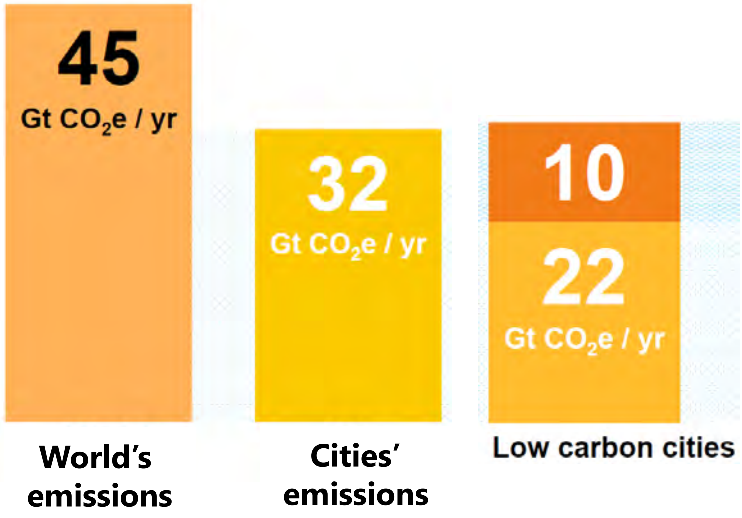
Monitoring the CO_2 emissions from cities using space-borne images of CO_2 and co-emitted species

Dominik Brunner[1]

with contributions by
Gerrit Kuhlmann[1], Julia Marschall[2], Yasjka Meijer[3], Grégoire Broquet[4], Michael Buchwitz[5], Max Reuter[5]

[1] Empa, Swiss Federal Laboratories for Materials Science and Technology, Switzerland
[2] Max Planck Institute for Biogeochemistry, Germany
[3] ESA ESTEC, the Netherlands
[4] Laboratoire des Sciences du Climat et de l'environnement, France
[5] Institute of Environmental Physics, University of Bremen, Germany

Empa Materials Science and Technology | CO2 Human Emissions | VERIFY



Cities account for ~70% of global CO_2 emissions and have a large reduction potential

Sources: IPCC, World Resources Institute, World Bank

Cities increasingly recognize responsibility for, and vulnerability to, climate change

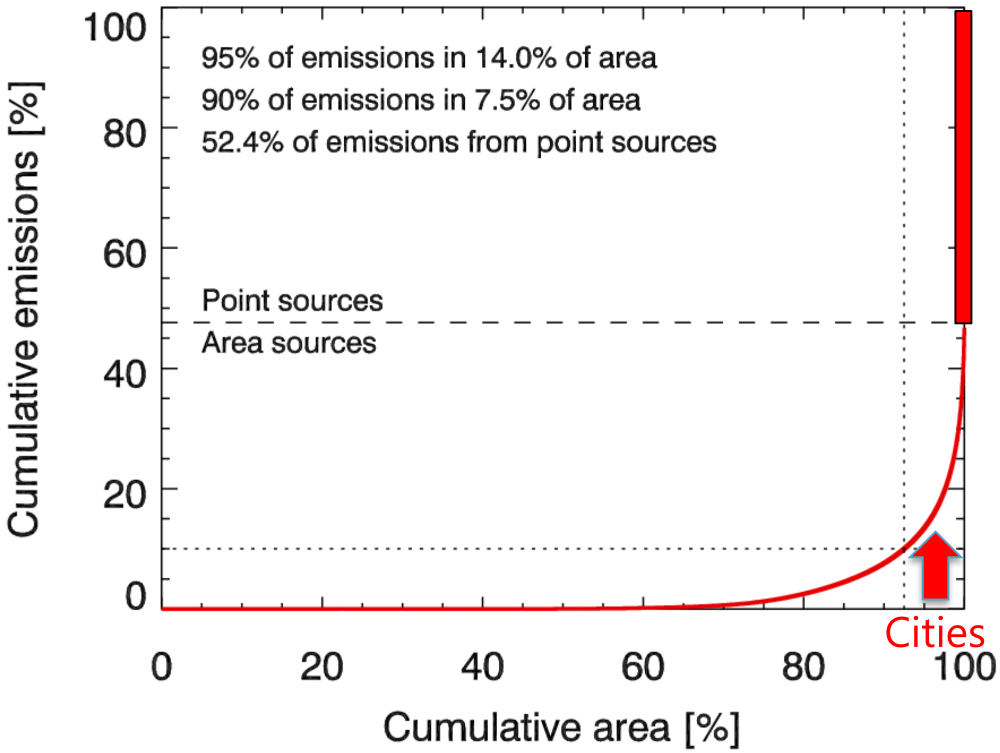
C40 CITIES

Covenant of Mayors
Committed to local sustainable energy

113 out of 164 submitted NDCs show clear urban references, stressing key role of cities in climate change mitigation

Why are we interested in CO_2 emissions from cities?

Cumulative CO_2 emissions vs. cumulative area over Europe, based on TNO/MACC-III inventory



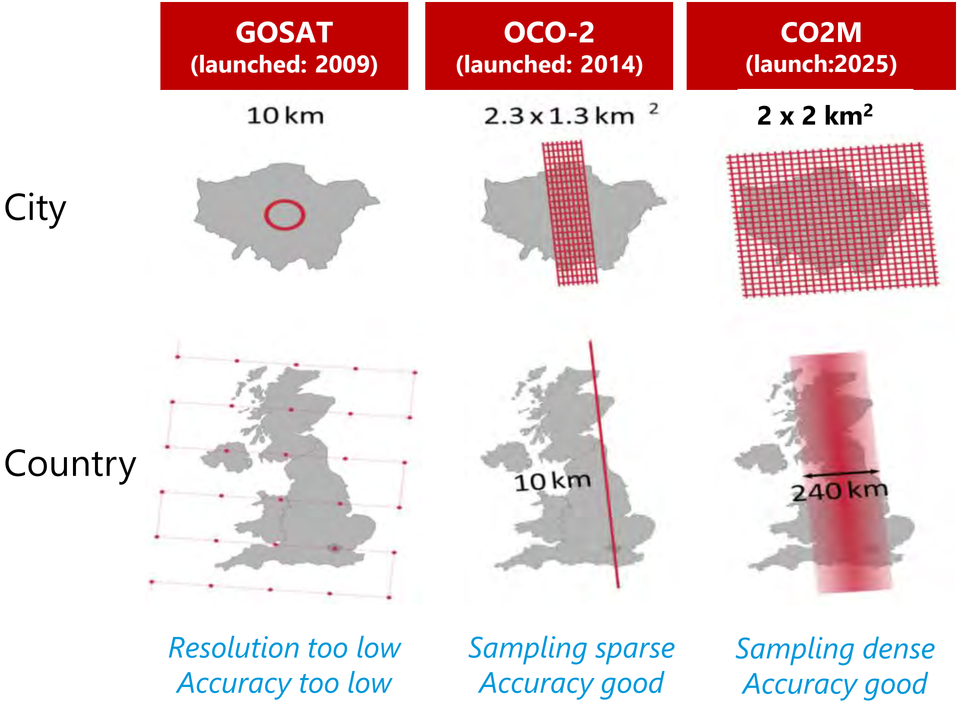
CO_2 emissions are concentrated on a small area:

- 90% emitted over less than 8% of area of Europe
- 52% from point sources, primarily power plants

Planned Sentinel-CO_2 satellite versus existing satellites

Future CO_2 satellite must have

- **Dense sampling**
  imaging of CO_2 plumes
- **High spatial resolution**
  capture emission hotspots and avoid clouds
- **High accuracy**
  because atmospheric column XCO_2 gradients are small
- **Global coverage**
  Support for Paris Agreement requires a global scope



Adadpted from Philippe Ciais,
presentation at CarbonSat UCM, 15-16 Sep 2015

Challenges for quantifying city CO_2 emissions from space

- XCO_2 enhancements in city plumes are weak and often close to detection limit
- Tradeoffs between swath width, pixel size and precision, i.e., tradeoffs between coverage, ability to resolve small-scale plumes, and SNR
- Detection of anthropogenic XCO_2 signal against variability in background and biospheric XCO_2
- Frequent cloud cover and other unfavorable meteorological conditions (e.g. very low or strong winds) preventing plume detection
- Temporal variability of source requires sufficient number of plume observations to build up a representative annual estimate
- Confounding signals from other sources, e.g. nearby power plants

Measurements of co-emitted species like NO_2 or CO may help with several of these points, e.g. distinction between anthropogenic and biospheric signals

Studies on city CO_2 emission quantification from satellites

ESA funded studies

- **LOGOFLUX** and **LOGOFLUX-2**: Scientific support study to evaluate the greenhouse gas surface flux estimate capabilities of the CarbonSat mission
- **SMARTCARB**: Study added benefit of NO_2 and CO satellite measurements for quantifying CO_2 emissions using high-resolution OSSEs
- **PMIF**: Investigate capability of Sentinel-CO_2 for quantifying emissions from clumps (e.g. cities) using simple, efficient Gaussian plume modeling
- **AEROCARB**: Study influence of aerosols on ability to retrieve XCO_2 in city plumes based on chemistry-transport simulations
- **CCFFDAS**: Translate mission specifications into uncertainty reductions in fossil fuel fluxes using Quantitative Network Design of a Carbon Cycle/Fossil Fuel Data Assimilation System

EU funded study

- **CHE**: Explores development of a European system to monitor human activity related CO_2 emissions

OSSE approach

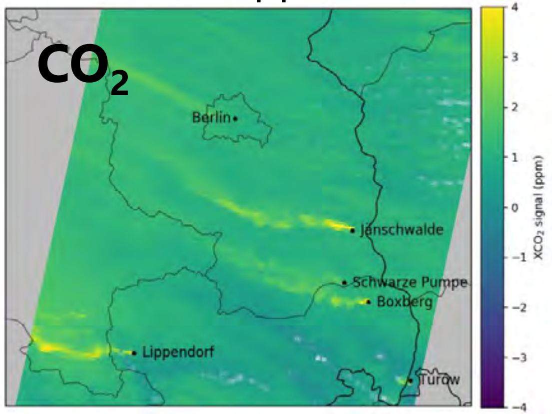
- High-resolution (1 km) simulations of atmospheric CO_2, NO_2 and CO simulations with COSMO-GHG model
- Synthetic observations of CO_2, CO and NO_2 using SRON orbit simulator and different instrument noise scenarios
- Quantification of emissions using analytical inversion applied to tagged tracers (e.g. tracer of CO_2 emitted from Berlin)
- Quantification using a data-driven approach based on plume detection algorithm and mass balance

Goals

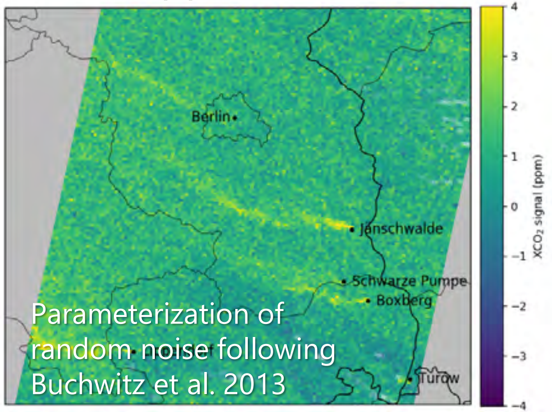
- How well can plumes be detected by different CO_2, NO_2, CO instruments?
- How well can emissions be quantified with or without measurements of co-emitted species NO_2 or CO?

Synthetic satellite observations

σ=0 ppm

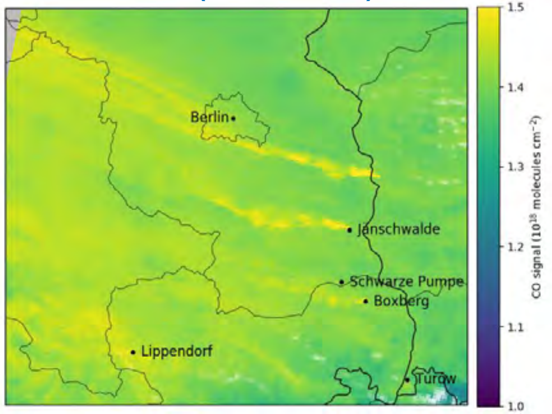


σ=0.5 ppm (low noise)

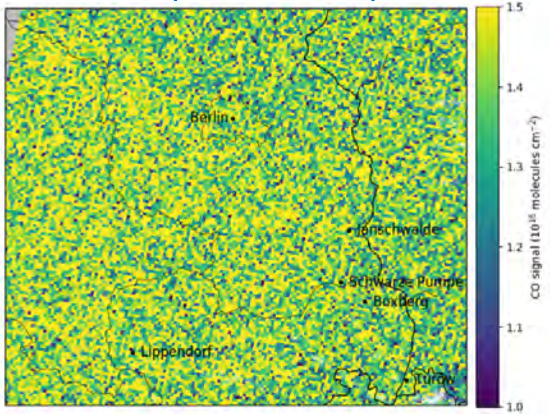


σ=1.0 ppm (high noise)

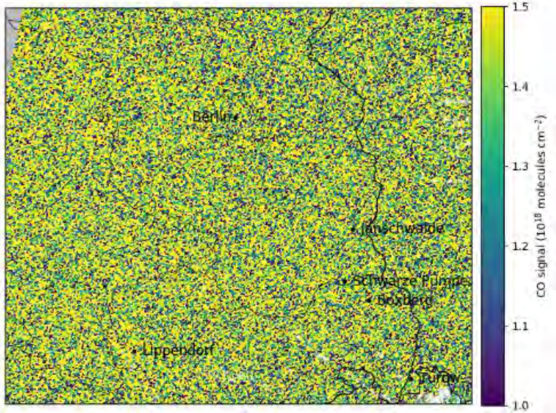
σ=0 molecule cm^{-2} / CO (no noise)



σ=1×10^{15} cm^{-2} / CO (10% noise)



σ=2×10^{15} cm^{-2} / CO (20% noise)



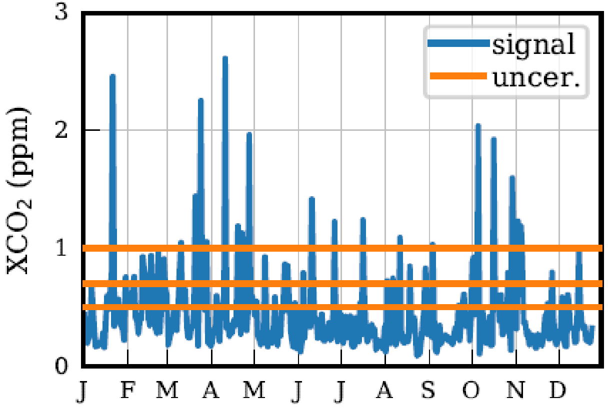
Detection of plumes against noise & background variability

Empa
Materials Science and Technology
CO2 Human Emissions
VERIFY

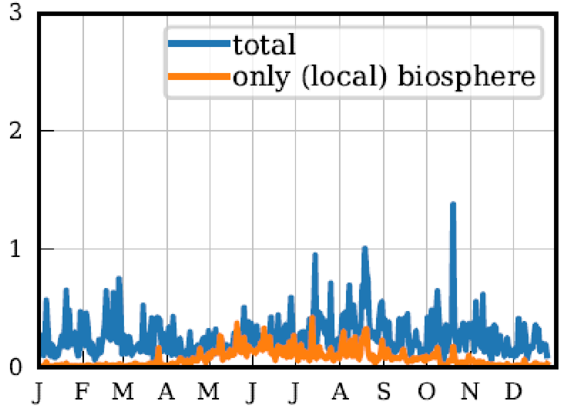
Berlin plume peak signal

Spatial variability of background

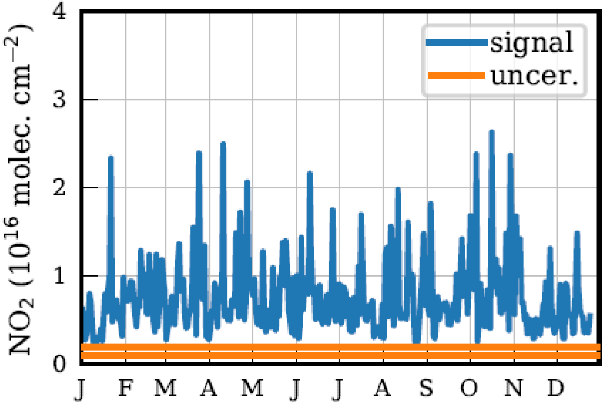
CO_2

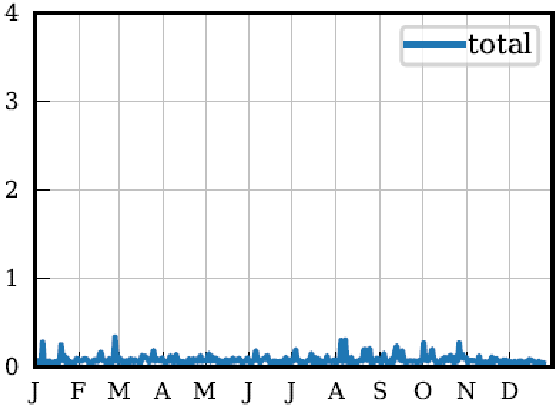


High noise
medium noise
low noise
instrument



NO_2

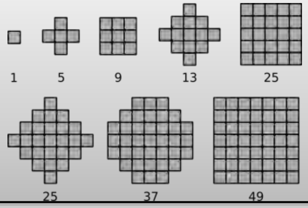




Plume detection example of 21 Apr 2015, 11 UTC

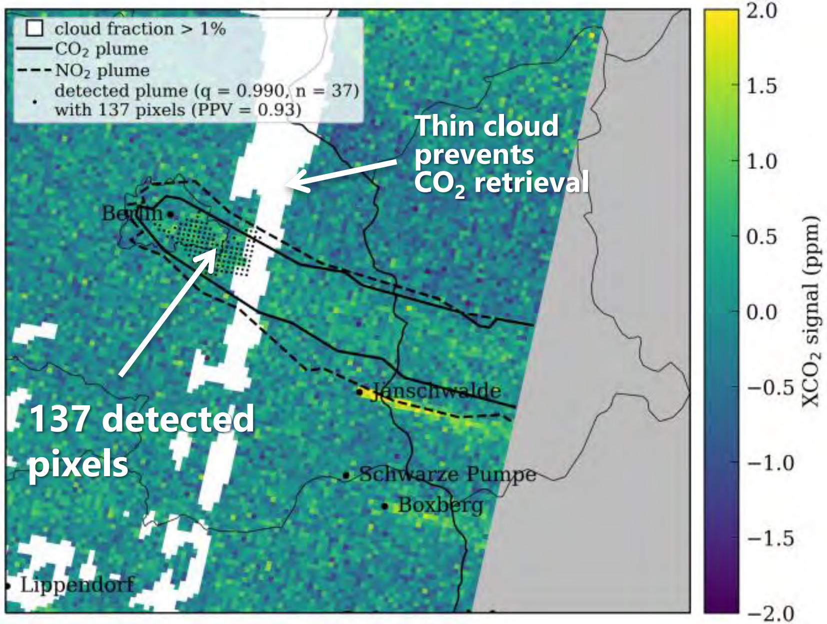
Plume detection algorithm

$$\frac{\bar{X}_p - \bar{X}_{BG}}{\sqrt{\frac{s_p^2}{n_p} + \frac{s_{BG}^2}{n_{BG}}}} > z(p)$$

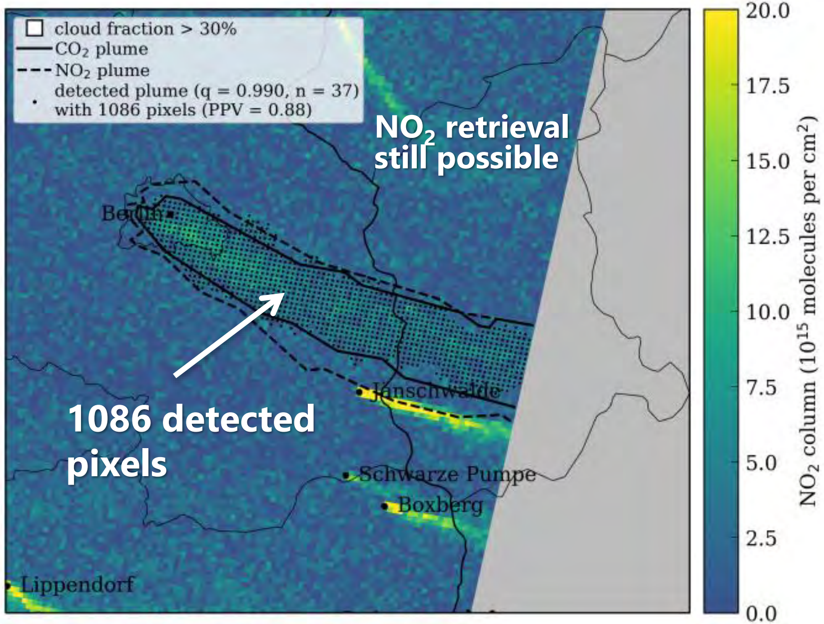


Kuhlmann et al. (in preparation)
See also SMARTCARB final report

CO_2 (σ_{ref} = 0.5 ppm)



NO_2 (σ_{ref} = 2×10^{15} cm^{-2})



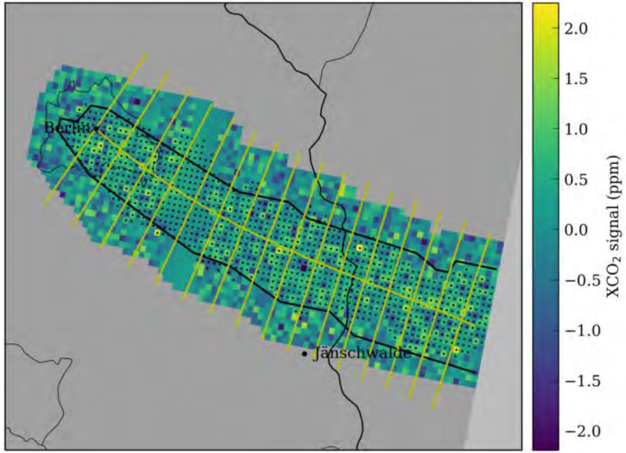
Number of successfully detected plumes

- Total number of detectable plumes (defined as plumes with > 100 pixels with XCO_2 signals above 0.05 ppm) **about 10 per satellite** (250 km swath)
- Plume detection algorithm finds **only 20%-30%** of these plumes to be useful (>100 detected pixels) with a high- and low-noise CO_2 instrument, respectively
- For NO_2 instrument, success rate is much higher, **about 70%** for both low and high noise instruments

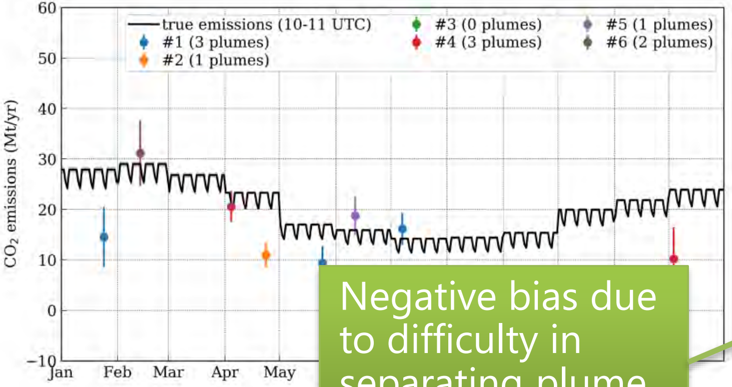
Estimation of CO_2 emissions by mass balance

Analysis for constellation of six satellites

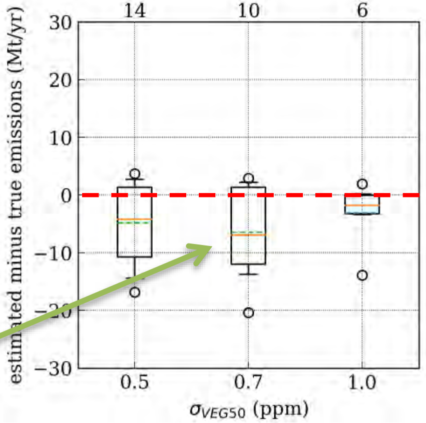
Approach:
Estimation of flux through vertical control surfaces



With CO_2 instrument only

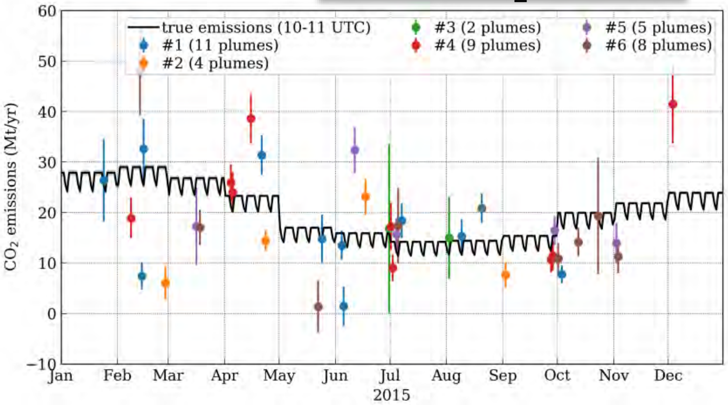


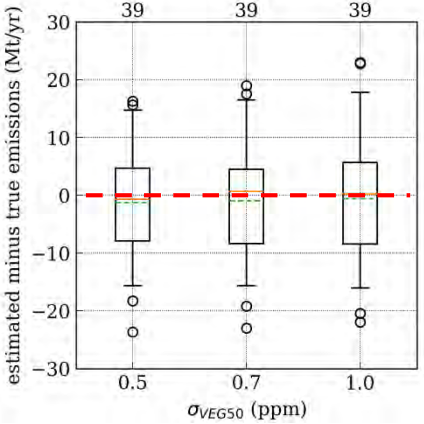
Deviations from truth



Negative bias due to difficulty in separating plume from background

Plumes detecte... ent





Summary of SMARTCARB emission estimates

σ_{VEG50} (ppm)	Mean bias		Standard deviation		Root mean square deviation of mean		Number of plumes*
	Mt yr^{-1}	%	Mt yr^{-1}	%	Mt yr^{-1}	%	
Analytical inversion using tracer information provided by the model, time-varying emissions							
0.5	0.1	0.6	3.3	17	0.4	2.1	69
0.7	0.0	0.1	3.2	16	0.4	2.1	62
1.0	0.2	0.9	4.1	20	0.6	2.9	55
Mass balance approach using CO_2 for plume detection with n_s = 37 and q = 0.99							
0.5	-4.8	-24	6.7	34	5.2	26	14
0.7	-6.5	-32	7.6	38	6.9	35	10
1.0	-3.1	-16	5.1	26	3.8	19	6
Mass balance approach using NO_2 for plume detection with n_s = 37 and q = 0.99							
0.5	-1.3	-6	9.2	46	1.9	10	39
0.7	-1.0	-5	9.7	48	1.9	9	39
1.0	-0.6	-3	10.7	53	1.8	9	39

* constellation of 6 satellites

LOGOFLUX case study for Berlin by IUP Bremen

Atmos. Chem. Phys., 16, 9591–9610, 2016
www.atmos-chem-phys.net/16/9591/2016/
doi:10.5194/acp-16-9591-2016

Atmospheric Chemistry and Physics
Open Access
EGU

Pillai et al., ACP, 2016

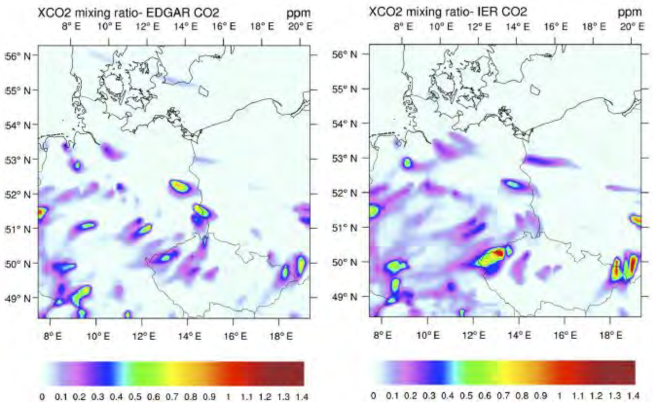
Tracking city CO_2 emissions from space using a high-resolution inverse modelling approach: a case study for Berlin, Germany

Dhanyalekshmi Pillai[1,2], Michael Buchwitz[1], Christoph Gerbig[2], Thomas Koch[2], Maximilian Reuter[1], Heinrich Bovensmann[1], Julia Marshall[2], and John P. Burrows[1]

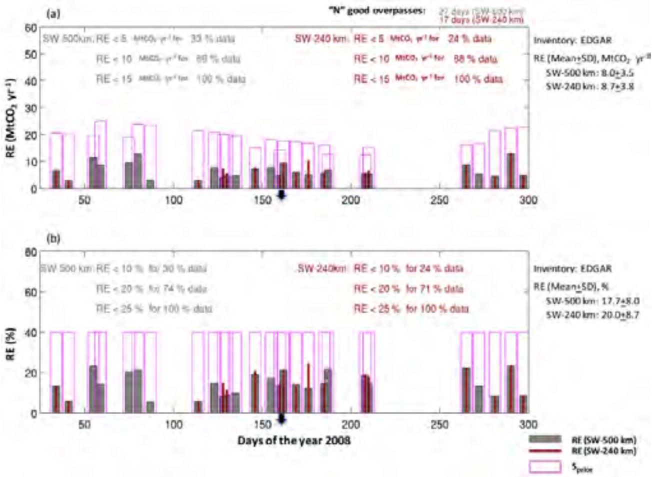
[1]Institute of Environmental Physics, University of Bremen, Bremen, Germany
[2]Max Planck Institute for Biogeochemistry, Jena, Germany

- Case study for Berlin for year 2008
- Satellite data: Simulation for CarbonSat ($2x2km^2$, swath width 240 km & 500 km)
- Model: WRF-GHG, $10x10km^2$ resolution
- Bayesian inversion

XCO_2 simulations using EDGAR & IER



A priori & a posteriori errors



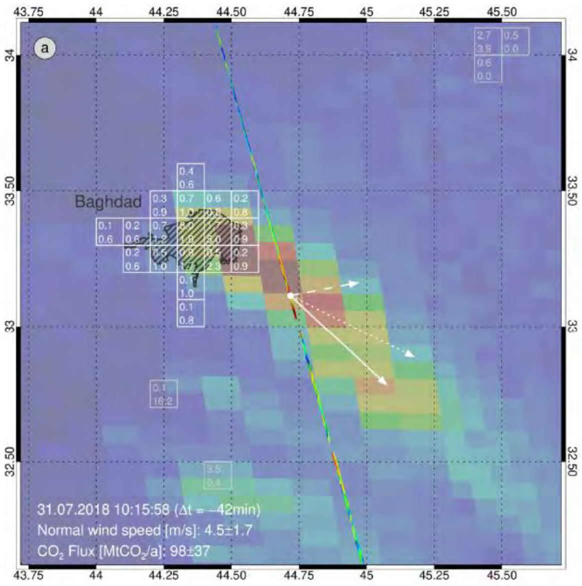
Summary:

- Number of „good“ overpasses per year: 17 (240 km) - 27 (500 km)
- Single overpass random error: typ. 9 $MtCO_2$/year
- Systematic: typically 6-10 $MtCO_2$/year depending on assumptions

Satellite XCO_2 & NO_2 imaging of localized CO_2 sources

Towards monitoring localized CO_2 emissions from space: co-located regional CO_2 and NO_2 enhancements observed by the OCO-2 and S5P satellites *Reuter et al., ACP (submitted)*

Maximilian Reuter[1], Michael Buchwitz[1], Oliver Schneising[1], Sven Krautwurst[1], C. W. O'Dell[2], Andreas Richter[1], Heinrich Bovensmann[1], and John P. Burrows[1]
[1]Institute of Environmental Physics, University of Bremen, Germany
[2]Colorado State University, Fort Collins, CO, USA



Example:

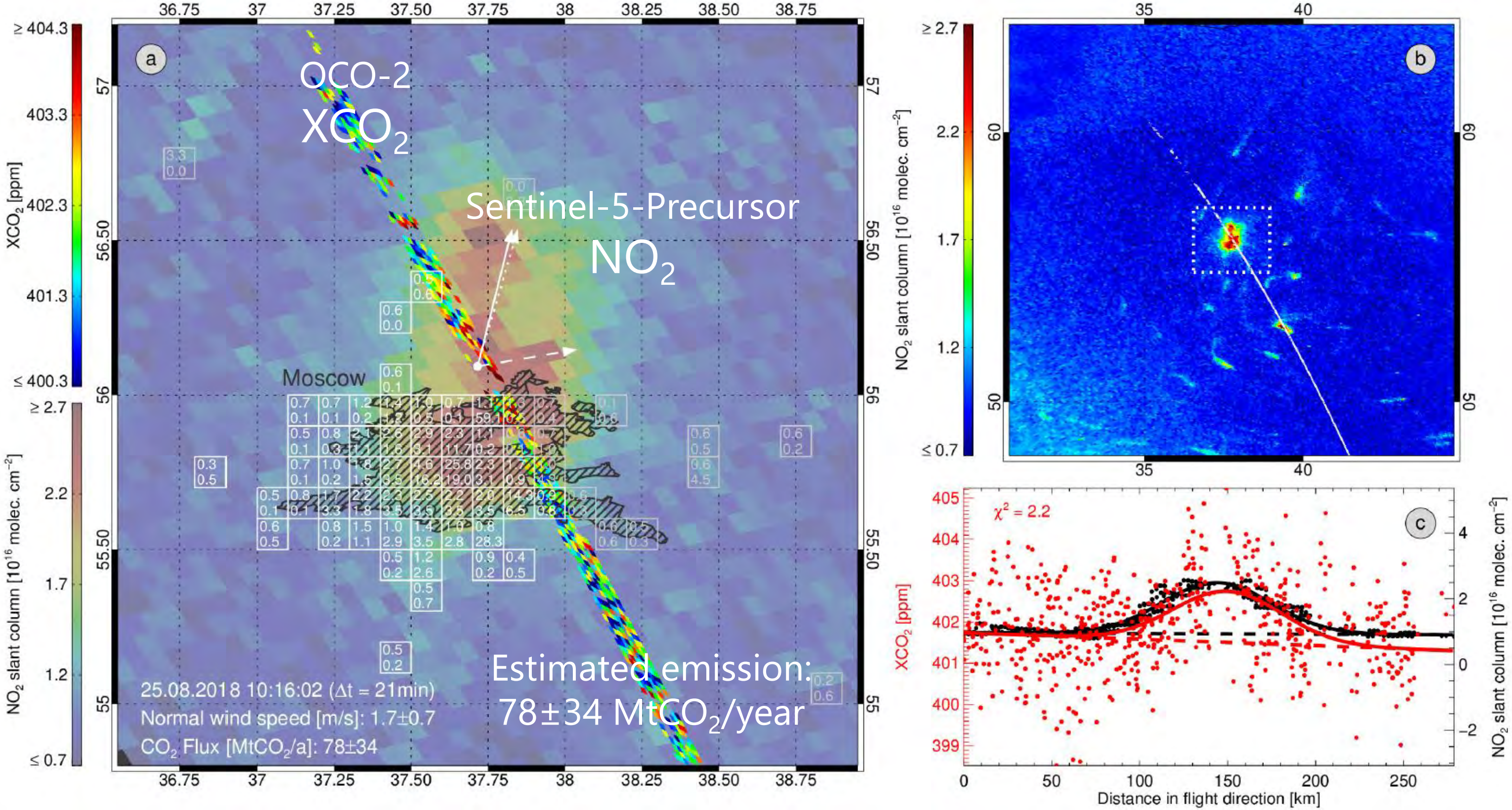
Baghdad,
31-July-2018

- Satellite data: OCO-2 XCO_2 and S5P NO_2
- NO_2 primarily for emission source identification
- Cross-sectional CO_2 flux via integration of Gaussian plume XCO_2 enhancement times wind speed (from ECMWF)
- 20 promising scenes identified during 03/2018-08/2018; 6 scenes discussed in detail in paper
- Comparisons with EDGAR, ODIAC, …
- Limitation: Narrow OCO-2 swath (10 km); will be much better with CO2M (> 200 km)

See also poster „OCO-2 XCO_2 retrievals using the FOCAL algorithm"

Satellite XCO_2 & NO_2 imaging of localized CO_2 sources

Moscow on 25-August-2018:



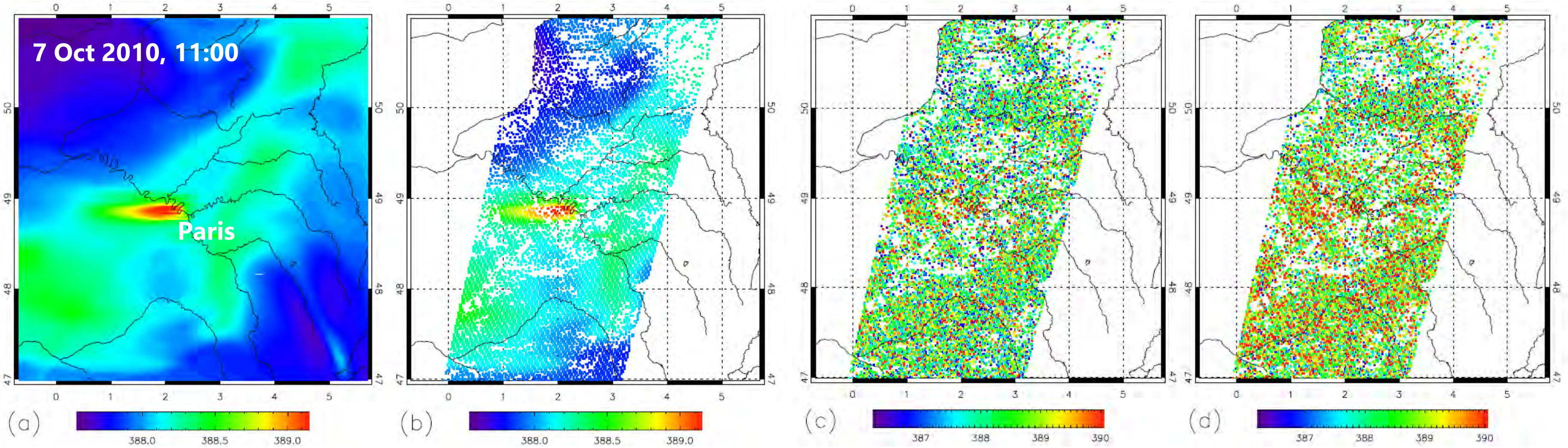
Reuter et al., ACP (submitted)

LOGOFLUX study for Paris by LSCE

Broquet et al., AMT 2018

- Typical width / amplitude of the Paris plume: 40km / +1ppm
- Signature of 1-hour emissions vanishes from the XCO_2 image in ~5-6 hours

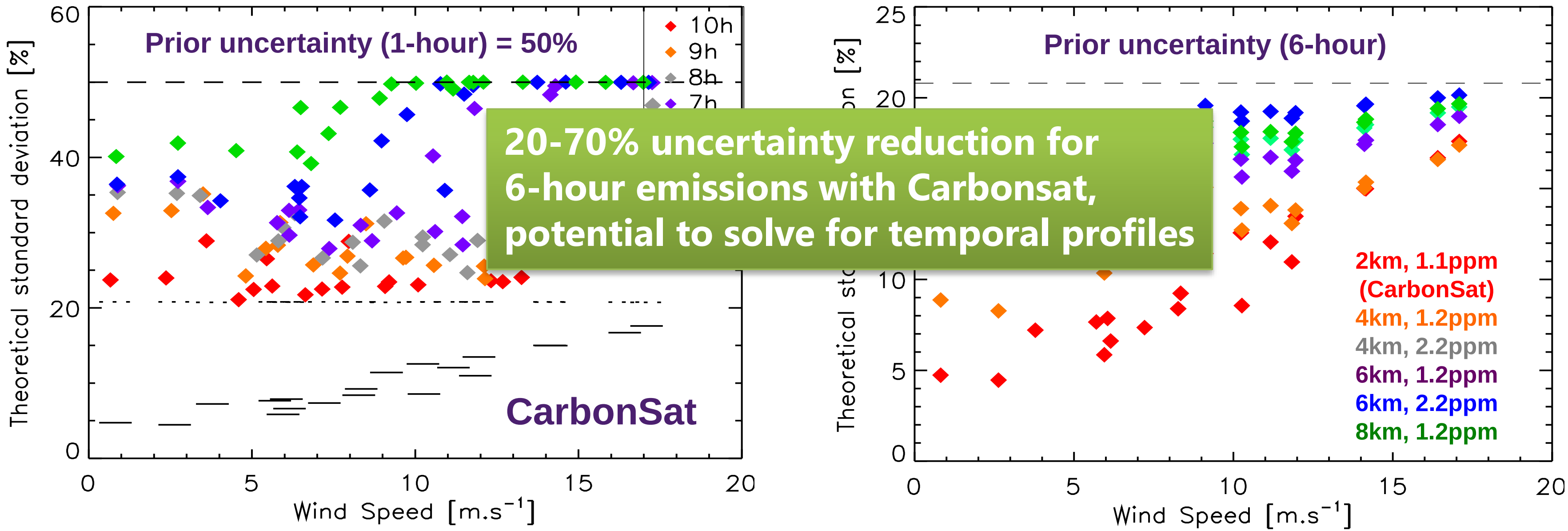
Simulations of XCO2 using the CHIMERE model at 2 km res & the AIRPARIF inventory (Paris ~14 $MtC.y^{-1}$)



no noise full domain | **no noise, CS sampling (240 km swath)** | **CS random noise (240 km swath)** | **CS random + systematic error (240 km swath)**

LOGOFLUX study for Paris by LSCE

- Use individual images at 11:00 to retrieve Paris emissions up to 6 hours before
- 20 test cases (20 days in Oct), estimation of hourly emissions by Bayesian inversion
- Neglected factors: transport errors, clouds, systematic errors, uncertainties in spatial distribution of Paris emissions and NEE
- Analysis for dependence of results on on wind speed, spatial resolution, noise, swath



20-70% uncertainty reduction for 6-hour emissions with Carbonsat, potential to solve for temporal profiles

Summary

- Quantifying city emissions from satellites is challenging since plume signals are small
- Single satellite with 250 km swath not sufficient: Can "see" Berlin plume only 10x per year, of these only 20-30% have well detectable CO2
- Additional NO_2 instrument has multiple benefits:
  - Approx. 3x more plumes detectable due to higher SNR and smaller background
  - Enables better distinction between plume and background, reducing biases in estimates
  - Potential demonstrated by Reuter et al. (submitted) for OCO-2
- Uncertainty of emission estimate from single overpasses ~20% of Berlin emissions (Pillai et al. 2016, Kuhlmann et al., in prep.) for perfect transport model inversion
- Satellite mainly sensitive to emissions 0-6 hr before overpass. Uncertainty of 6hr average emission may be reduced by ~50% (Broquet et al. 2018)
- Current inversion systems are not well adapted to problem, since plume information is only used to optimize emissions but not atmospheric transport

Thank you for your attention!