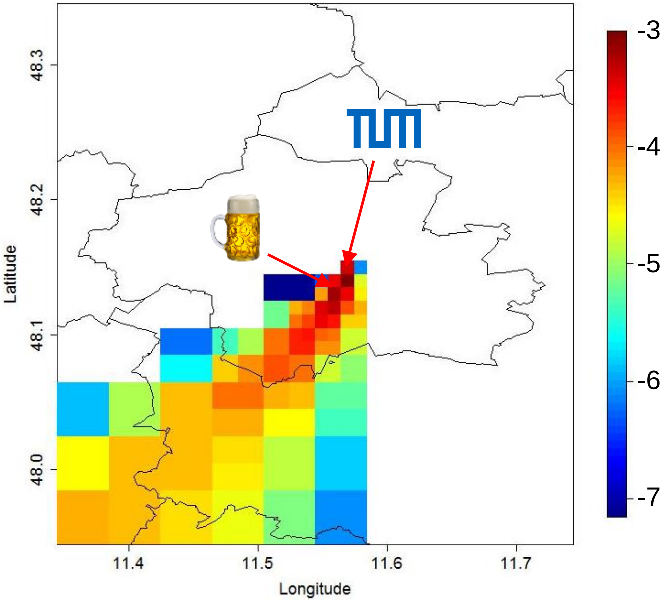
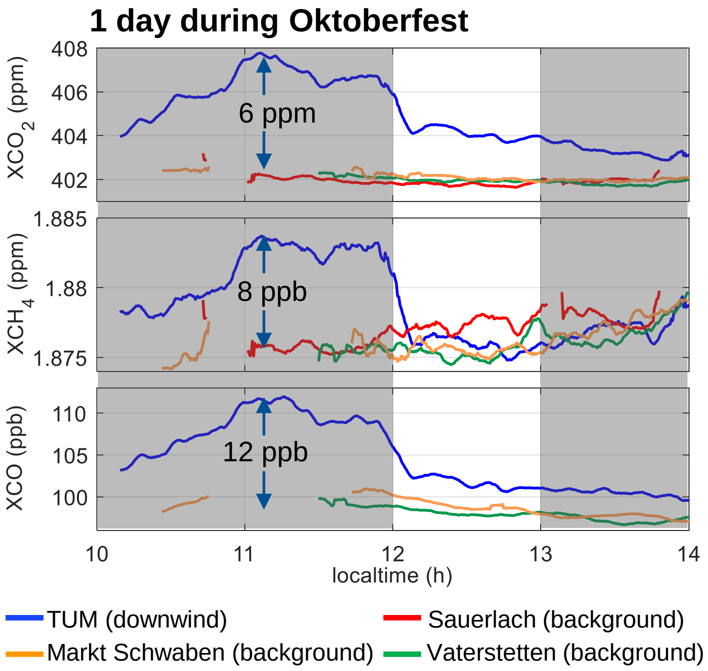


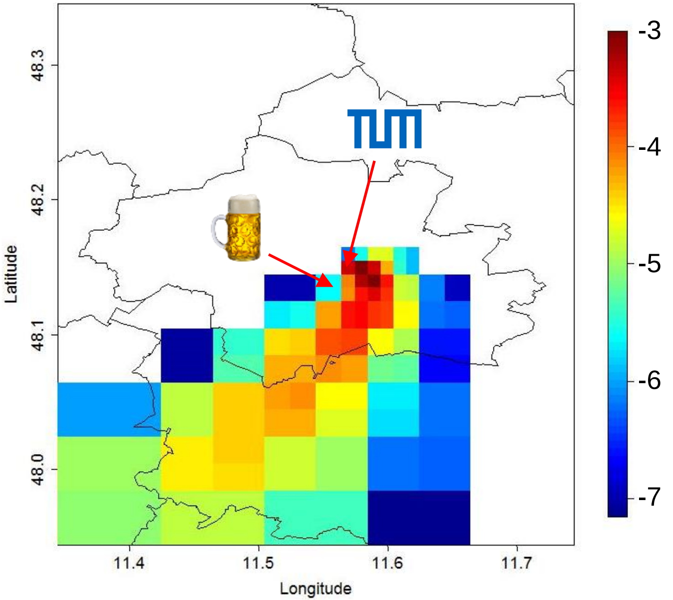
$$\log\left(footprint/\frac{ppm}{\frac{\mu mol}{m^2\cdot s}}\right)$$



Unknown Emission Sources

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





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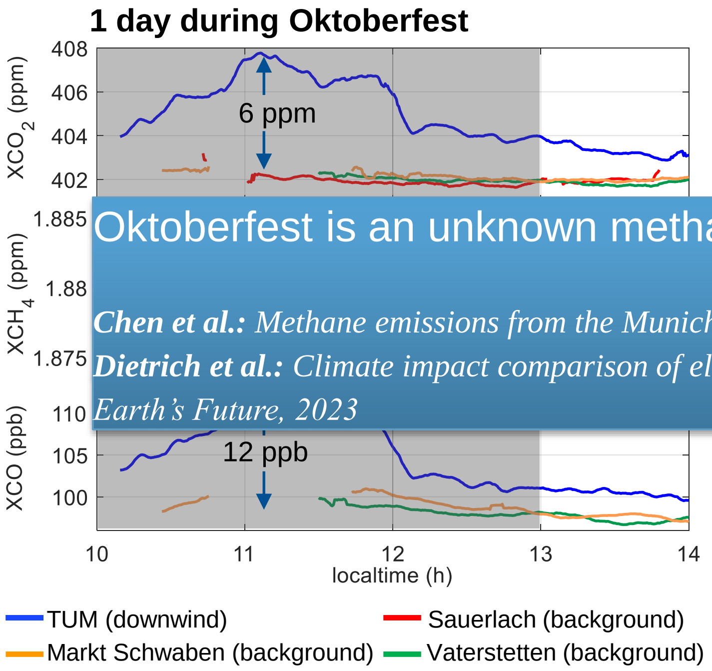
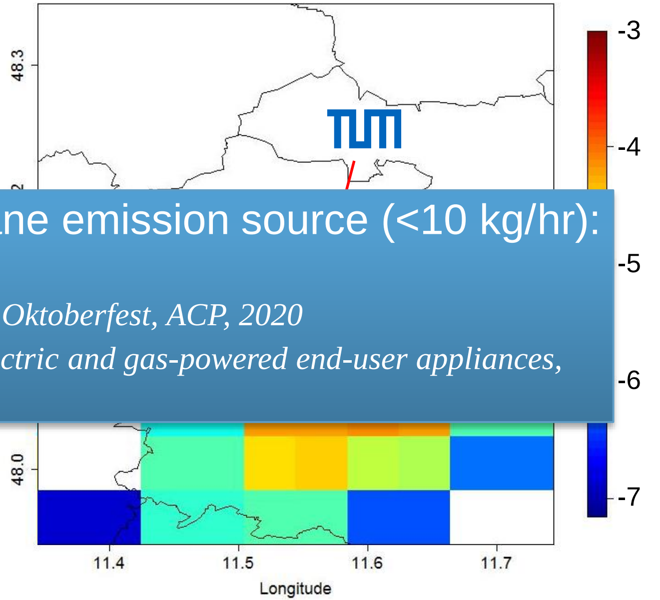
Unknown Emission Sources



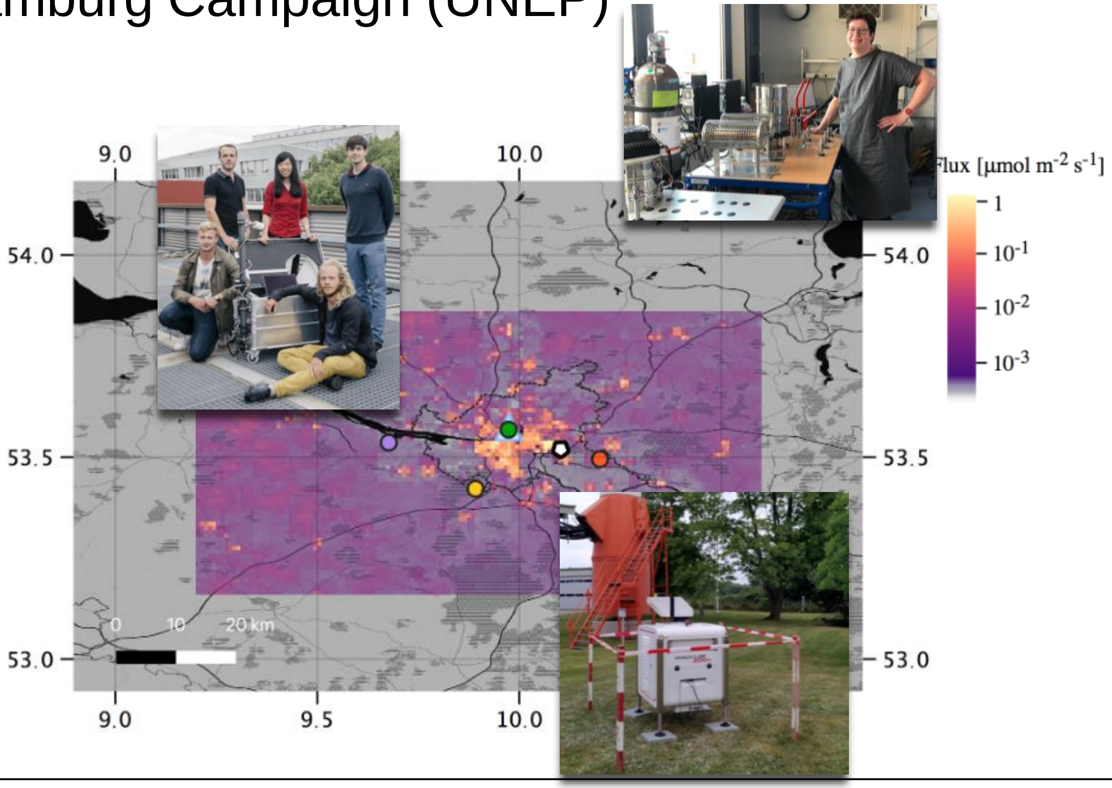
$$\log\left(footprint/\frac{ppm}{\frac{\mu mol}{m^2 \cdot s}}\right)$$



Oktoberfest is an unknown methane emission source (<10 kg/hr):

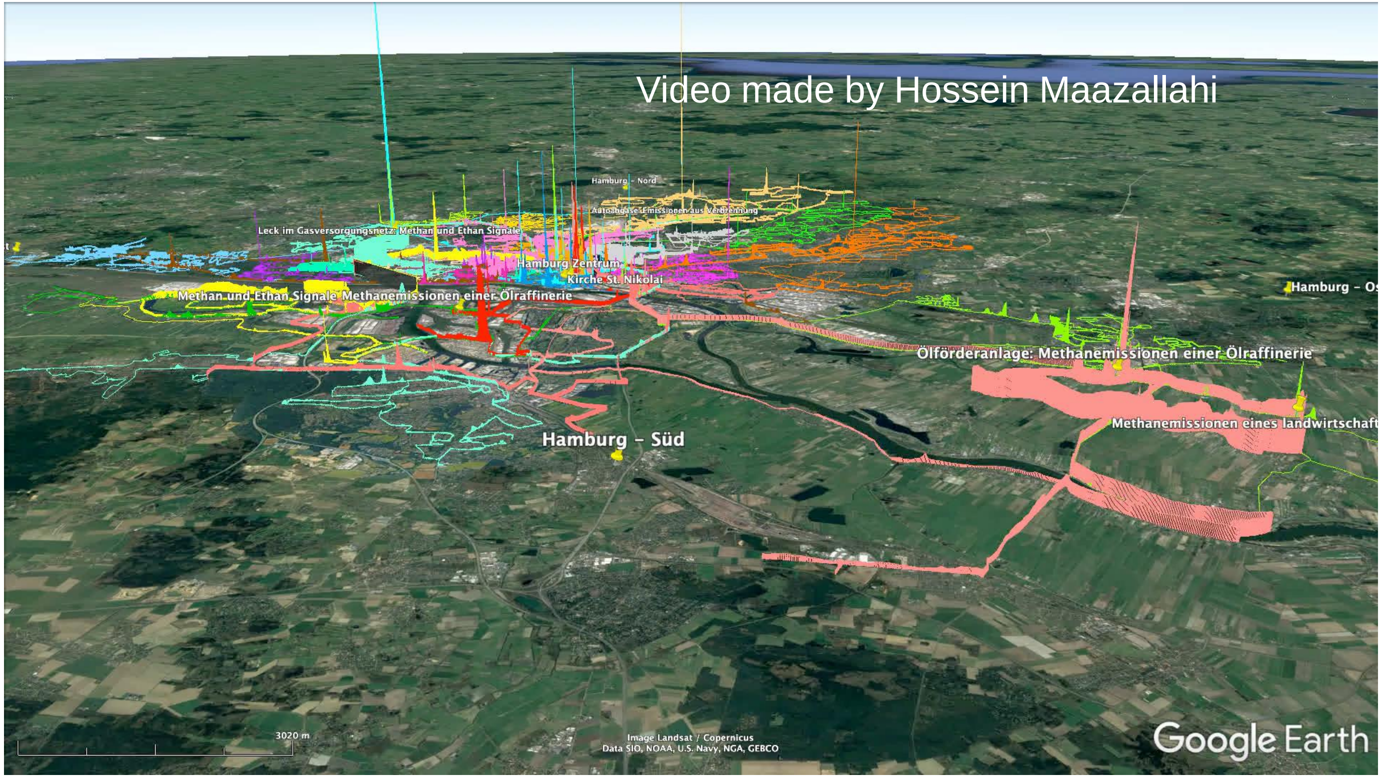
Chen et al.: *Methane emissions from the Munich Oktoberfest, ACP, 2020*
Dietrich et al.: *Climate impact comparison of electric and gas-powered end-user appliances, Earth's Future, 2023*

Hamburg Campaign (UNEP)

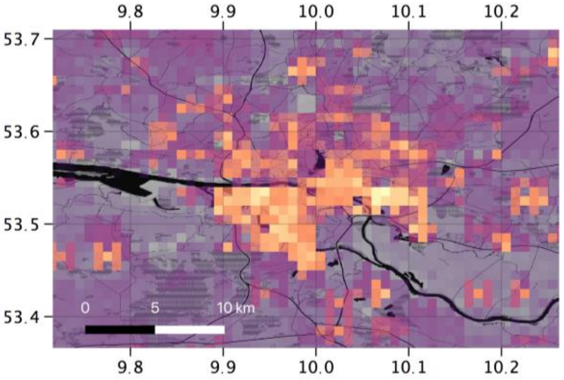


- **4 FTIR systems** around high emission zones in Hamburg
- 1 **LiDAR** system in city center captures 3D wind information → improving **transport modeling**
- **Isotope** measurement → **source attribution**
- **Mobile Measurements** → refining the **prior emission** inventory

Hamburg Campaign: Methane Sources

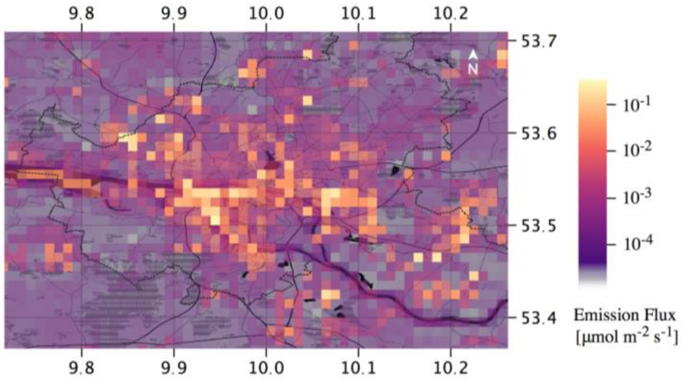


Improving an A-Priori Emission Inventory



Original emission inventory
(e.g. TNO GHGco)

Measurements
(e.g. using Picarro instruments)



Corrected emission inventory for inversion

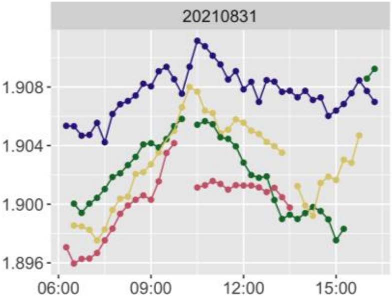
→ Correcting spatial distribution of emisison inventory
→ Adding the Elbe river and the associated wetlands

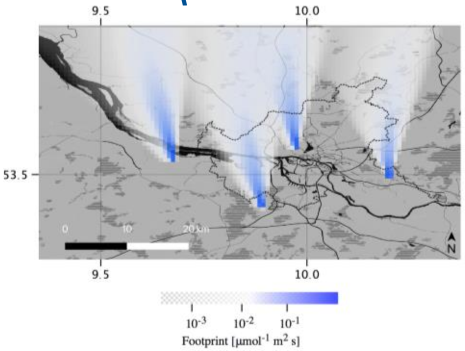
Forstmaier, Chen et al.*: Quantification of methane emissions in Hamburg using a network of FTIR spectrometers and an inverse modelling approach, accepted, ACP, 2023.*

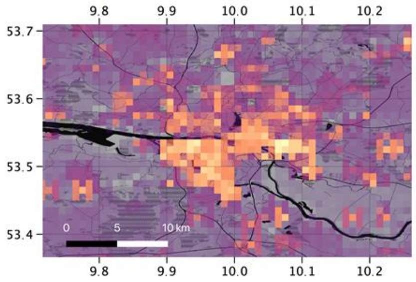
Bayesian Inversion

(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*

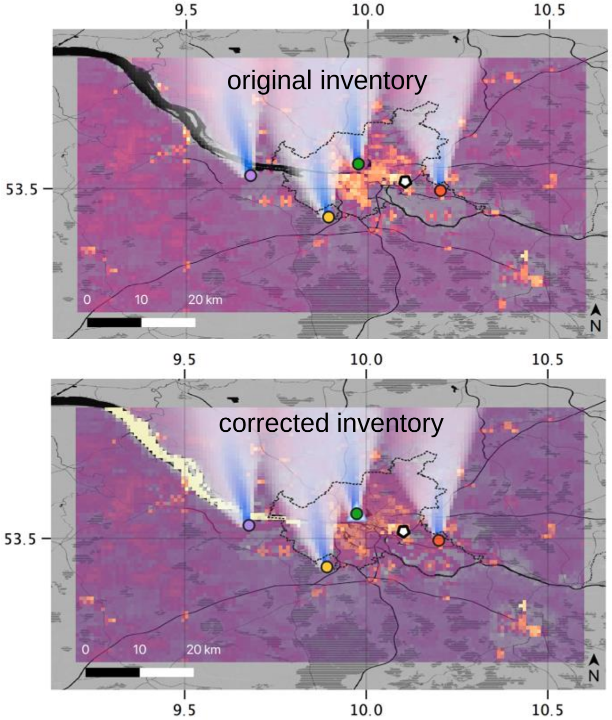
B: *background influence matrix*

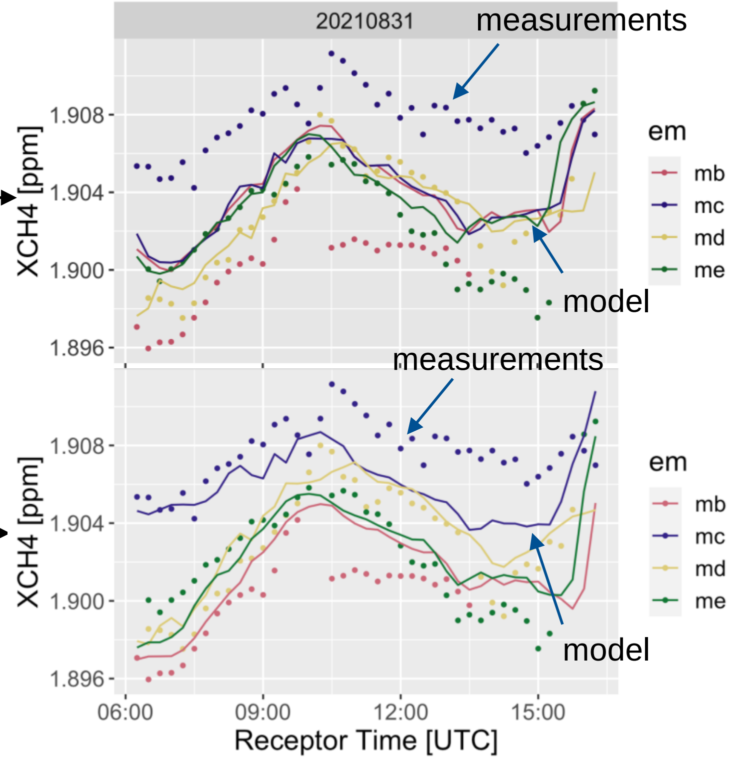
b: *background concentration*

S: *error covariance matrix*

Jones et al.: *Assessing Urban Methane Emissions using Column Observing Portable FTIR Spectrometers and a Novel Bayesian Inversion Framework, Atmos. Chem. Phys., 2021, https://doi.org/10.5194/acp-21-13131-2021*

Updated Emission Inventory → Improved Inverse Modeling Results

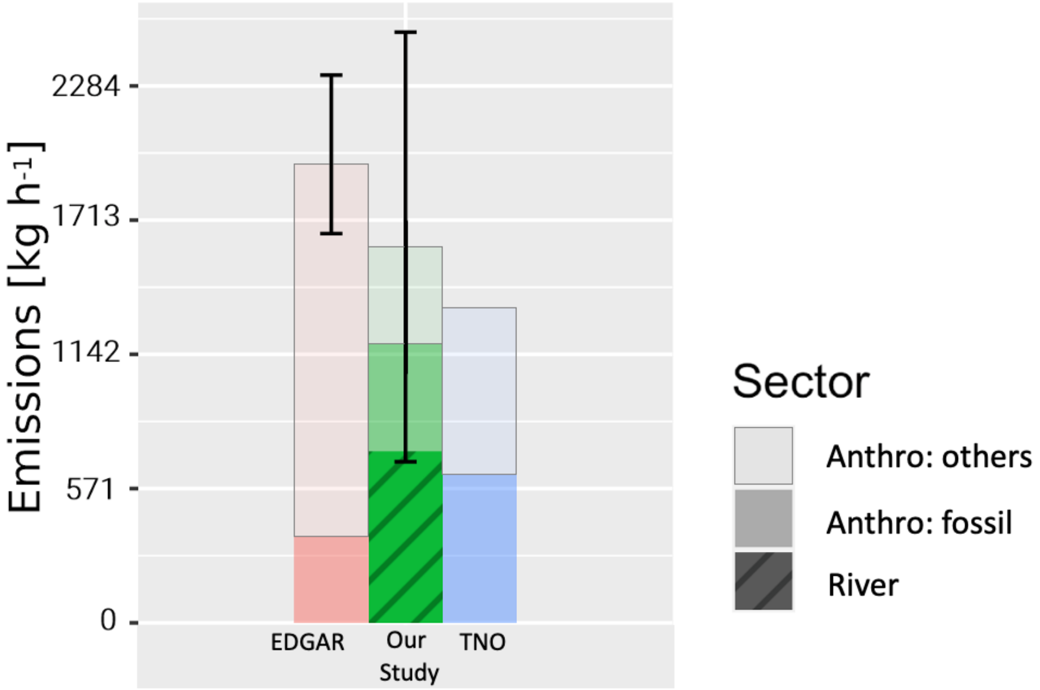




***Forstmaier, Chen et al.**: Quantification of methane emissions in Hamburg using a network of FTIR spectrometers and an inverse modelling approach, accepted, ACP, 2023.*

Hamburg Campaign – Results

(Forstmaier et al. 2023)



Forstmaier, Chen et al.: *Quantification of methane emissions in Hamburg using a network of FTIR spectrometers and an inverse modelling approach, accepted, ACP, 2023.*

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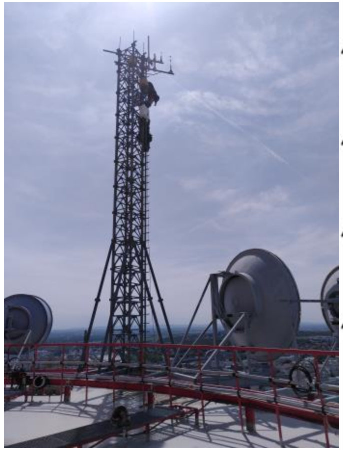
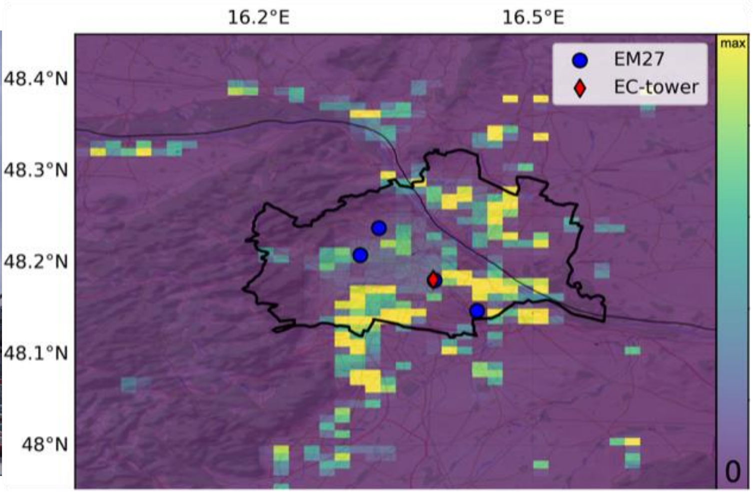
Vienna Campaign (colab. with ViennaUrbanCarbonLaboratory)



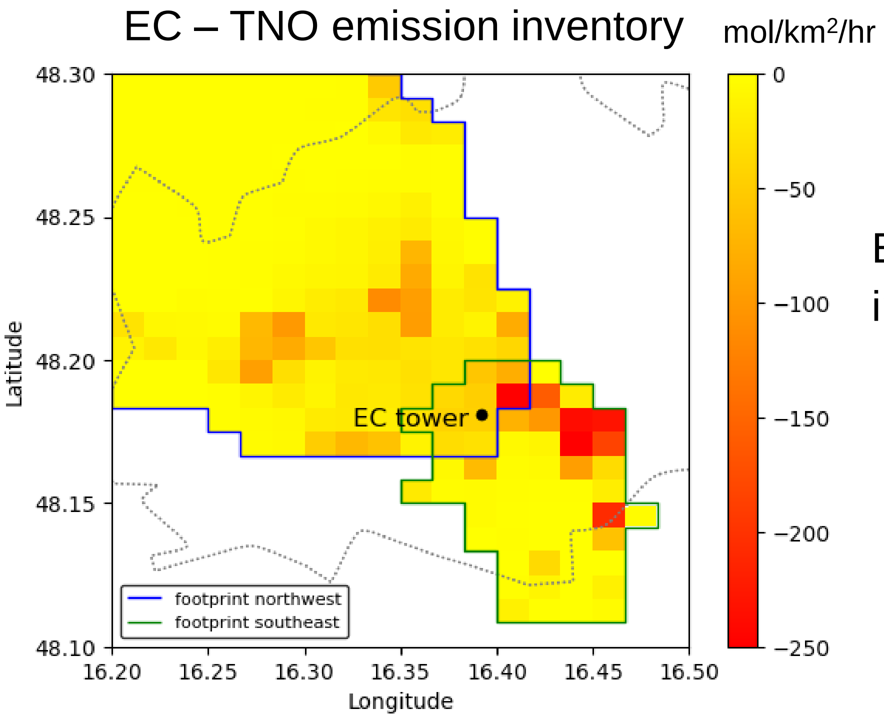


Combining total column and EC-tower measurements

4 FTIR @ 4 locations
and one tower at Arsenal

***Luther et al.**: MUCCnet visiting Vienna: refining inverse model prior information with tall-tower flux measurements, EGU General Assembly 2023, EGU23-15369*

EC Measurements for Prior Correction

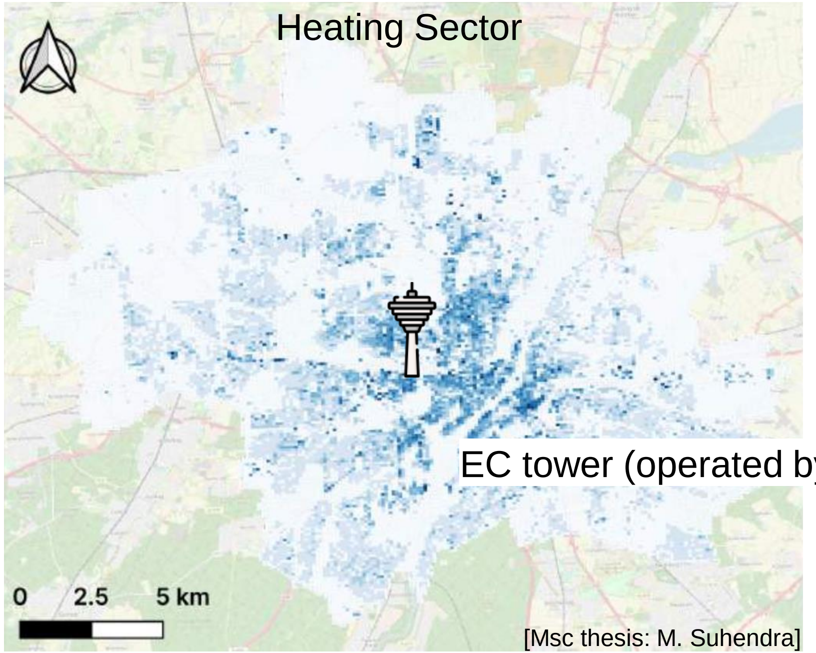


EC sees much less emission in southeast

EC data provided by B. Matthews/E. Fasano (BOKU)

Munich High Resolution Bottom-up Emission Inventory (100m, 1hr)

(In collaboration with TNO)

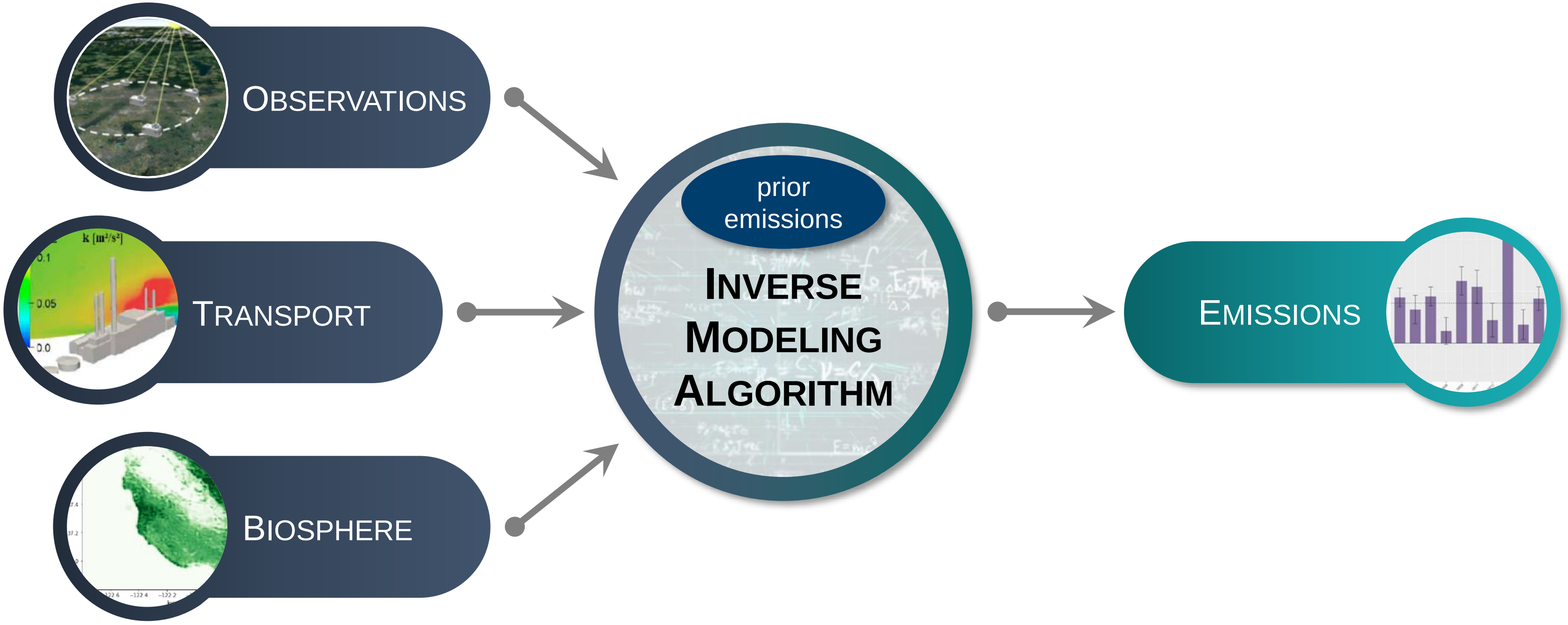


EC tower (operated by KIT) to improve the prior

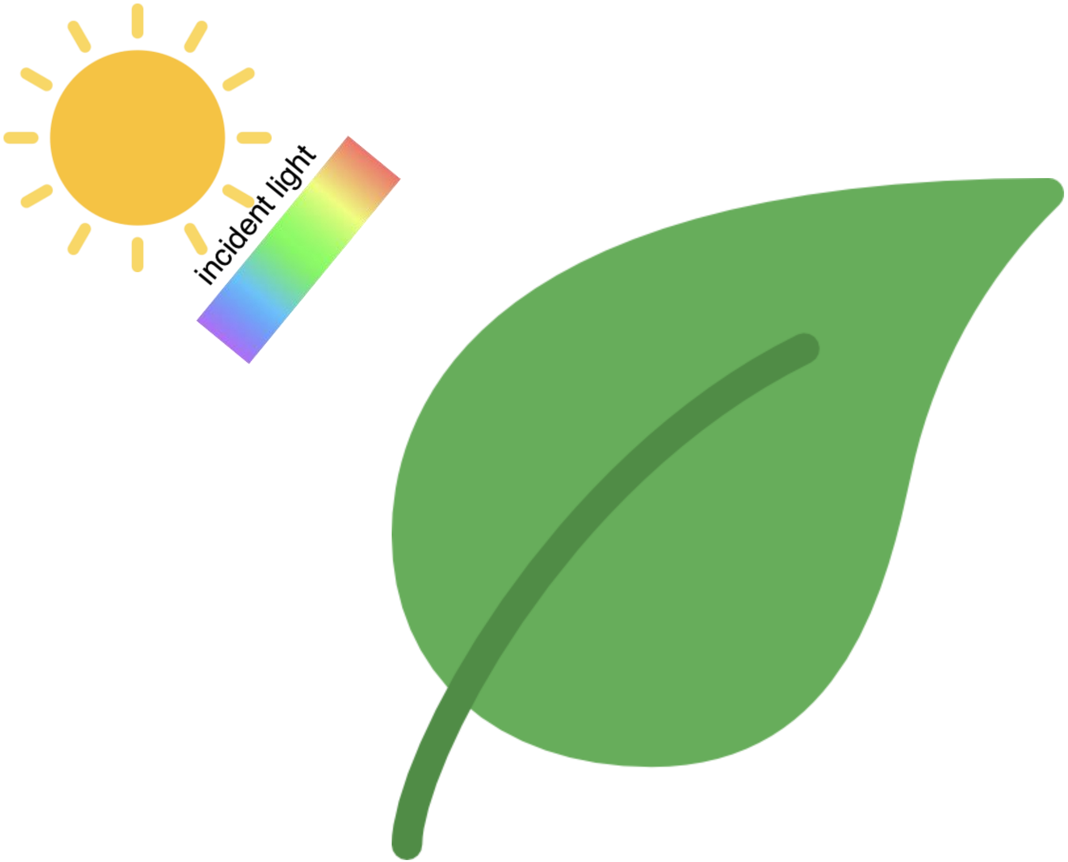
Aigner et al.: *CO_2 bottom-up emission inventory based on municipal power generation and heating data in Munich, EGU General Assembly 2023, EGU23-13451*

Kühbacher et al.: *Bottom-up estimation of traffic emissions in Munich based on macroscopic traffic simulation and counting data, EGU General Assembly 2023, EGU23-12997*

Emission Monitoring

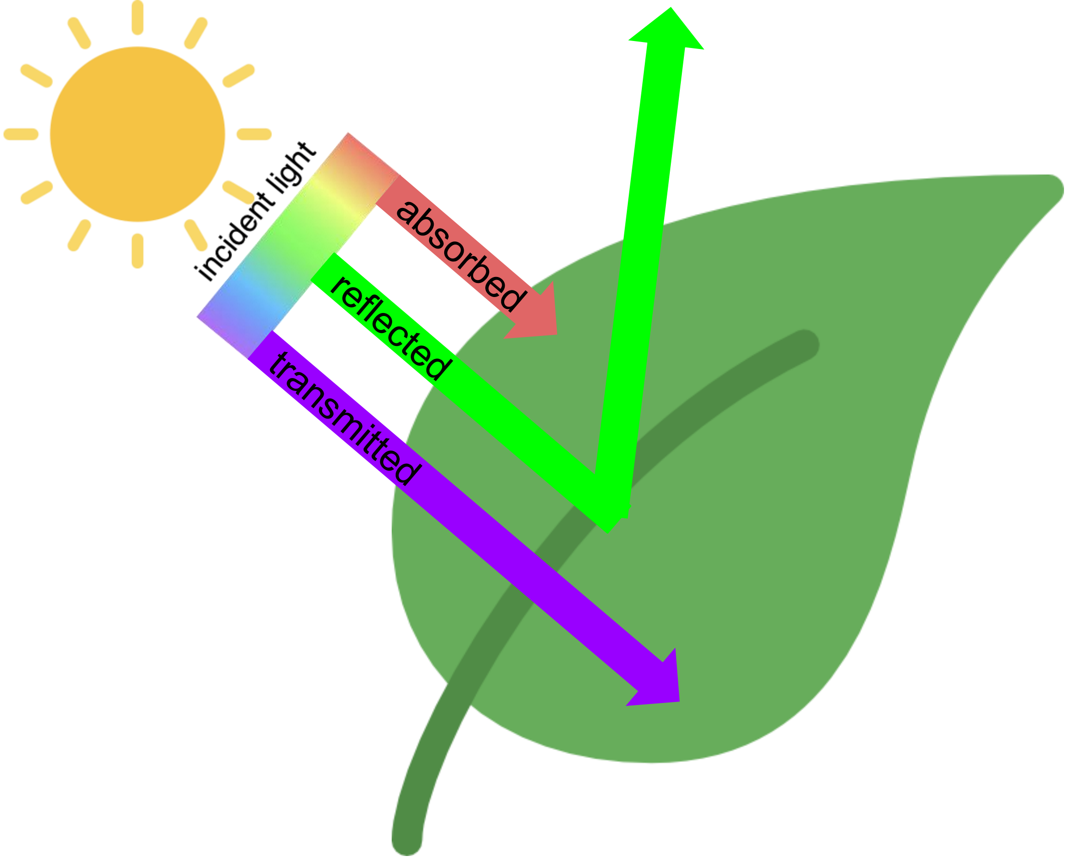


Photosynthesis

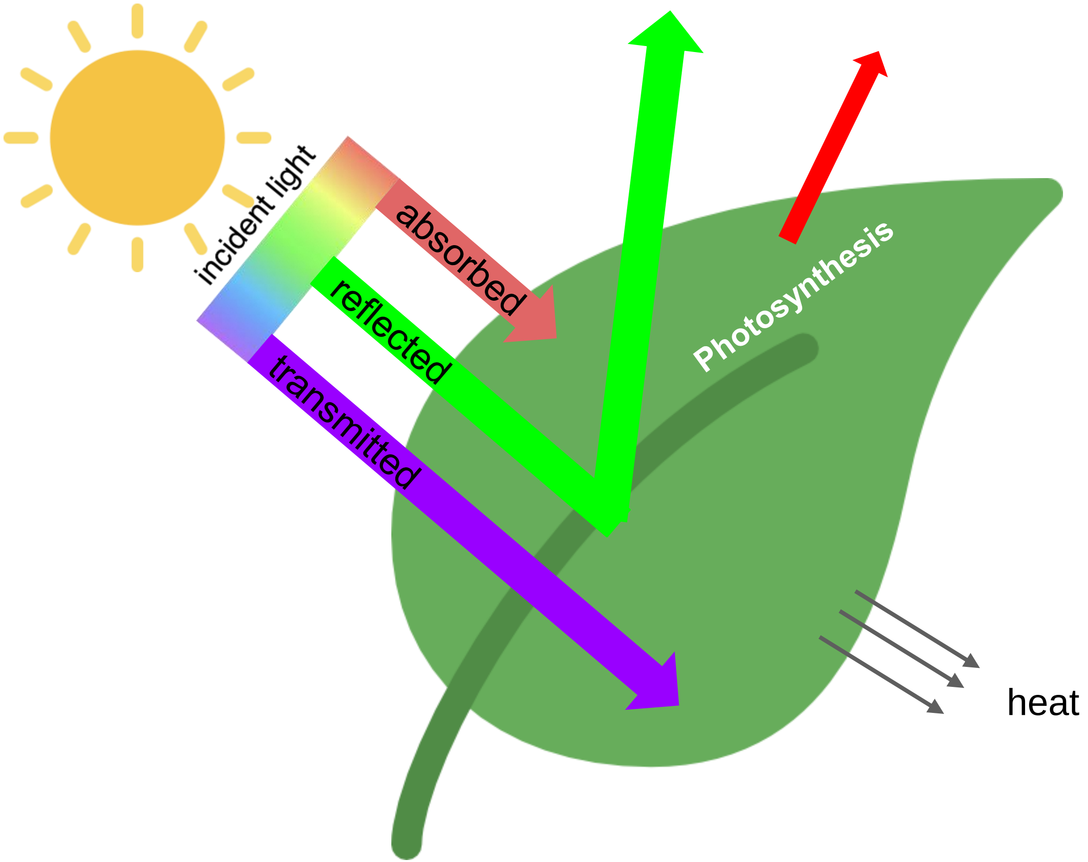


Slide by J. Gensheimer

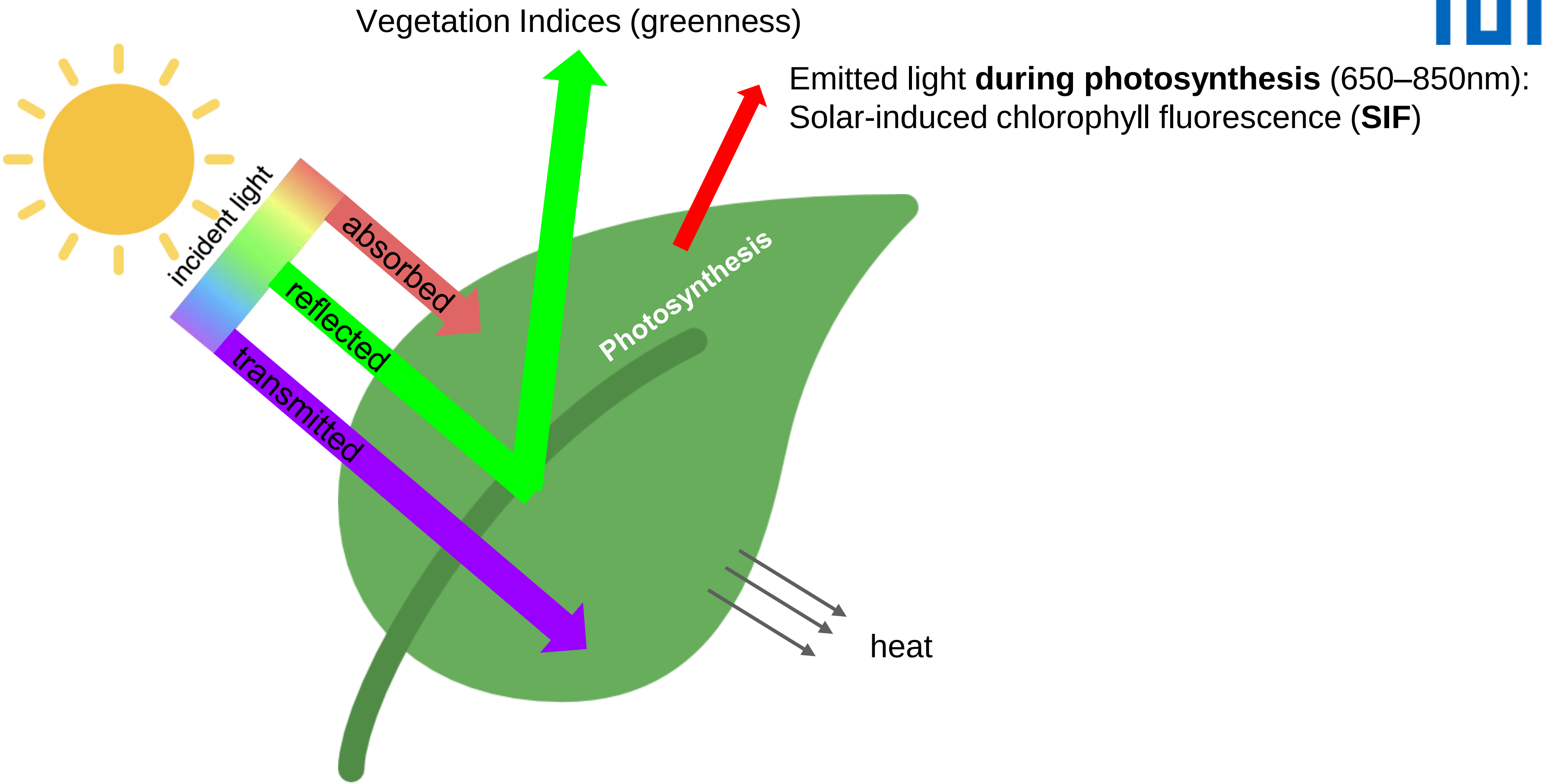
Photosynthesis



Slide by J. Gensheimer

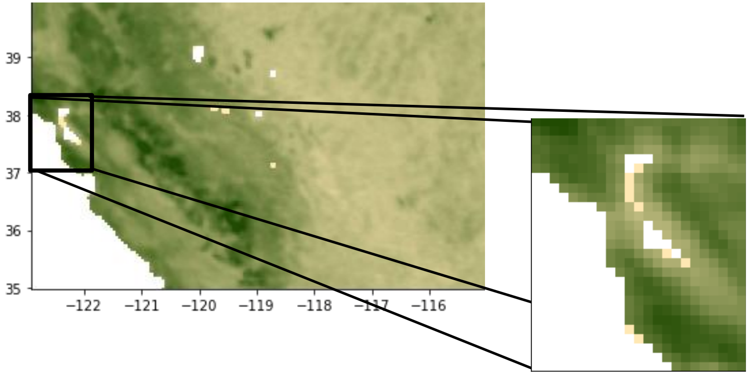


Slide by J. Gensheimer


Vegetation Indices (greenness)
Emitted light **during photosynthesis** (650–850nm):
Solar-induced chlorophyll fluorescence (**SIF**)
incident light
absorbed
reflected
transmitted
Photosynthesis
heat

TROPOMI SIF measurements

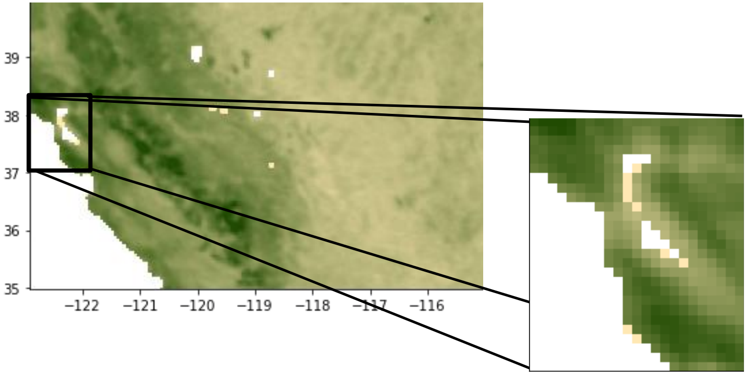
SIF@0.05°



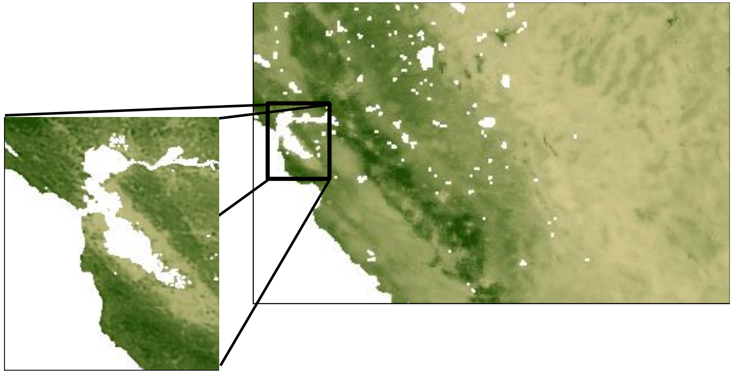
TROPOMI SIF measurements

<u>Goal:</u> Estimate SIF at 0.005° resolution (10 times finer)

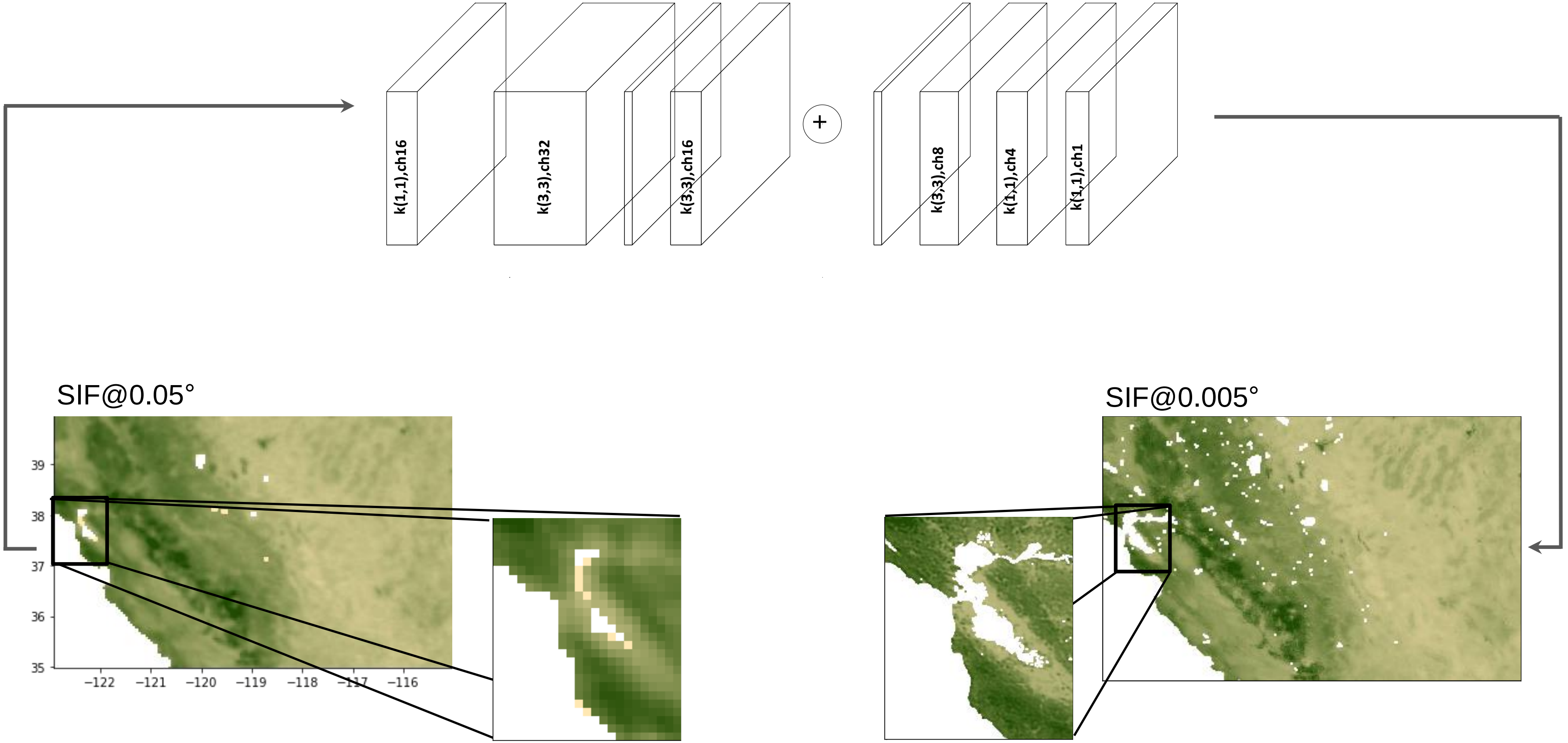
SIF@0.05°



SIF@0.005°



Convolutional Neural Network



Slide by J. Gensheimer

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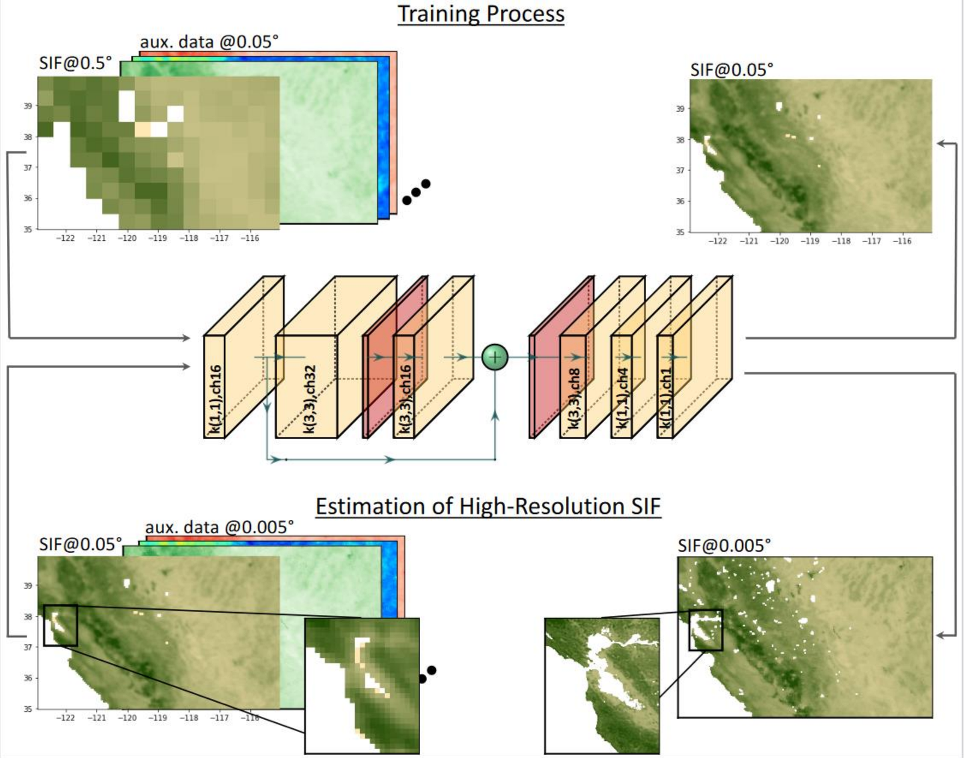
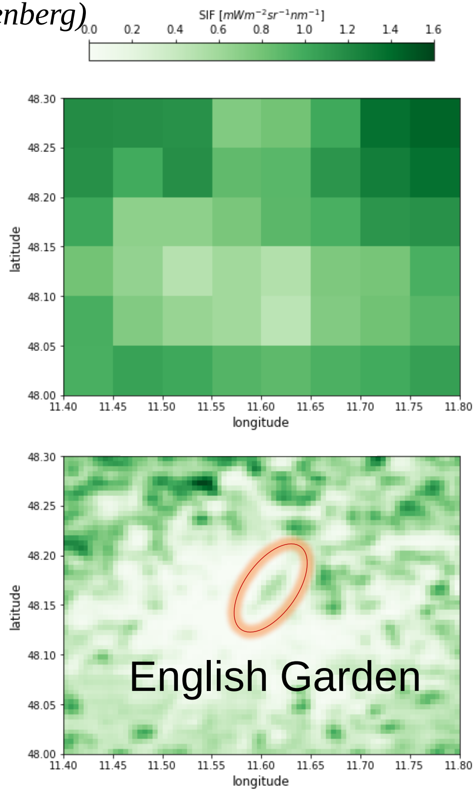
SIFnet: Super-Resolution Convolutional Neural Network for SIF

(Gensheimer et al., 2022 – In collaboration with A. Turner and C. Frankenberg)





Munich

Google Earth Scene

Gensheimer et al.: *A Convolutional Neural Network for Spatial Downscaling of Satellite-Based Solar-Induced Chlorophyll Fluorescence (SIFnet), Biogeosciences, https://doi.org/10.5194/bg-19-1777-2022, 2022*

Munich Greenhouse Gas Observation Landscape in 2015

Munich Greenhouse Gas and Air Quality Landscape Today

- Multiscale measurements
- Combining greenhouse gas and air pollutant measurements

Munich Greenhouse Gas and Air Quality Landscape 2019

- 5 MUCCnet station

Munich Greenhouse Gas and Air Quality Landscape 2020

- 5 MUCCnet station
- OCO target mode

Munich Greenhouse Gas and Air Quality Landscape 2021

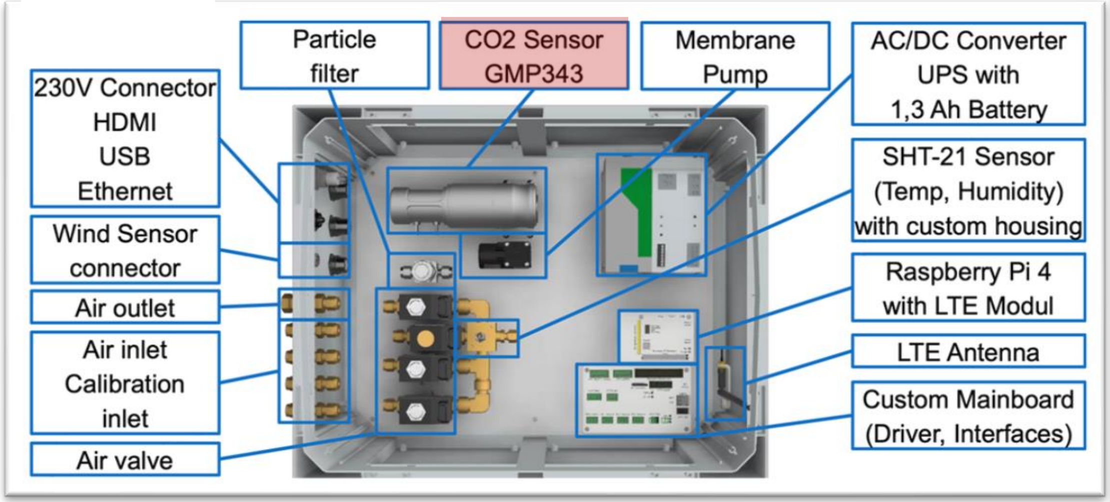
- 5 MUCCnet station
- OCO target mode
- 100m, 1hr emission inventory

Munich Greenhouse Gas and Air Quality Landscape Today

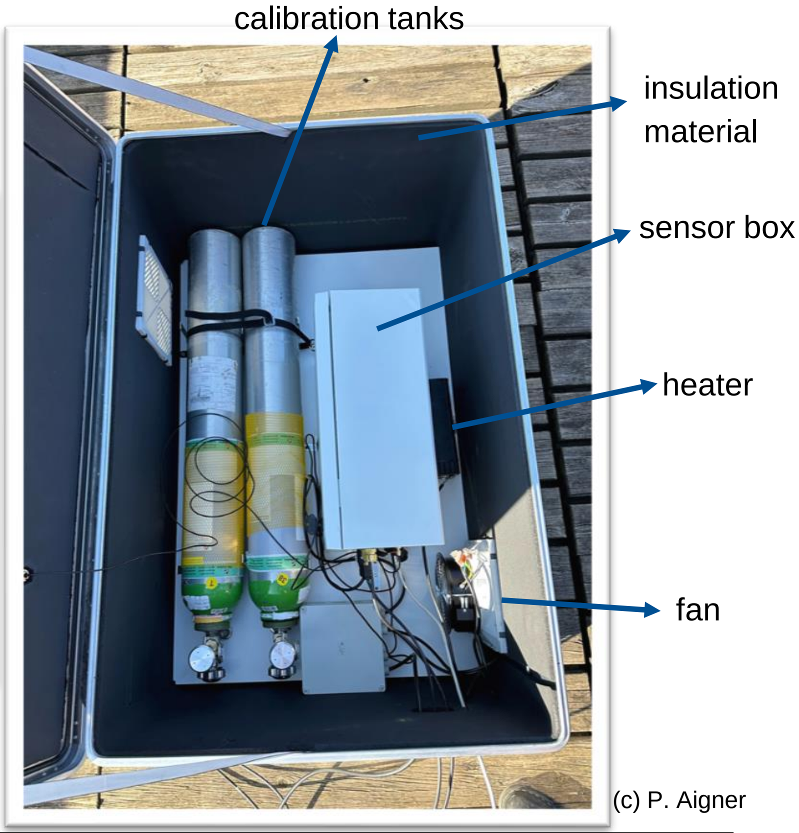
- 5 MUCCnet station
- OCO target mode
- 100m, 1hr emission inventory
- 20 mid-cost CO_2 sensors

Mid-Cost Sensor System

NDIR



[Msc thesis: A. Schmitt]

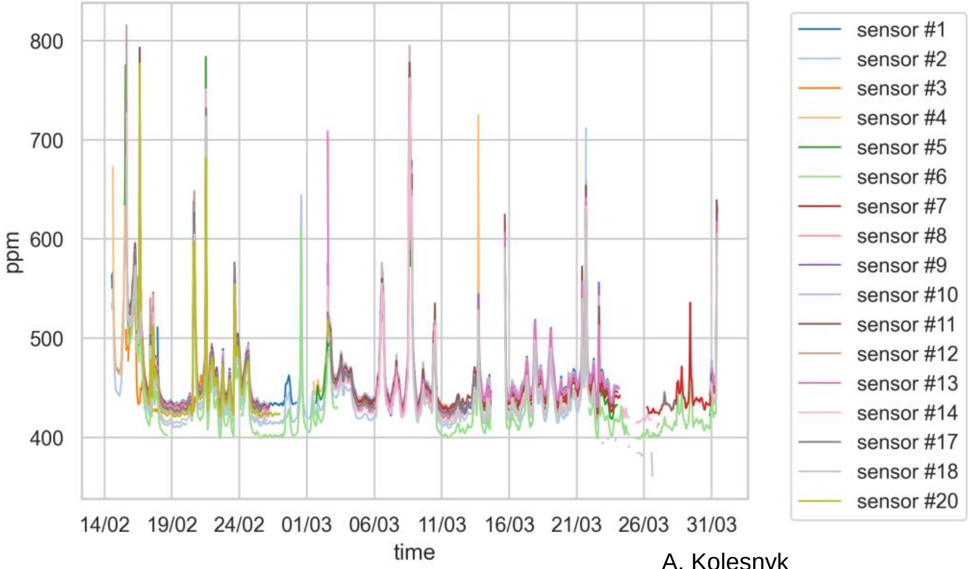


(c) P. Aigner

Mid-Cost Sensor System

(c) P. Aigner

1.5 months lab test



A. Kolesnyk

Munich Greenhouse Gas and Air Quality Landscape Today

- 5 MUCCnet station
- OCO target mode
- 100m, 1hr emission inventory
- 20 mid-cost CO_2 sensors
- 100 low-cost CO_2 sensors and 50 low-cost air quality sensors

Air Quality Sensors


(c) F. Dietrich

Side-by-side

Measure NOx, O_3, CO and PM

Calibration Unit


(c) A. Wenzel

Available positions for PhD and Postdoc
Please contact: jia.chen@tum.de