Assessing the constraint of the CO2 monitoring mission on fossil fuel emissions from power plants and a city in a regional carbon cycle fossil fuel data assimilation system

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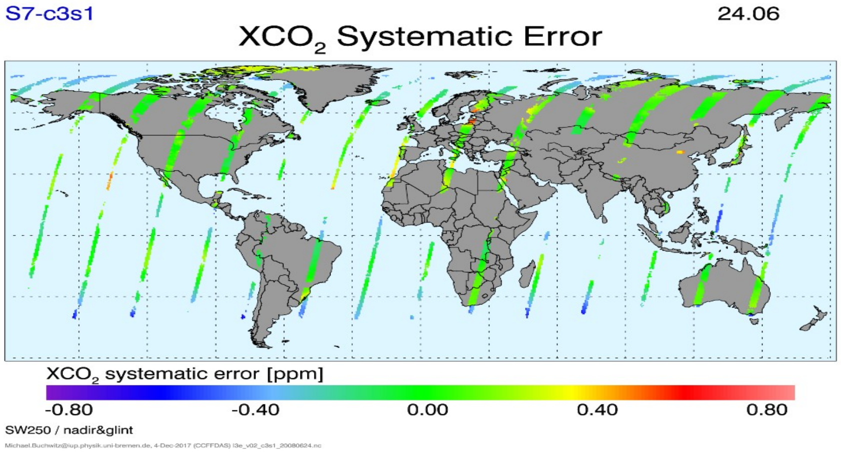
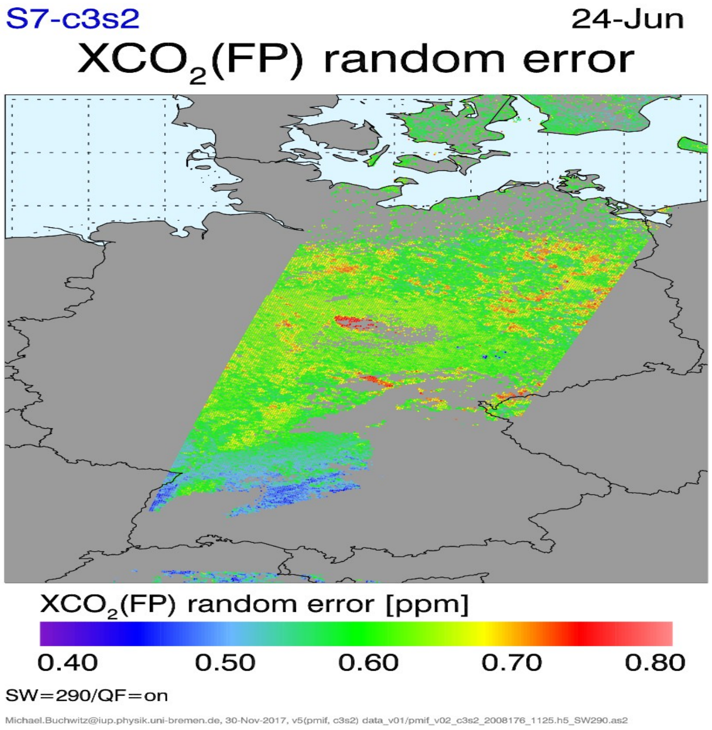
Study funded by ESA

CO2 Monitoring Mission (CO2M)

- Planned by Copernicus Programme
- Fossil fuel carbon emissions
- Multi-Satellite Constellation
- Imaging Capability
- 2 km x 2 km grid
- wide swath
- XCO2
- NO2
- Multi-Angular Polarimeter (Aerosols)





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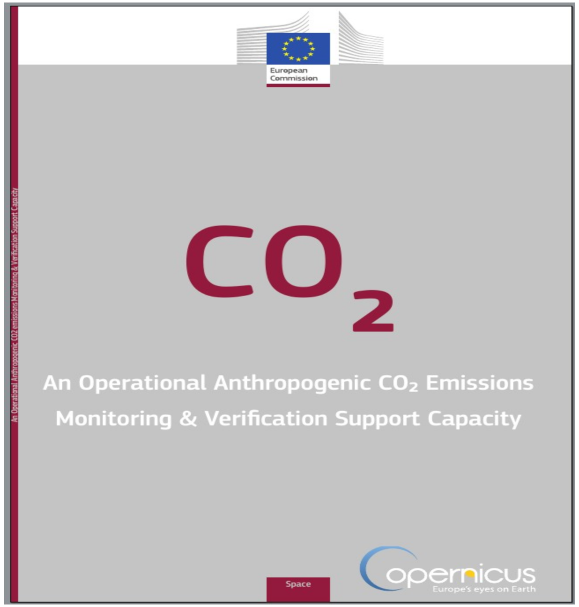
Capabilities of MVS capacity



1.5.1 Stepwise approach for a CO_2 emissions MVS capacity

The need and capabilities for a Monitoring and Verification Support capacity have been illustrated in previous sections using projections of emissions based on current inventories and two plausible scenarios. These analyses have highlighted the necessity for this system to properly address the following set of capabilities:

C1. Detection of hot spot. A hot spot is defined as a small area surrounded by a strong CO_2 concentration gradient, because the area contains a large emitting CO_2 source. This can be a large power plant, a megacity or any other activity characterized by strong CO_2 emissions with different time evolution;

C2. Monitoring the emissions of the hot spot. Consecutive measurements are needed to link the measured emission level to previous measurements and to monitor local emission reductions of the activities within the hot spot. The accuracy of the measurements must ensure the capability to attribute CO_2 emissions anomalies relative to the CO_2 concentration background level;

C3. Assessing emission changes against local reduction targets. This concerns the monitoring of the implemented emission reduction strategies on the hot spots, which all add up to achieve NDC targets. In the EU this requires the monitoring, at the most appropriate time scale, of not only the point source facilities (which are under the Emissions Trading System) but also the megacities with peak emissions of transport and buildings;

C4. Assessing the national emissions and changes with 5 year time steps. This requires the entire screening of the full area covered by the country, in order to account for changes in emission patterns with new or occasional hotspots.

Capabilities of MVS capacity

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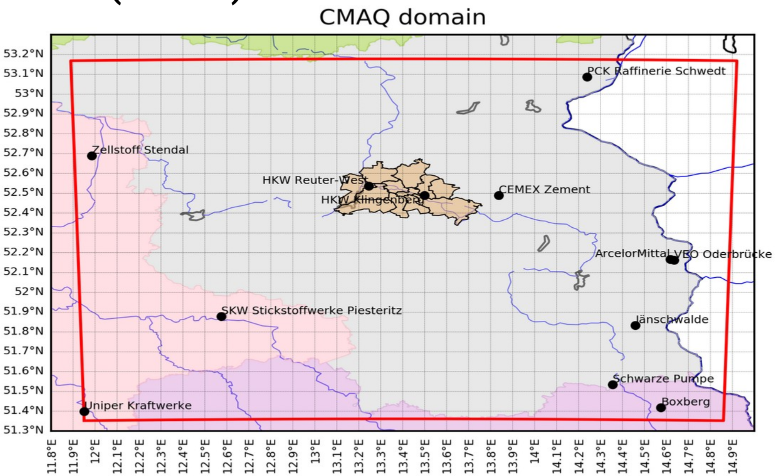
Assessments require High resolution Modelling of CO2M Images

High Resolution over Berlin

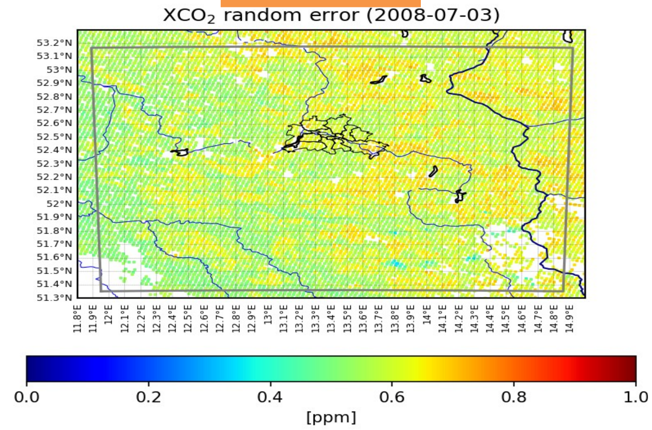
Modelling System:

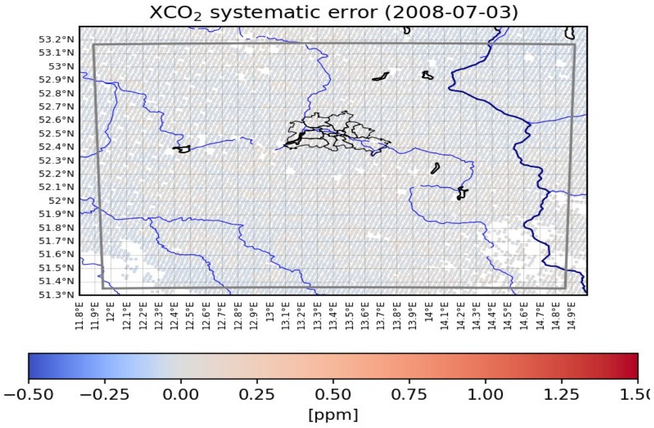
- CMAQ in 2 km x 2 km resolution
- 200 km area around Berlin
- Use simulated CO2M images
- Assess accuracy requirement for XCO2 alone
- And in conjunction with NO2
- Assess added value of a multi-angular polarimeter (MAP)
- Simulating 24 hour period before overpass



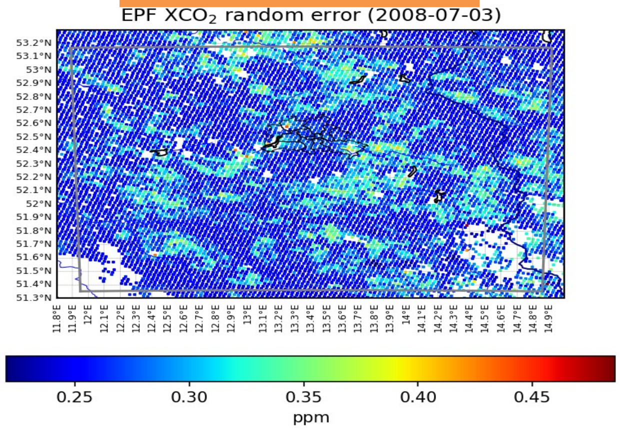
Simulated Random and Systematic Errors over Berlin

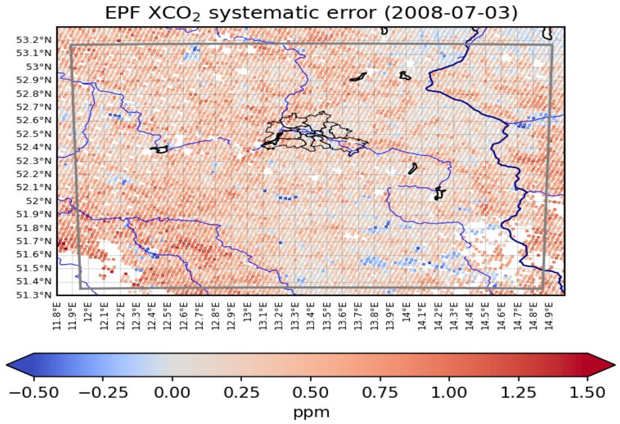
IUP/PMIF



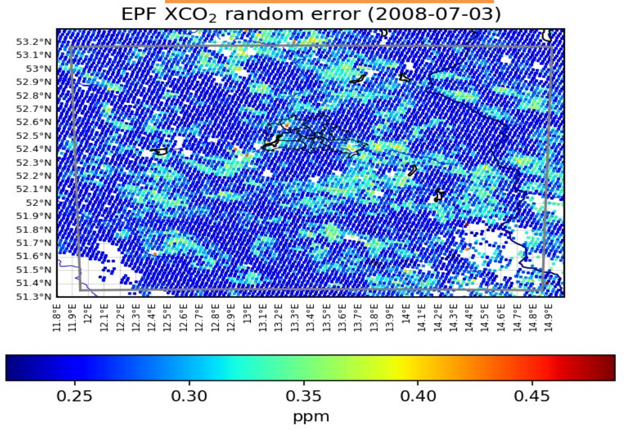


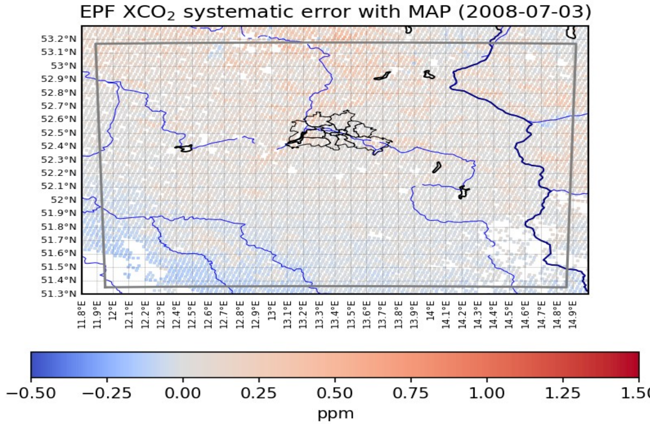
ANN EPF w/o MAP



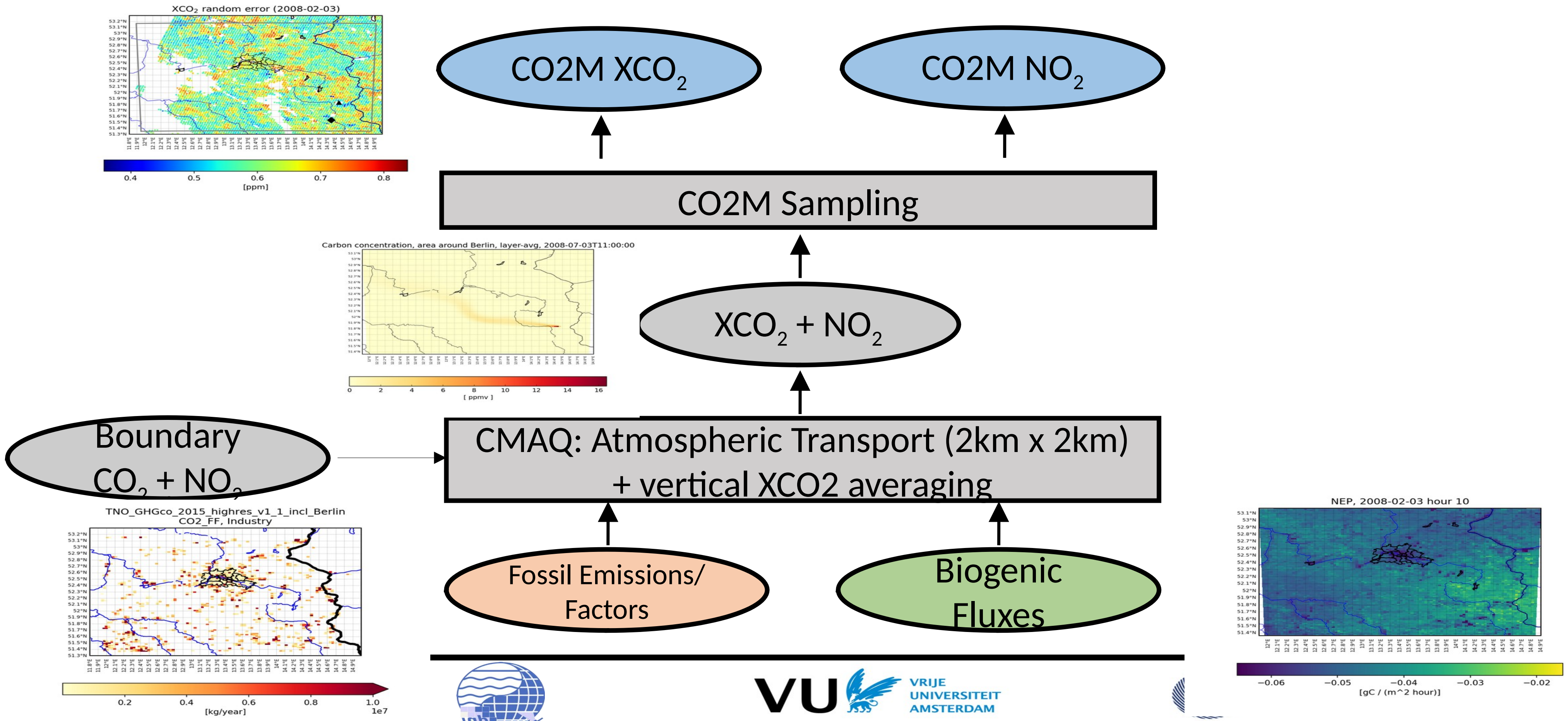


ANN EPF w MAP





Modelling Chain



Modelling Chain for XCO2

$XCO_2 = XCO_{2,initial} + T_{Surf}\ e_{CO2} + T_{lateral}\ f_{CO2}$

$e_{CO2} = e_{CO2,energy} + e_{CO2,other} + e_{CO2,bio}$

$e_{CO2,bio} = B(x_{bio})$

$T_{Surf}\ e_{CO2} = T_{Surf,energy}\ e_{CO2,energy} + T_{Surf,other}\ e_{CO2,other} + TB'(x_{bio})$

e_{CO2} : emissions over 24 hours
f_{CO2} : lateral inflow over 24 hours
$XCO_{2,initial}$: column 24 hours before overpass (ignored)
T : atmospheric Transport and CO2M sampling
B : terrestrial biosphere model

Compact Notation:

$XCO_2 = M'\ x$

Quantitative Network Design Method

Uncertainty

$$\mathbf{C}(d)^2 = \mathbf{C}(d_{\text{obs}})^2 + \mathbf{C}(d_{\text{mod}})^2 .$$

$$\mathbf{C}(x)^{-1} = \mathbf{M}'^{\mathrm{T}}\mathbf{C}(d)^{-1}\mathbf{M}' + \mathbf{C}(x_0)^{-1} .$$

What we do know already

Coverage

$$\sigma(y)^2 = \mathbf{N}'\mathbf{C}(x)\mathbf{N}'^{\mathrm{T}} + \sigma(y_{\text{mod}})^2 . \quad 4)$$

$$\sigma(y_0)^2 = \mathbf{N}'\mathbf{C}(x_0)\mathbf{N}'^{\mathrm{T}} + \sigma(y_{\text{mod}})^2 . \quad (5)$$

Performance Metric “uncertainty reduction”

$$\frac{\sigma(y_0) - \sigma(y)}{\sigma(y_0)} = 1 - \frac{\sigma(y)}{\sigma(y_0)} . \quad (6)$$

Notation:

y:	vector of target quantities
d:	vector of observations
x:	vector of unknowns/control variables
d=M(x):	model linking unknowns to observations
y=N(x):	model linking unknowns to target quantities
C:	covariance of uncertainty

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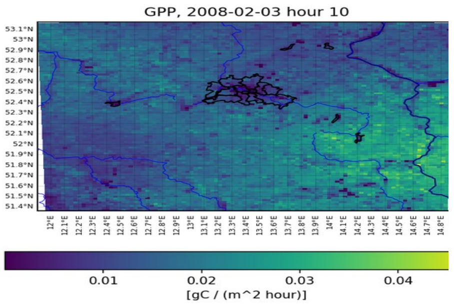
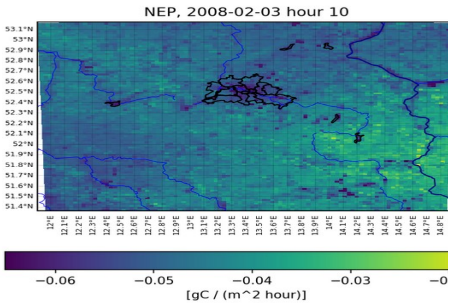
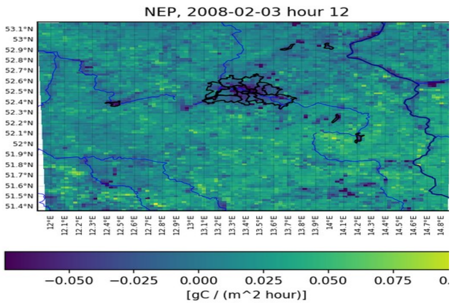
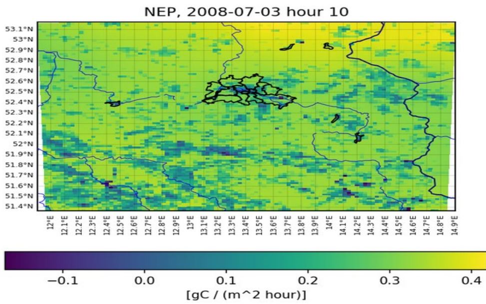
Model for Natural Fluxes

- Newly developed (W. Knorr)
- Based on Knorr and Heimann (1995), used in Kaminski et al. (2017)
- Runs on transport model grid (2 km by 2 km)
- Simulates Net and Gross (GPP, eocsystem respiration) Fluxes at hourly time step
- Diagnostic
- Driven by JRC-TIP FAPAR and climate (Incoming solar/thermal radiation, precipitation, 2m-temperature) from ERA5
- Calibrated 5 parameters against complete ensemble of Tier-1 166 Fluxnet 2005 sites
- Prior parameter uncertainty 20%





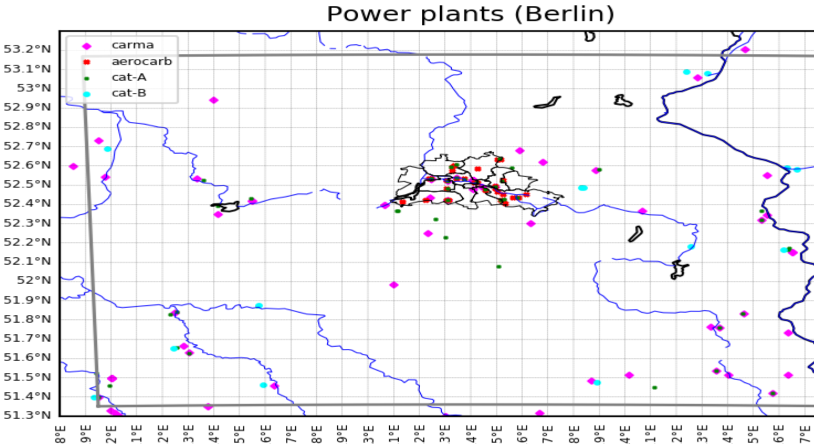




Fossil fuel emissions

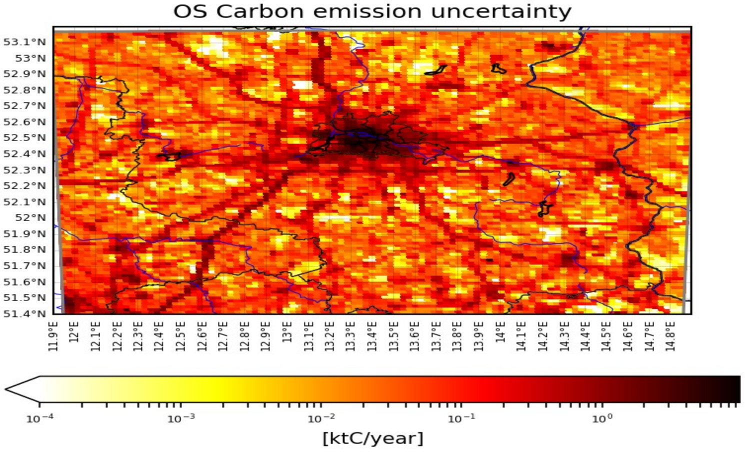
Energy Generation

- TNO data set (from CHE, see also Super et al, ACP, 2020)
- Detailed plume simulation (VDI guidelines implemented by G. Kuhlmann) for largest power plants and some Vattenfall plants within Berlin: 11 plants in total; Stack information from A. Kerschbaumer (Berlin Kataster) and G. Kuhlmann.
- Standard Vertical Profile (Bieser et al., 2011) for the remainder
- Further input not (yet) used: Power Production from large Plants (F. Sandau, Umweltbundesamt).
- Fixed temporal profile
- Prior Uncertainty: 20%

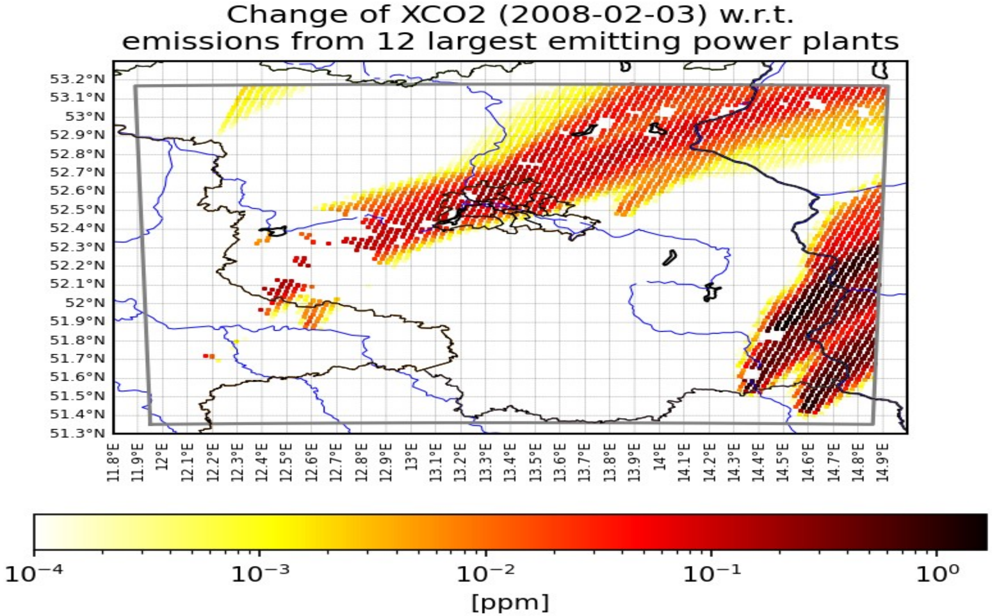


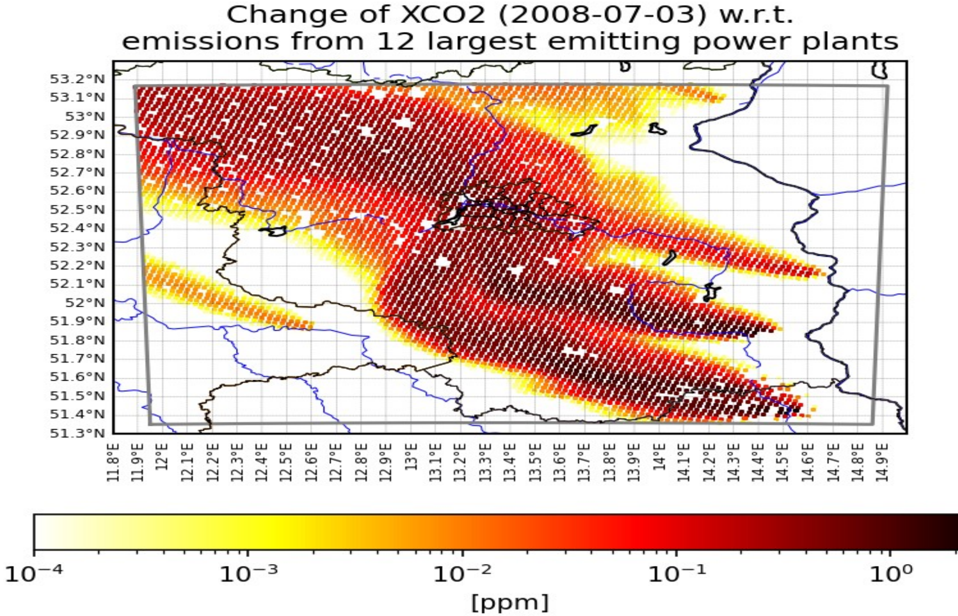
Other Sector

- TNO data set (from CHE, see also Super et al, ACP, 2020):
- “High resolution (1/60° x 1/120°; ~1x1km) regional gridded emission inventory for a zoom domain in Europe”
- Fixed temporal profile
- Prior Uncertainty: 20%



Plumes from Power Plants





One Study Period in Winter (left) and one in Summer (right)

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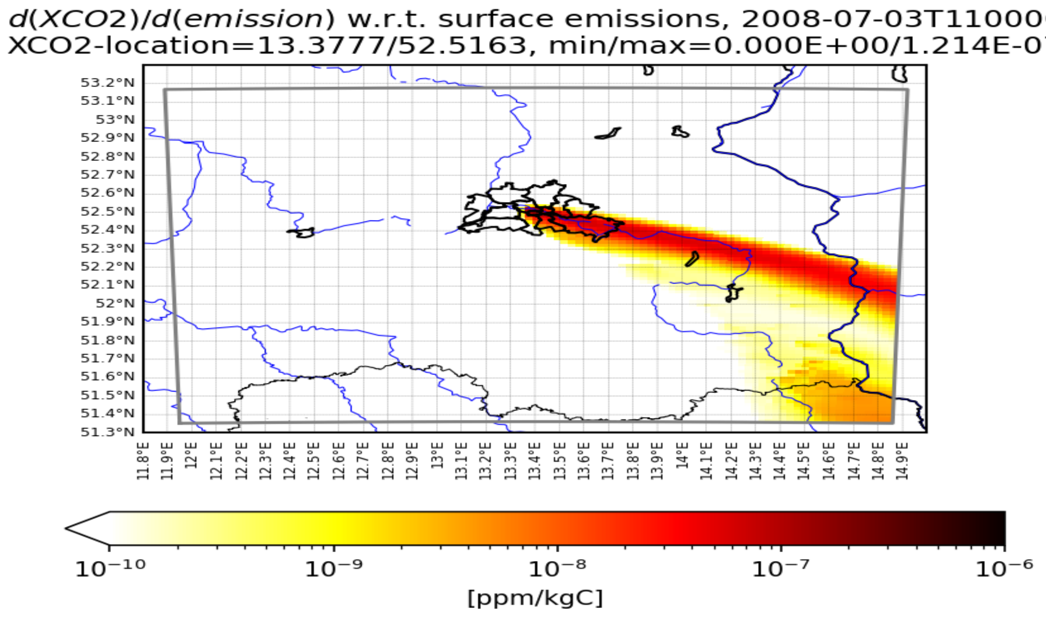
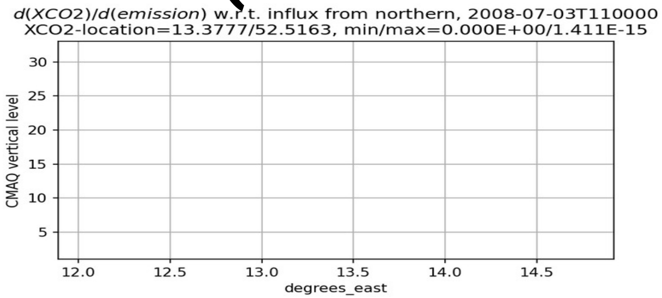
XCO2 Jacobian (Brandenburg Gate)



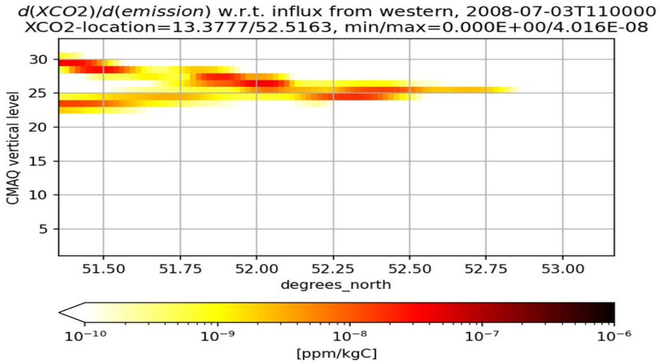
Footprint of XCO2 over Brandenburg Gate in summer

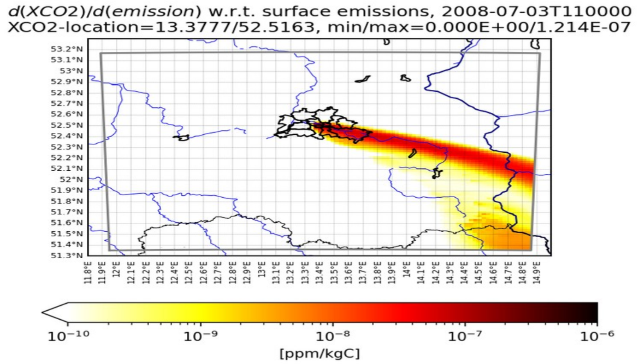
- Shows for each grid cell sensitivity of the XCO2 over Brandenburg Gate wrt to emission into that grid cell.
- Change in ppm for an emission of 1kgC

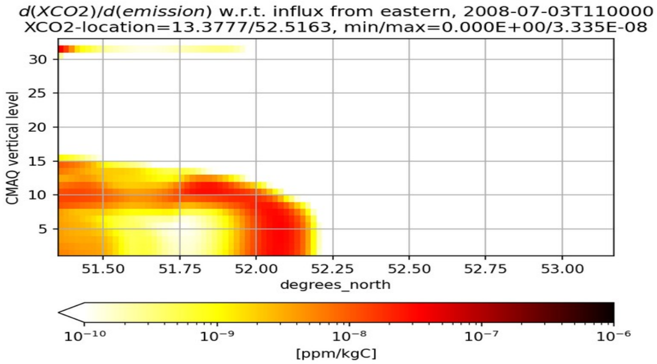
XCO2 Jacobian (Brandenburg Gate)

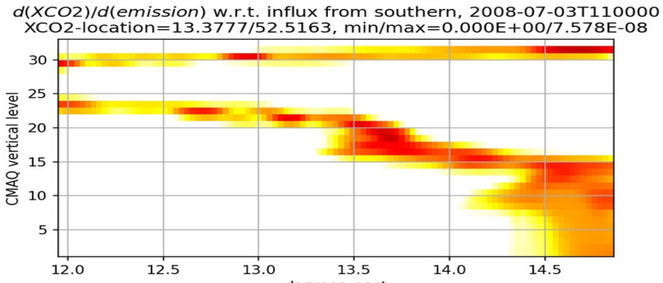


And with lateral inflow

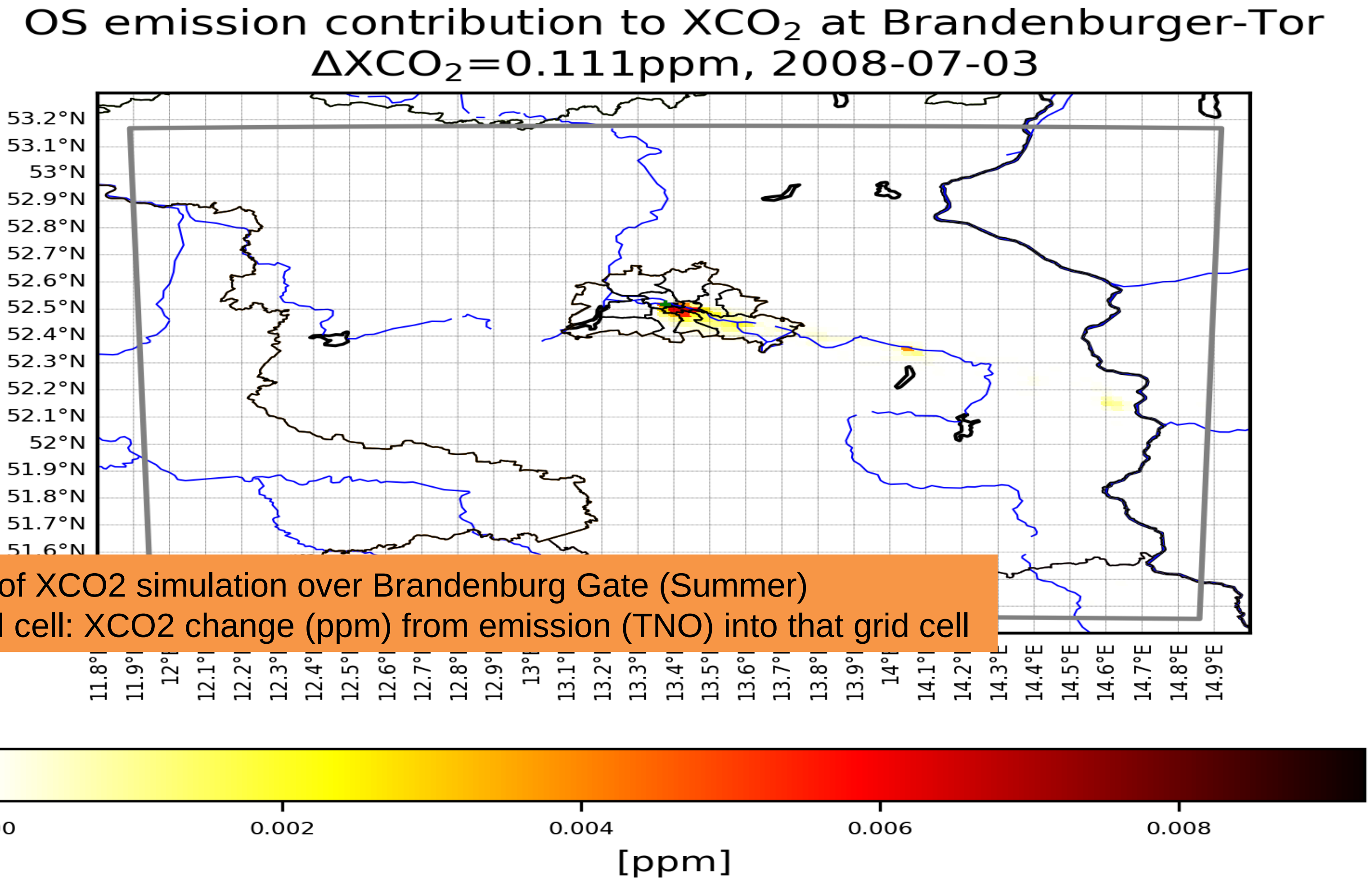








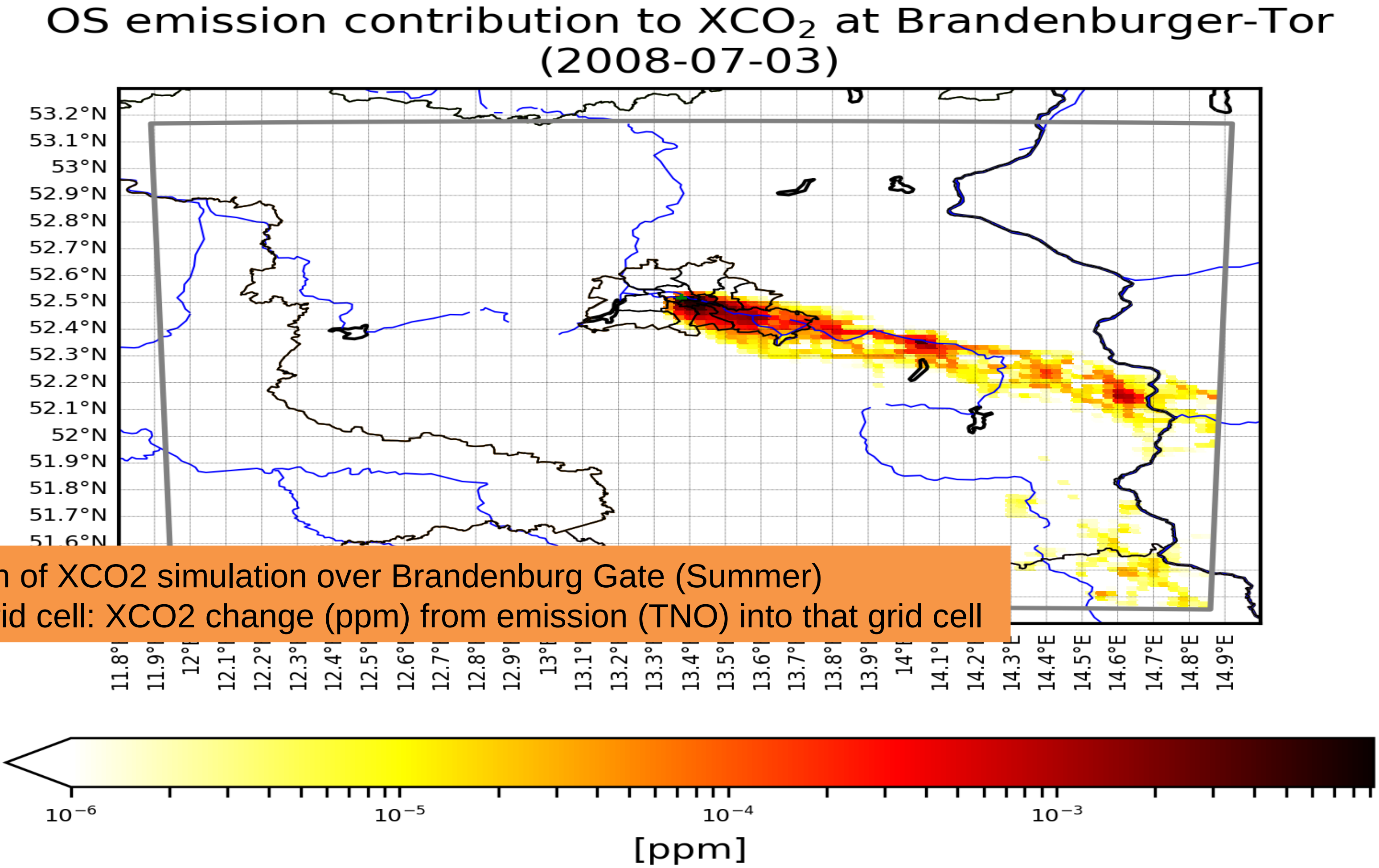
Multiplied with TNO emission field: Decomposition of XCO2 signal



Decomposition of XCO2 simulation over Brandenburg Gate (Summer)

- For each grid cell: XCO2 change (ppm) from emission (TNO) into that grid cell

Multiplied with TNO emission field: Decomposition of XCO2 signal



Decomposition of XCO2 simulation over Brandenburg Gate (Summer)

- For each grid cell: XCO2 change (ppm) from emission (TNO) into that grid cell

NO2

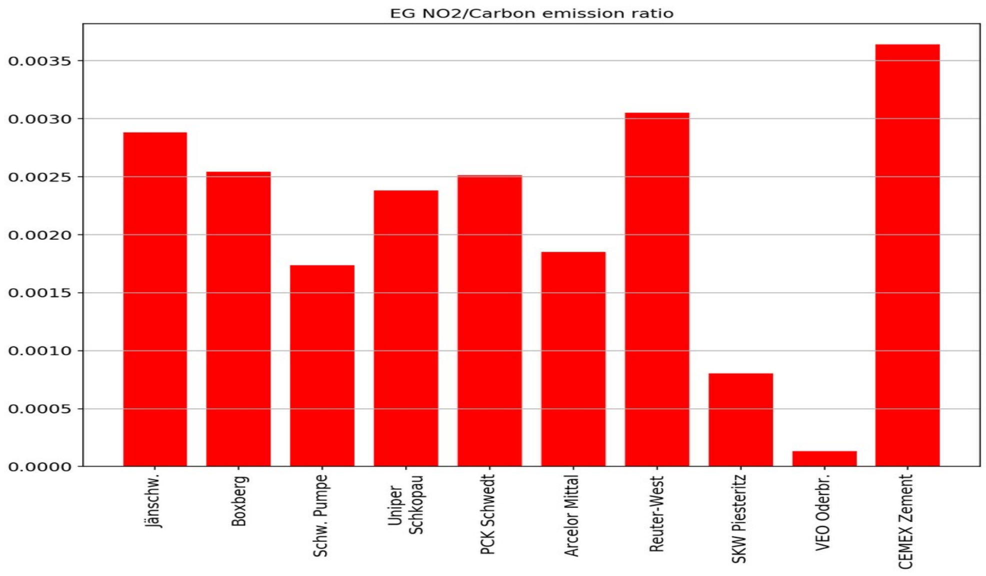
$XCO_2 = T_{CO2} \; e_{CO2}$

$NO_2 = T_{NO2} \; e_{NO2}$

$e_{NO2} = r \; e_{CO2}$

$NO_2 = T_{NO2} \; r \; e_{CO2}$

r: emission ratio, provides link to CO2



- Combined use of XCO2 and NO2 observations provides constraint on **r**
- We need a prior and an uncertainty in **r**
- Can we transfer what we learn from one plant to
  - the other plants of the same type (e.g. fuel/washer)?
  - all other plants?

- TNO data base provides reported "**r**" for each plant (prior)
- "**r**" in TNO data base shows large variability between plants

Emission Factor Uncertainty

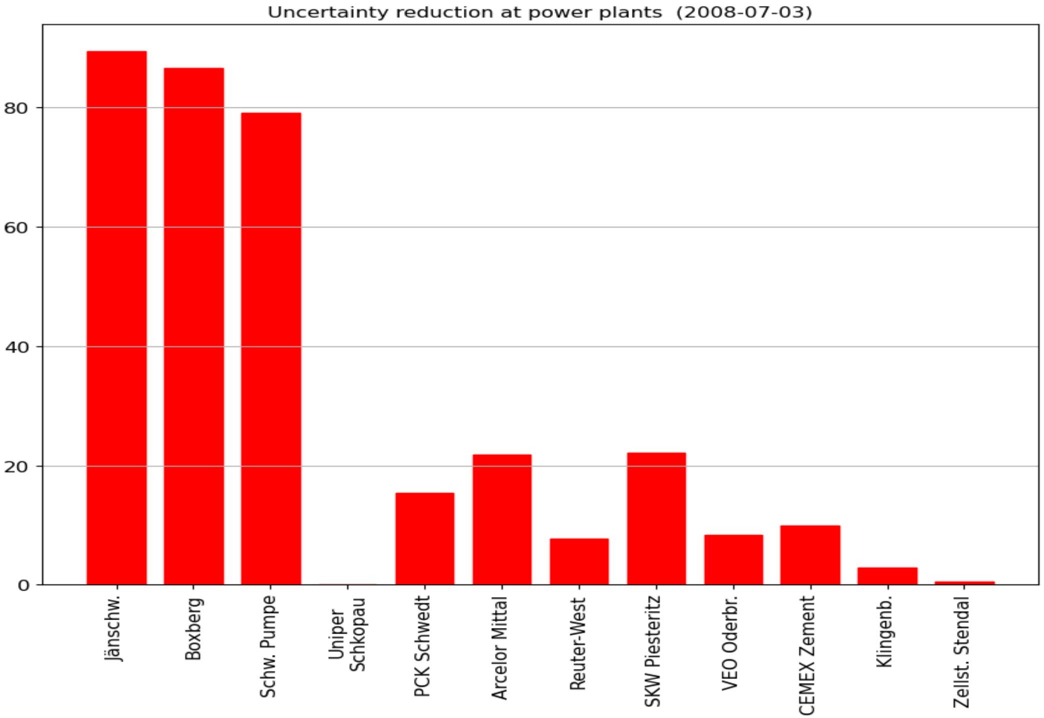
- The prior uncertainty for the ratio of the emission factors is calculated from reported emission factor uncertainties averaged for several countries, following the approach used by Super et al. (2020)
- Relative Uncertainty in individual emission factors for CO2 and NOX
- provided by Ingrid Super (TNO)
- r= NOx/CO2 approximated by normal distribution
- running three cases:
  - unknown scaling factor per plant
  - unknown scaling factor per fuel type (solid, liquid, gaseous)
  - unknown scaling factor for all plants (average uncertainty)

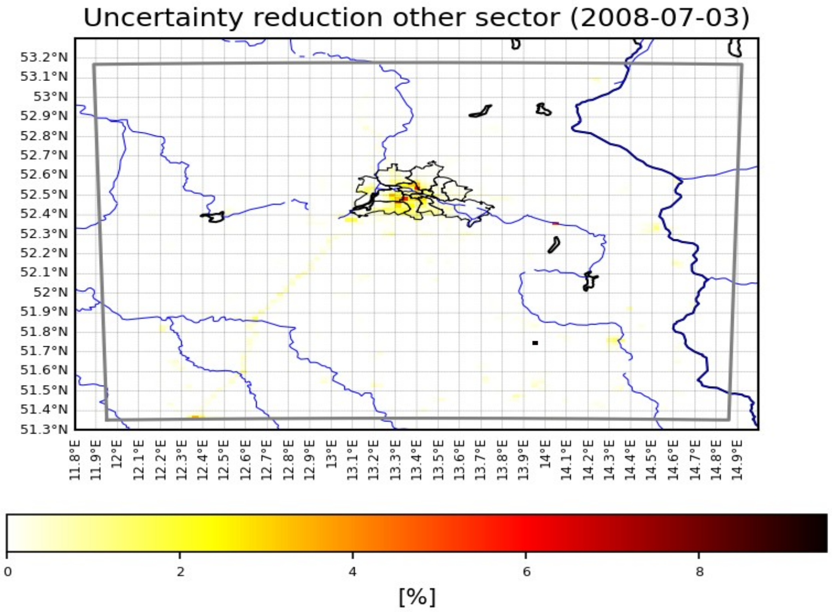
	CO2		Nox		Nox/CO2
Solid	0.03	normal	0.093	lognormal	0.098
Liquid	0.031	normal	0.243	normal	0.245
Gaseous	0.015	normal	0.924	lognormal	0.924
Biomass	0.05	normal	0.231	lognormal	0.236
Waste	0.111	normal			

Setup Default Experiment

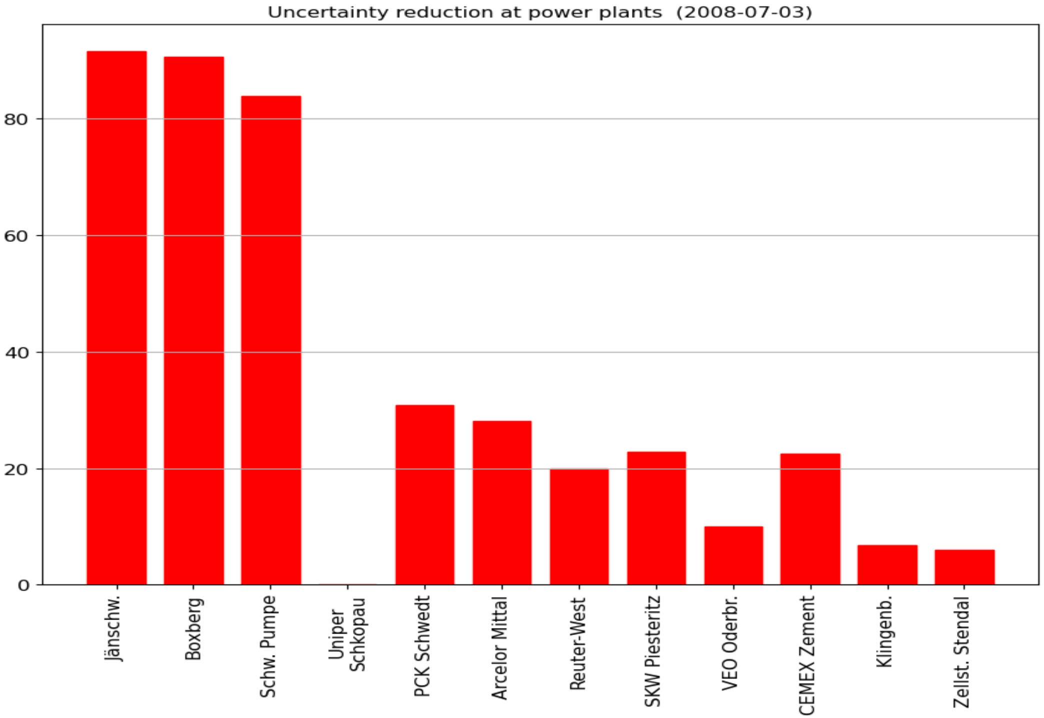
- XCO2 retrieval uses MAP
- no NO2
- 20% prior uncertainty for each power plant
- 20% prior uncertainty for each natural flux parameter
- 20% prior uncertainty of other sector for Berlin (52.8% at pixel level)
- 1 ppm uncertainty of lateral inflow, fully correlatated at 10 km horizontally, otherwise uncorrelated

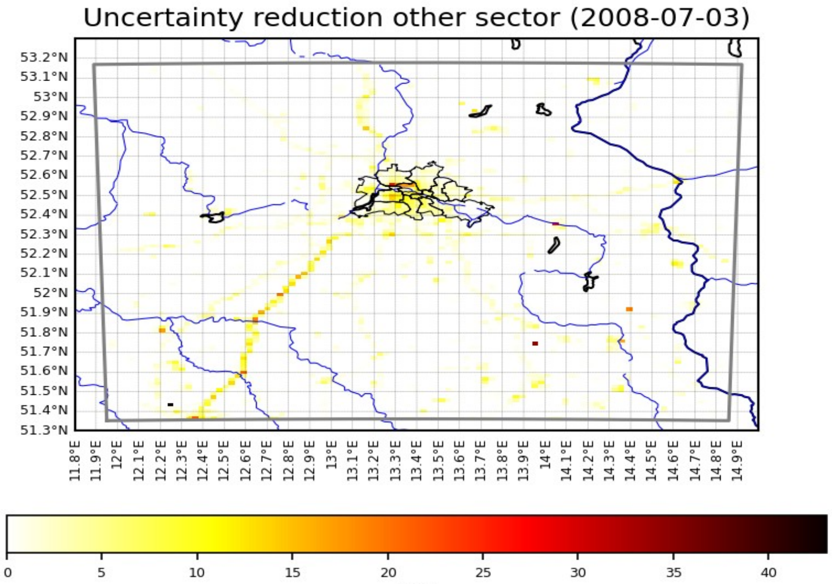
Default Experiment Summer

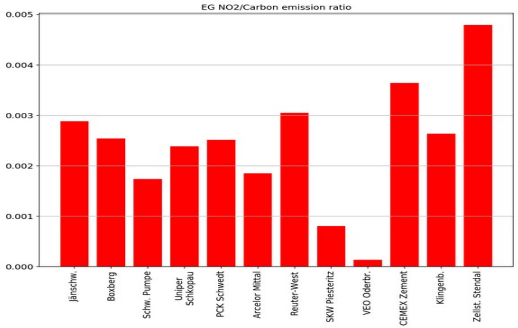




Experiment NO2 (uniform) Summer



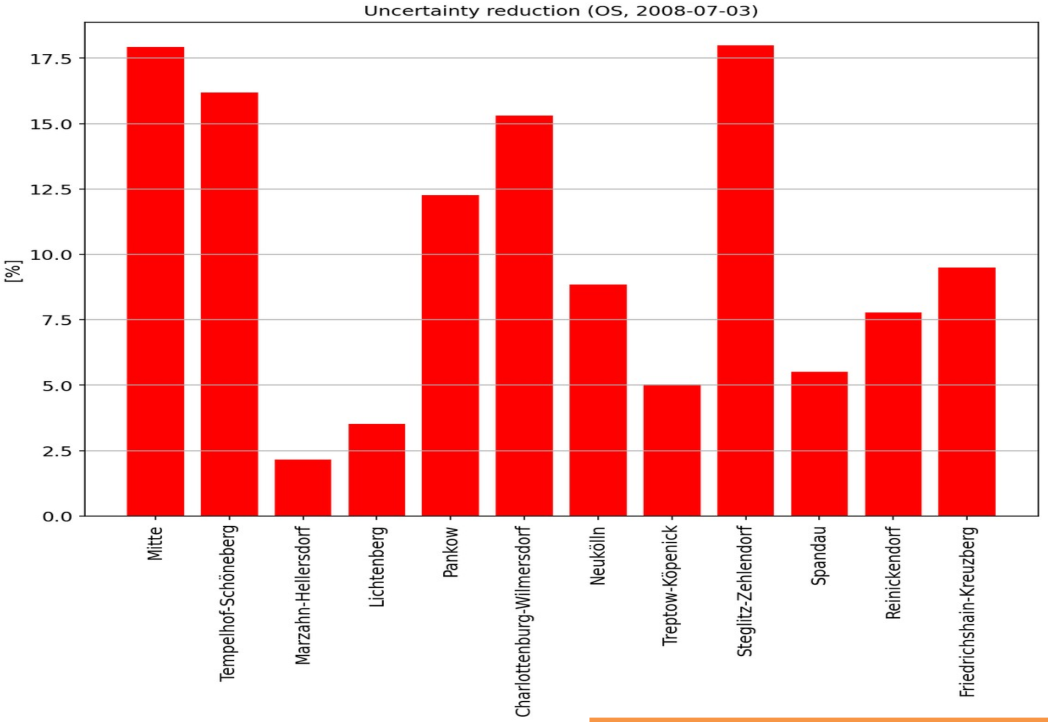


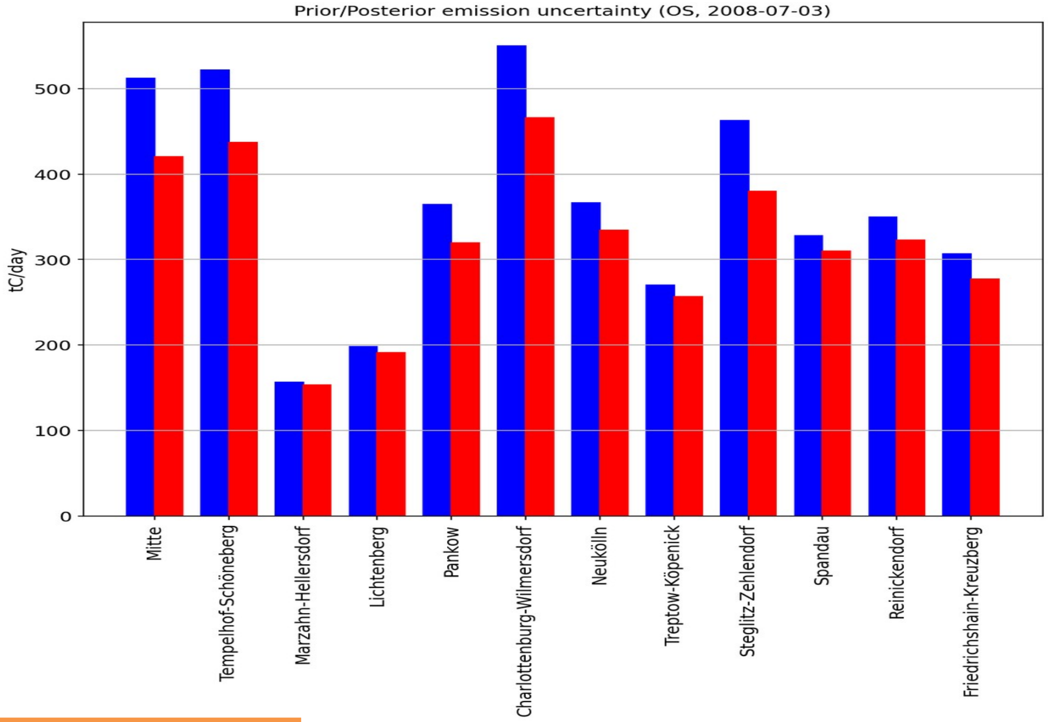


Adding NO2:

- Added value for power plants larger in winter,
  where XCO2 leaves more scope for improvement and where lifetime is longer
- But combined performance for XCO2 and NO2 better in summer

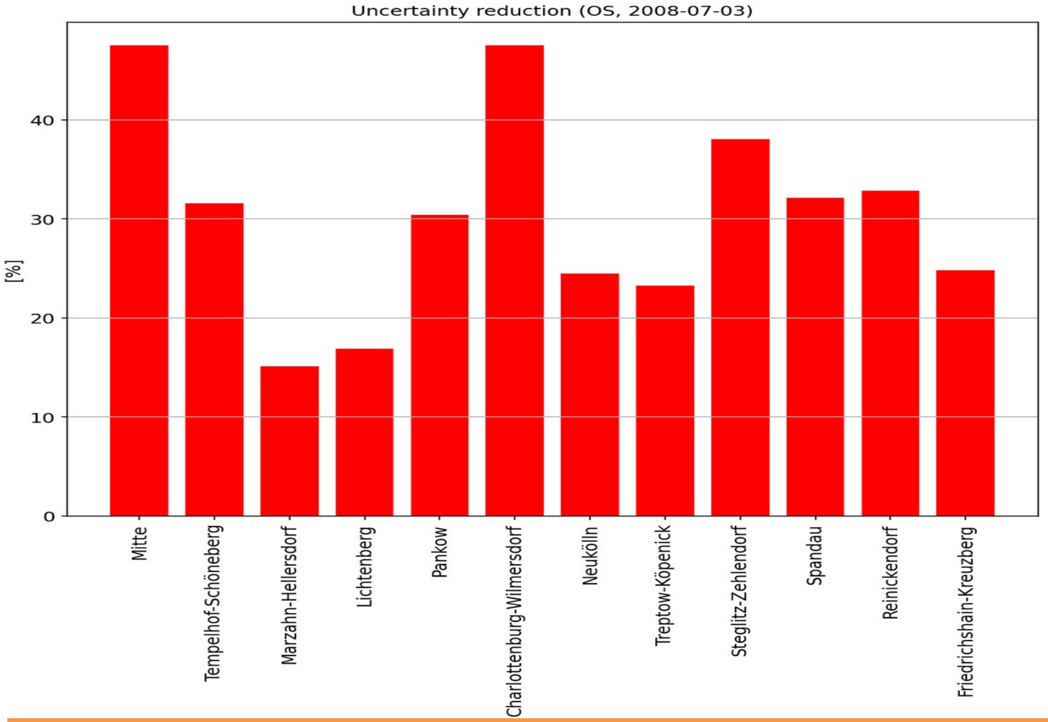
Default Experiment Summer

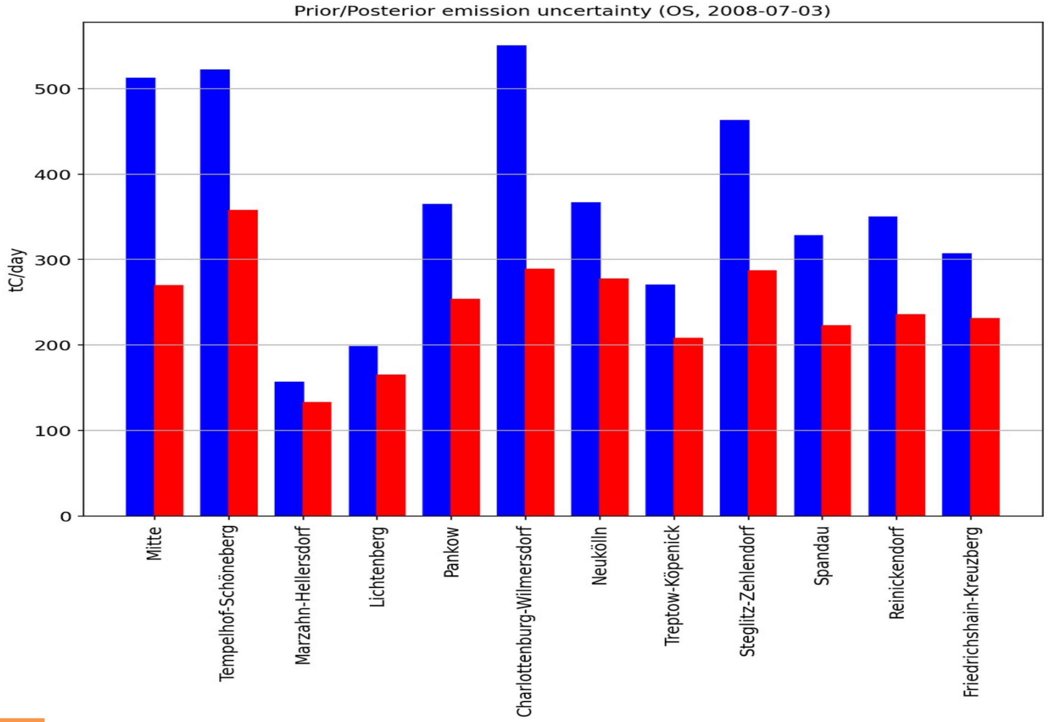




Other Sector emissions from Berlin districts

Experiment NO2 (uniform) Summer





Effect of adding NO2 on other sector at scale of Berlin districts:

- Stronger where emissions are large

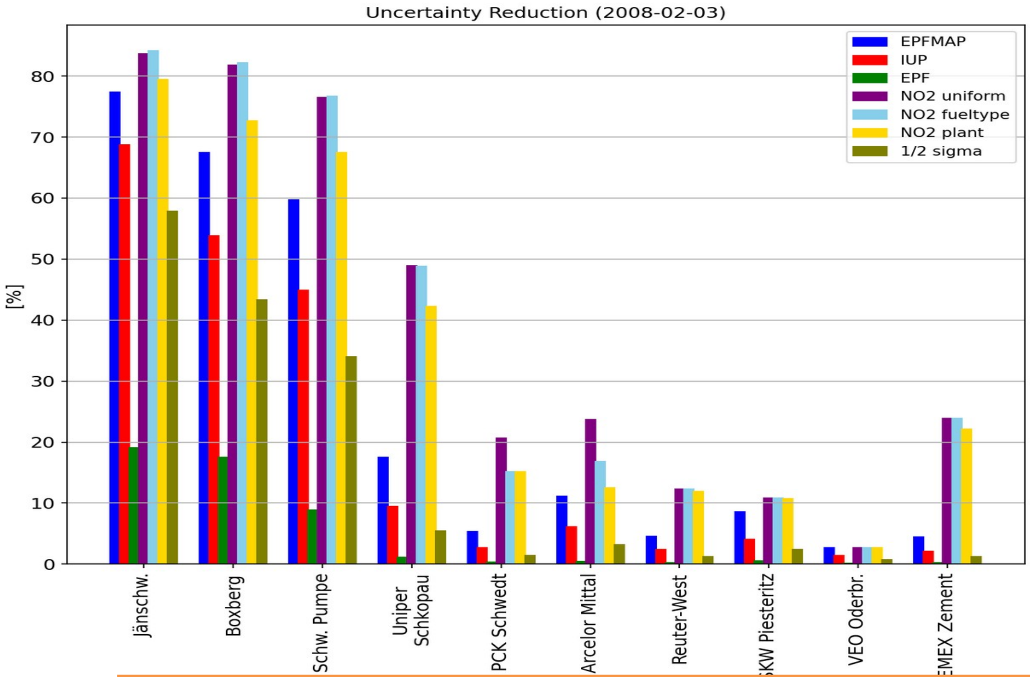
Experiments

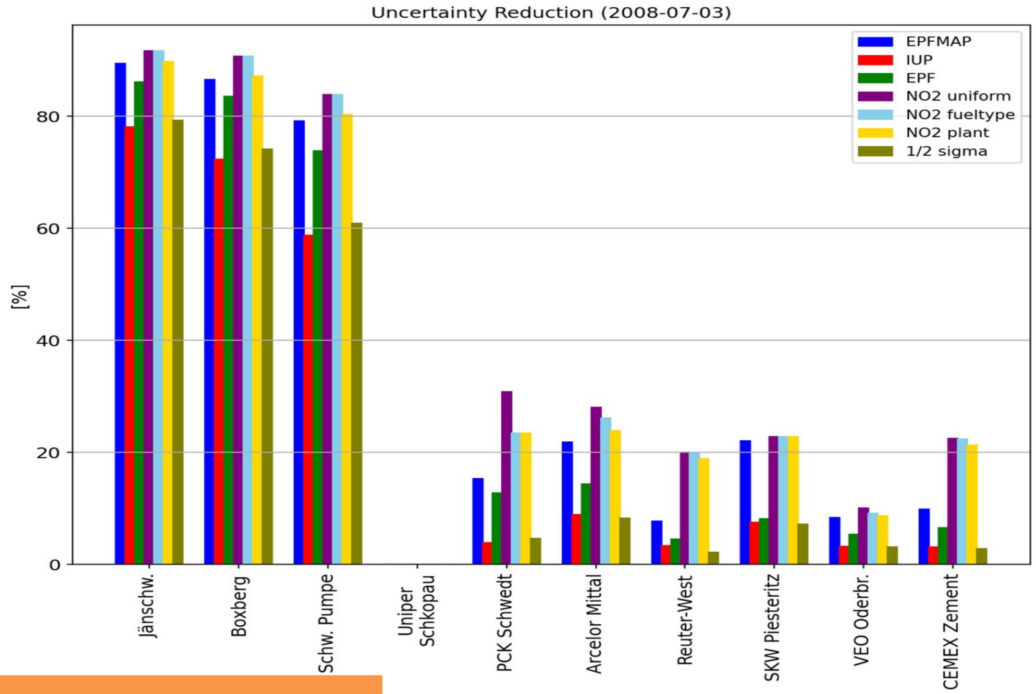
Table 3: List of experiments

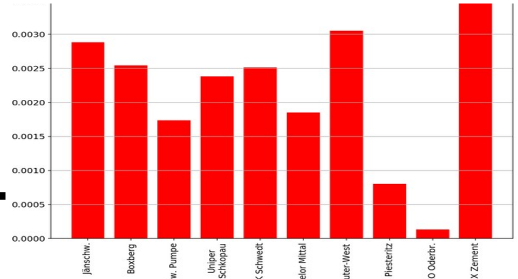
#	name	XCO2	NO2	Comment
1	EPFMAP (default)	NN w/ MAP	-	-
2	PMIF	PMIF	-	-
3	EPF	NN w/o MAP	-	-
4	NO2 per type	NN w/ MAP	σ_r per fuel type	-
5	NO2 per plant	NN w/ MAP	σ_r per plant	-
6	NO2 uniform	NN w/ MAP	σ_r uniform	-
7	1/2 plant prior σ	NN w/ MAP	-	-

We have seen experiments 1 and 6

Results Overview power plants



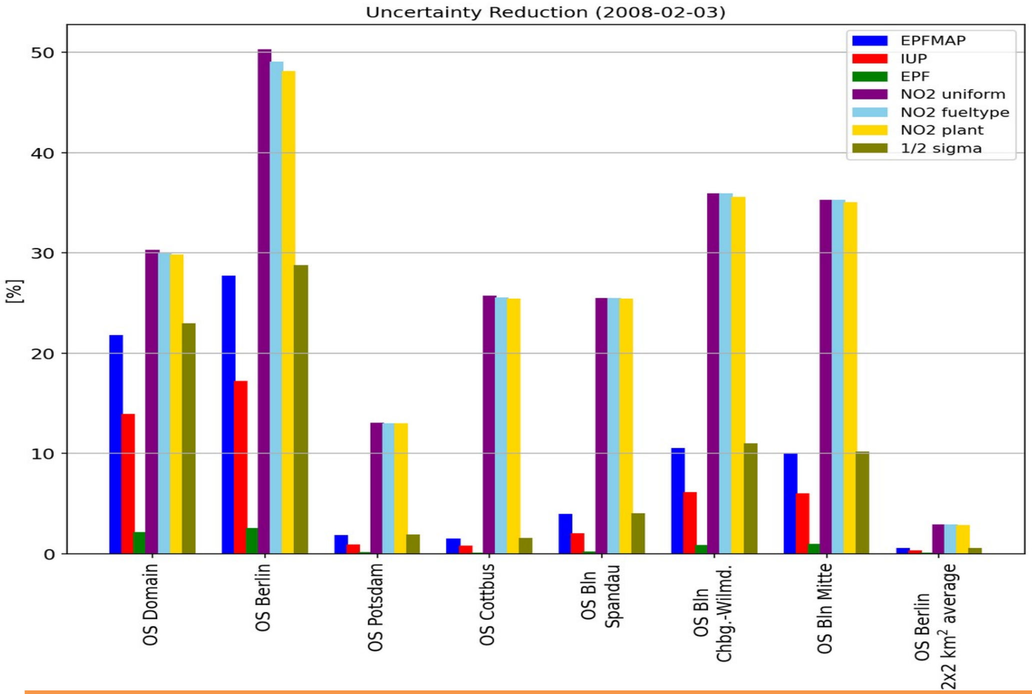


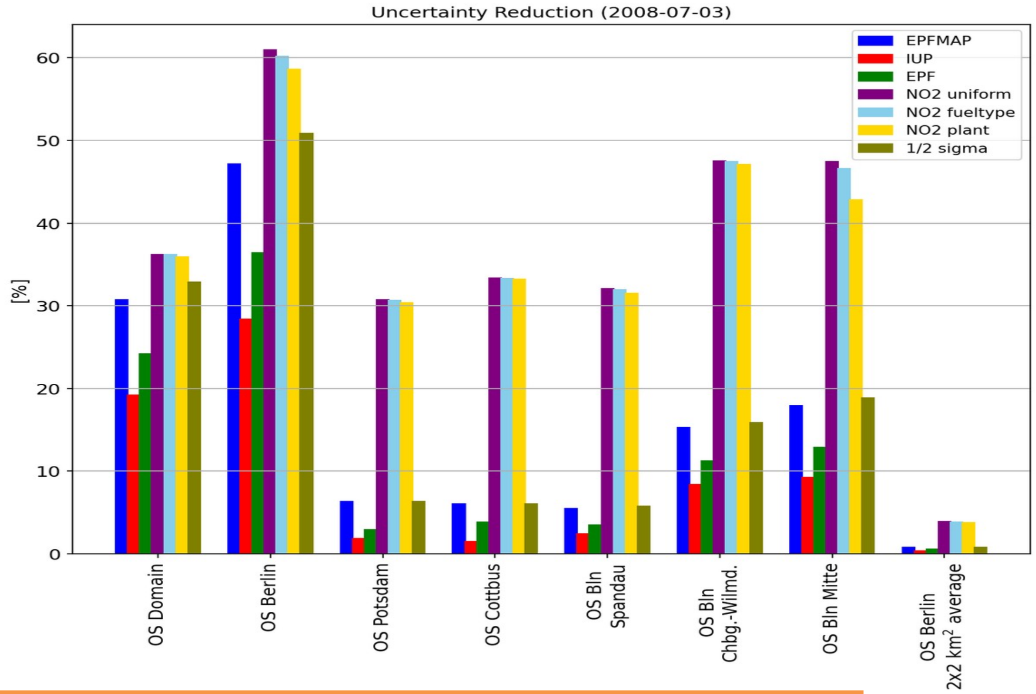


Performance for power plants:

- Strong uncertainty reduction for large power plants in default case
- Performance of default case better than that of IUP XCO2 error files for all plants
- The MAP has a strong impact in winter, where the performance w/o MAP is low, its impact in summer is moderate
- Even with reduced prior uncertainty strong uncertainty reduction for large plants,
- in particular in winter

Results Overview other sector





Performance for the other sector:

- Performance of default scenario better than that of IUP XCO2 error files on all scales
- The MAP has a strong impact, the added value is higher in winter, where the performance w/o MAP is low
- The smaller the scale the larger the effect of adding NO2
- The differentiation of uncertainty in the emission factor has a small impact over Berlin and some of its districts
- Reducing the prior uncertainty on plant emissions yields small improvement for the other sector

Summary and Conclusions

- Developed error parameterisation formula based on artificial neural network for XCO2 w/ and w/o MAP
- Developed modelling chain from parameters to XCO2 and NO2 observations
- Full Jacobian allows
  - decomposition of XCO2 column in terms of spatial emission impact
  - rigorous uncertainty propagation (Quantitative Network Design approch) to assess CO2M observation impact
- Assessments include temporal and spatial scales typically not covered by inventories
- High XCO2 constraint on emissions from larger power plants
- XCO2 constraint on other sector emissions increasing with spatial scale from 2km (uncertainty reduction: <1% average; ~8% maximum) to scale of Berlin district (~2-18 %) to the scale of Berlin (28-48%).
- Higher XCO2 constraint in summer on both, power plants and other sector
- The MAP has a strong impact in winter, where the performance w/o MAP is lower, its impact in summer is moderate
- Reducing prior uncertainty yields slightly weaker but still strong XCO2 impact for large plants (in particular in winter) and slightly higher impact on the other sector
- NO2 powerful additional constraint for power plants and other sector
- Adding NO2 has particularly high impact
  - in winter when XCO2 leaves more scope for improvement and lifetime is longer
  - on other sector on smaller scales and on smaller plants where XCO2 leaves more scope for improvement
  - where emission ratio is high
- Overall best performance for combination of XCO2 and NO2 in summer
- Correlations in the uncertainties of NO2/C emission factors of plants have a moderate effect on added value of NO2