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# Assessing the constraint of the CO<sub>2</sub> 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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<sup>7</sup> TNO, Utrecht, The Netherlands

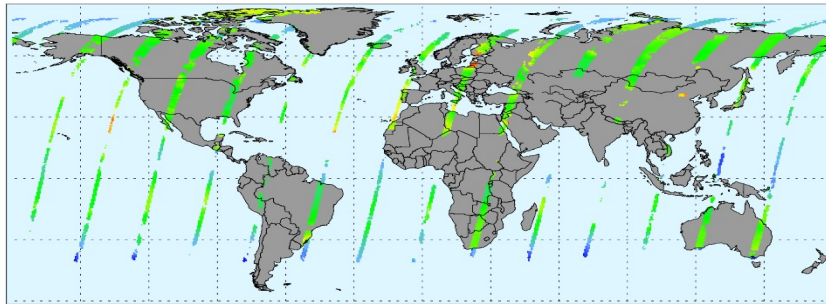
<sup>8</sup> ESA, Noordwijk, The Netherlands

EGU, General Assembly 2021

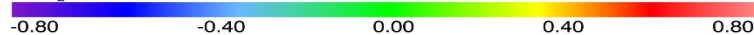
# CO2 Monitoring Mission (CO2M)

- Planned by Copernicus Programme
- Fossil fuel carbon emissions
- Multi-Satellite Constellation
- Imaging Capability
- 2 km x 2 km grid
- wide swath
- XCO<sub>2</sub>
- NO<sub>2</sub>
- Multi-Angular Polarimeter (Aerosols)

S7-c3s1  
XCO<sub>2</sub> Systematic Error 24.06



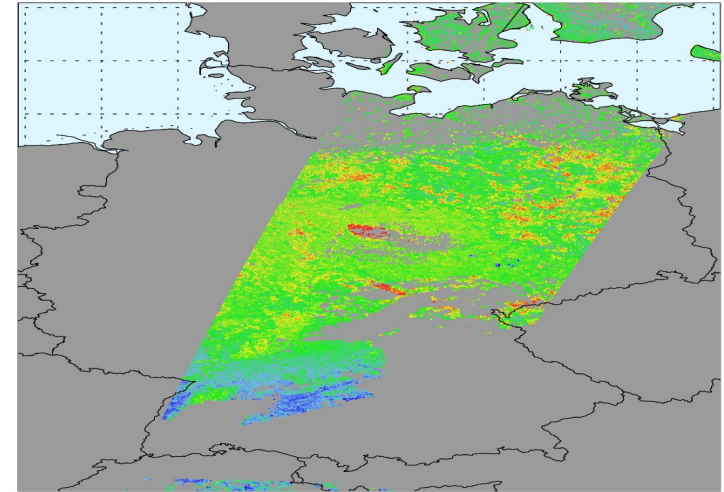
XCO<sub>2</sub> systematic error [ppm]



SW250 / nadir&glint

Michael.Buchwitz@iup.physik.uni-bremen.de, 4 Dec 2017 (COFFDAS) (he\_v02\_c0s1\_20080624.nc)

S7-c3s2  
24-Jun  
XCO<sub>2</sub>(FP) random error



XCO<sub>2</sub>(FP) random error [ppm]

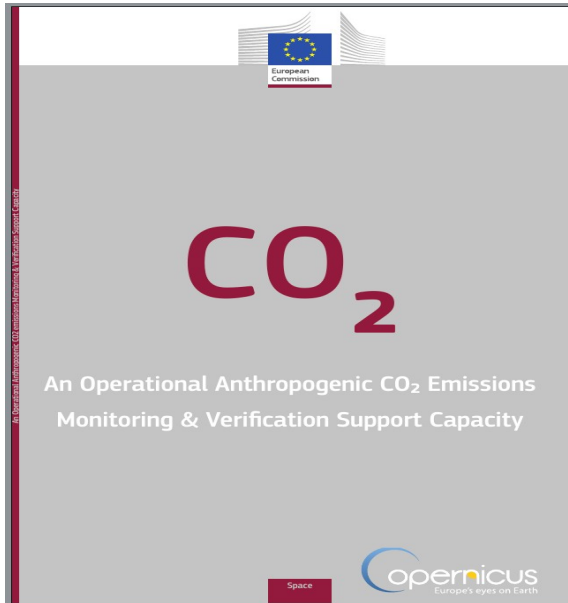


SW=290/QF=on

Michael.Buchwitz@iup.physik.uni-bremen.de, 30-Nov-2017, v5(pmlf, c3s2) data\_v01/pmlf\_v02\_c3s2\_2008176\_1125.h5\_SW290.as2

# Capabilities of MVS capacity

## 1.5.1 Stepwise approach for a CO<sub>2</sub> 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<sub>2</sub> concentration gradient, because the area contains a large emitting CO<sub>2</sub> source. This can be a large power plant, a megacity or any other activity characterized by strong CO<sub>2</sub> 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<sub>2</sub> emissions anomalies relative to the CO<sub>2</sub> 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

## 1.5.1 Stepwise approach for a CO<sub>2</sub> 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:

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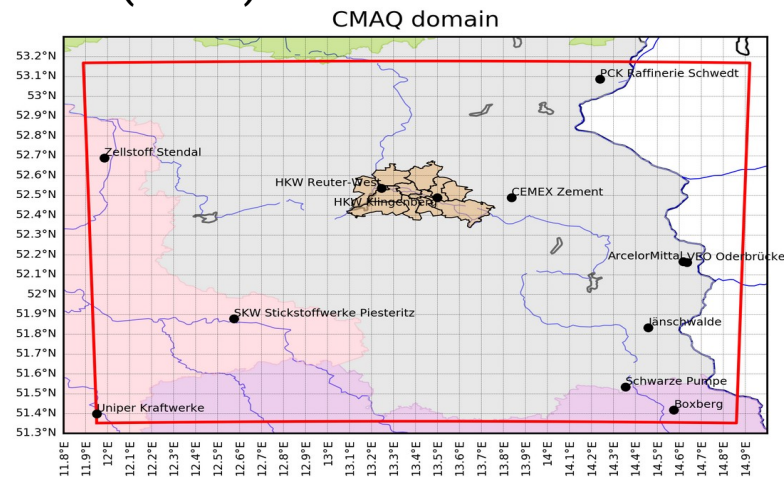
**C4. Assessing the national emissions and changes with 5 year time steps.** This requires the entire screening of the full area covered by the country, in order to account for changes in emission patterns with new or occasional hotspots.

Assessments require  
High resolution Modelling  
of CO<sub>2</sub>M 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

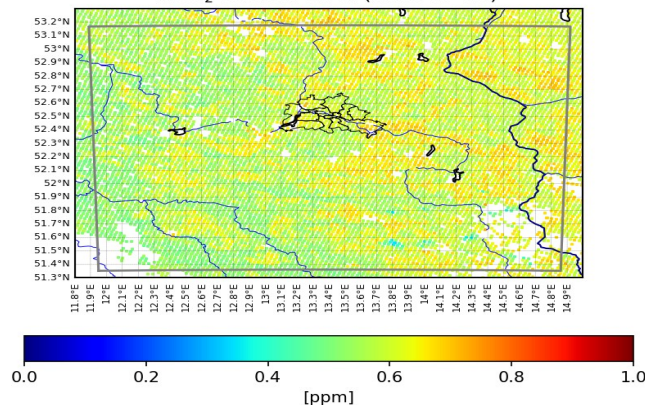




# Simulated Random and Systematic Errors over Berlin

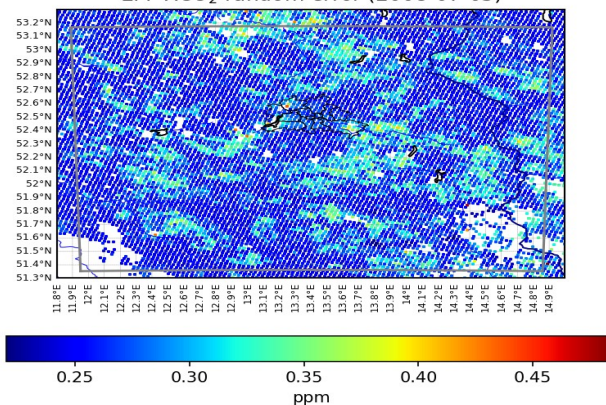
## IUP/PMIF

XCO<sub>2</sub> random error (2008-07-03)



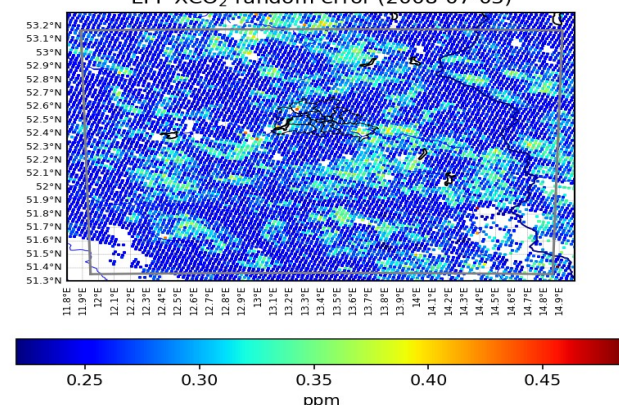
## ANN EPF w/o MAP

EPF XCO<sub>2</sub> random error (2008-07-03)

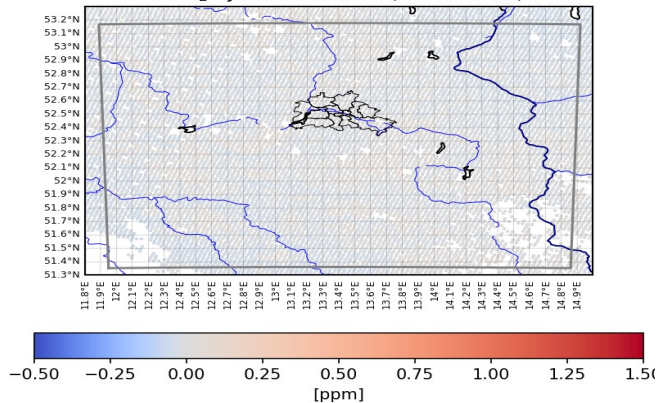


## ANN EPF w MAP

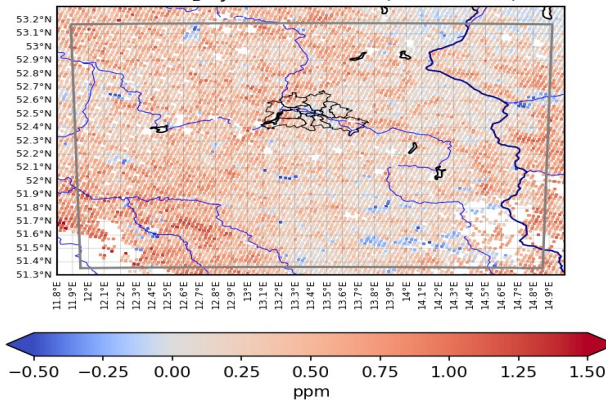
EPF XCO<sub>2</sub> random error (2008-07-03)



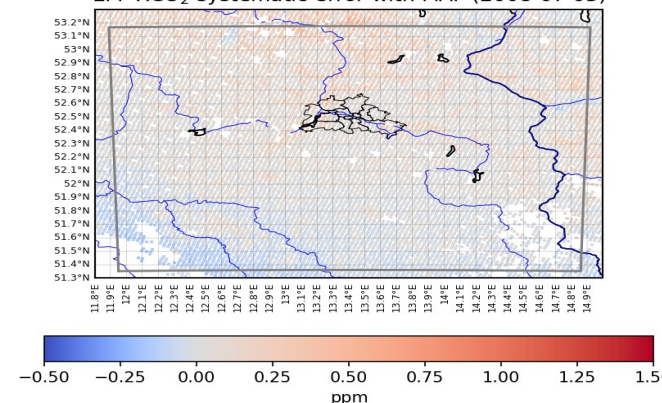
XCO<sub>2</sub> systematic error (2008-07-03)



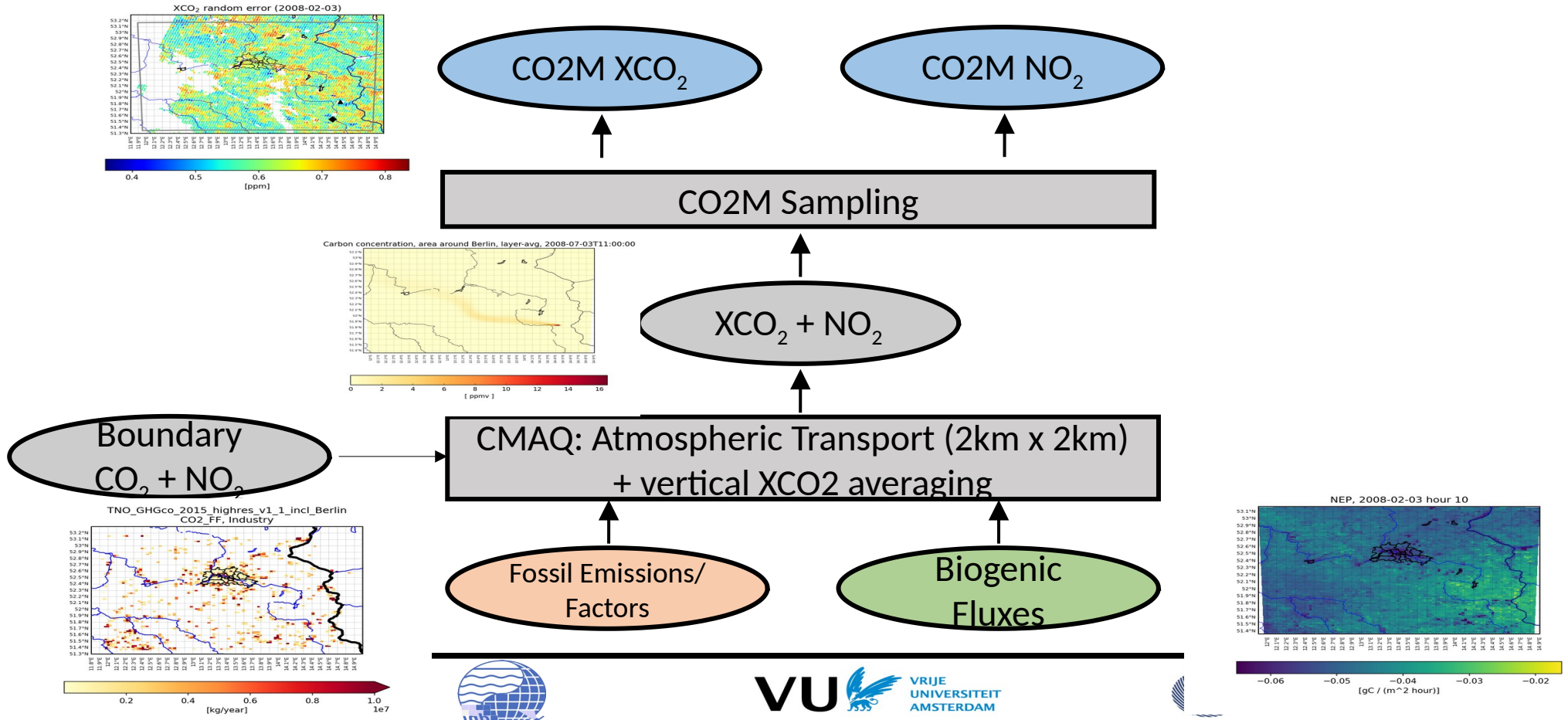
EPF XCO<sub>2</sub> systematic error (2008-07-03)



EPF XCO<sub>2</sub> systematic error with MAP (2008-07-03)



# Modelling Chain



# Modelling Chain for XCO<sub>2</sub>

$$XCO_2 = XCO_{2,initial} + T_{Surf} e_{CO_2} + T_{lateral} f_{CO_2}$$

$$e_{CO_2} = e_{CO_2,energy} + e_{CO_2,other} + e_{CO_2,bio}$$

$$e_{CO_2,bio} = B(x_{bio})$$

$$T_{Surf} e_{CO_2} = T_{Surf,energy} e_{CO_2,energy} + T_{Surf,other} e_{CO_2,other} + TB'(x_{bio})$$

$e_{CO_2}$  : emissions over 24 hours

$f_{CO_2}$  : lateral inflow over 24 hours

$XCO_{2,initial}$  : column 24 hours before overpass (ignored)

$T$  : atmospheric Transport and CO<sub>2</sub>M sampling

$B$  : terrestrial biosphere model

Compact Notation:

$$XCO_2 = M' x$$



# Quantitative Network Design Method

Uncertainty

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

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

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

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

Performance  
Metric  
“uncertainty  
reduction”

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

What we do  
know already

Coverage <sup>4)</sup>

(5)

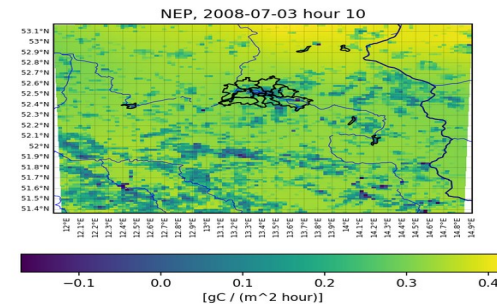
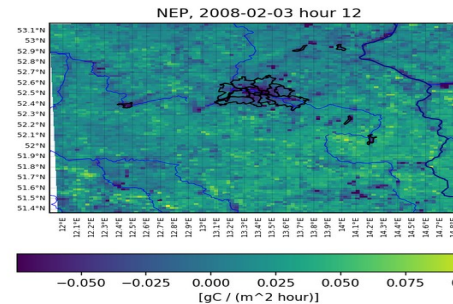
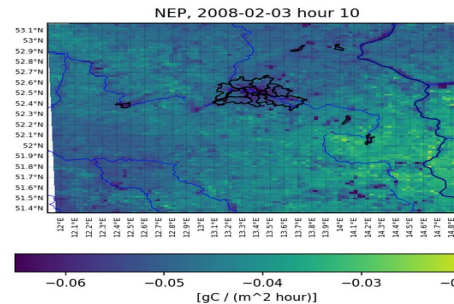
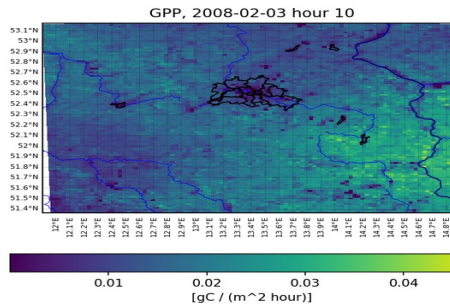
(6)

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

# Model for Natural Fluxes

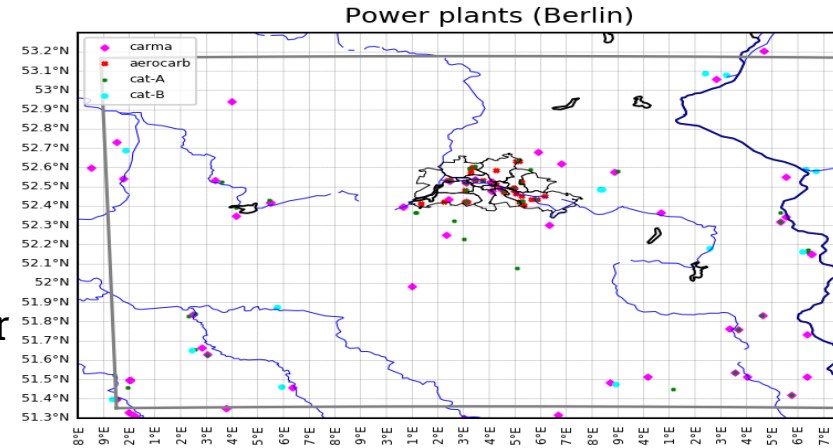
- Newly developed (W. Knorr)
- Based on Knorr and Heimann (1995), used in Kaminski et al. (2017)
- Runs on transport model grid (2 km by 2 km)
- Simulates Net and Gross (GPP, ecosystem respiration) Fluxes at hourly time step
- Diagnostic
- Driven by JRC-TIP FAPAR and climate (Incoming solar/thermal radiation, 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

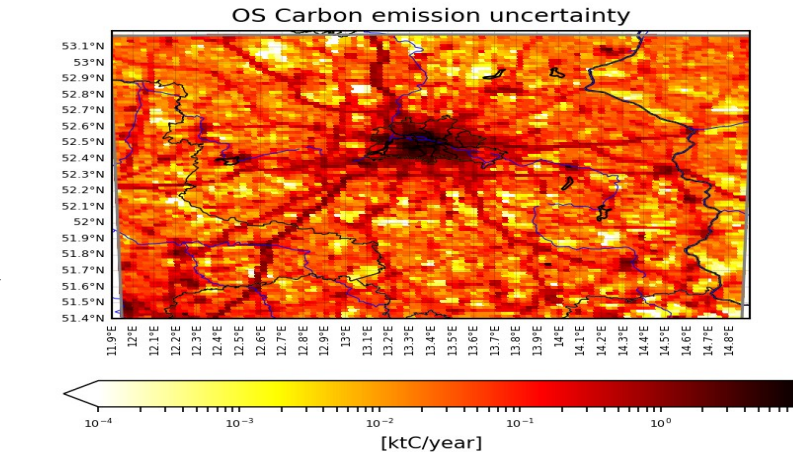
## Energy Generation

- 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%



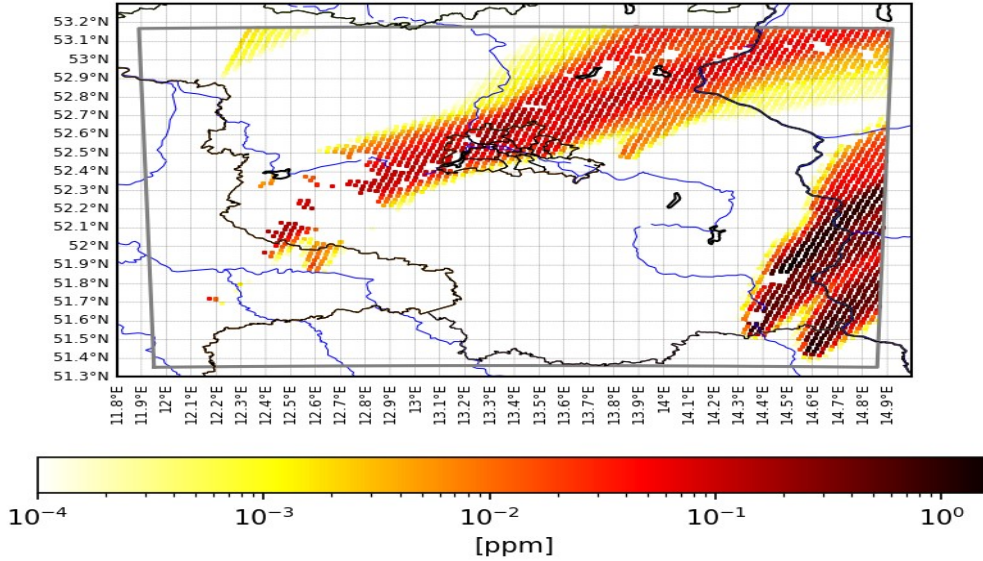
## Other Sector

- 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%

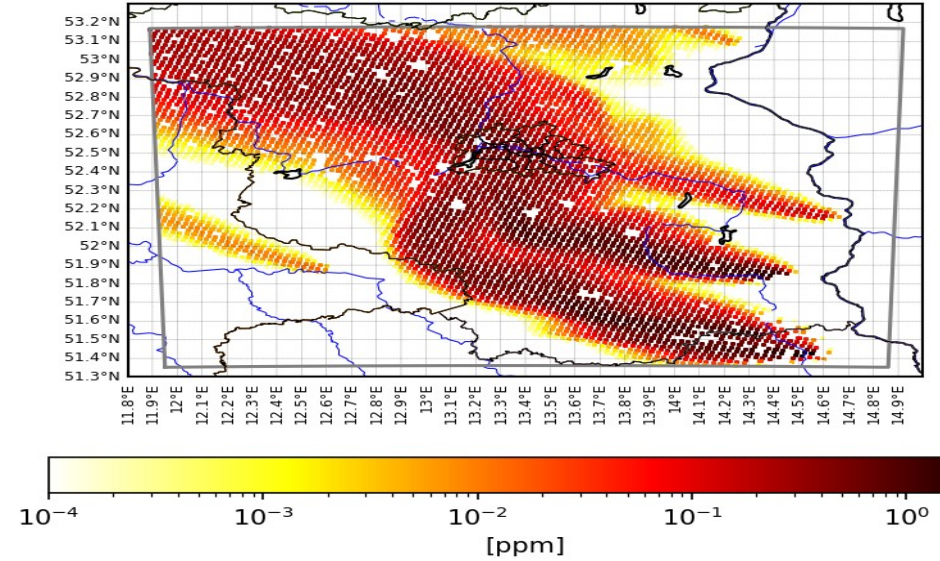


# Plumes from Power Plants

Change of XCO<sub>2</sub> (2008-02-03) w.r.t.  
emissions from 12 largest emitting power plants



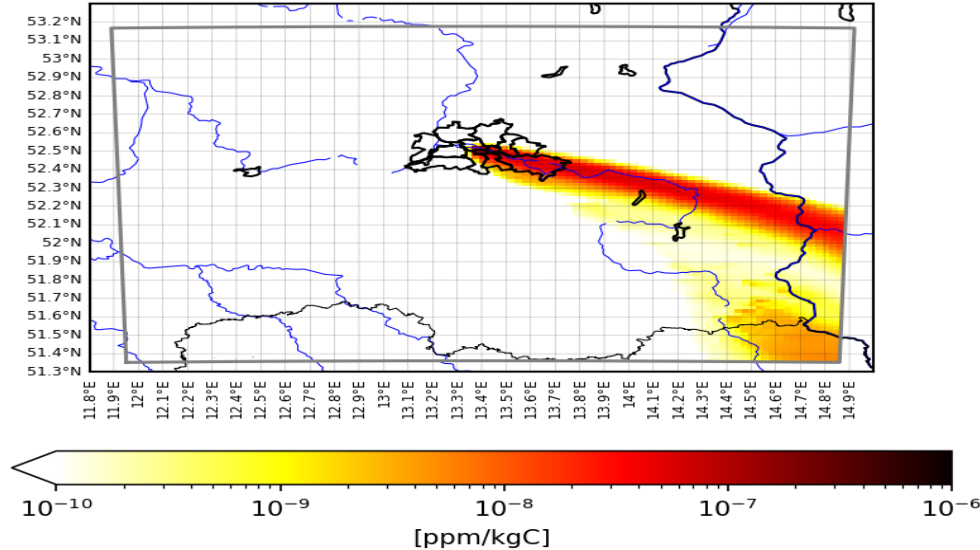
Change of XCO<sub>2</sub> (2008-07-03) w.r.t.  
emissions from 12 largest emitting power plants



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

# XCO2 Jacobian (Brandenburg Gate)

$d(XCO_2)/d(\text{emission})$  w.r.t. surface emissions, 2008-07-03T110000  
XCO2-location=13.3777/52.5163, min/max=0.000E+00/1.214E-07



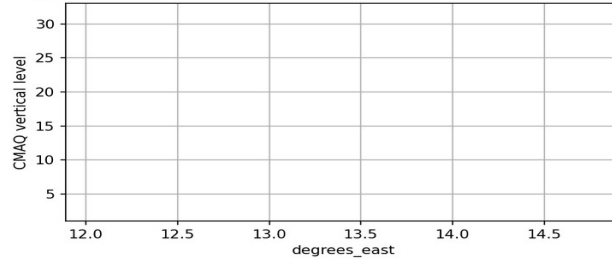
Footprint of XCO2 over Brandenburg Gate in summer

- 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



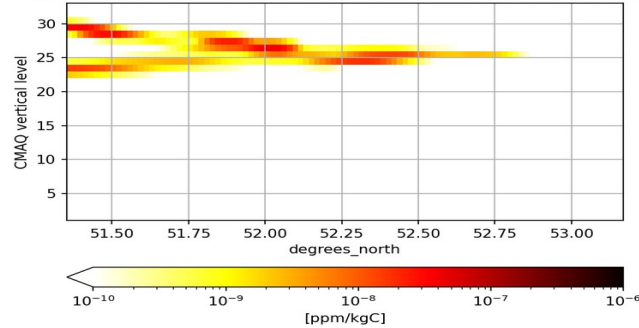
# XCO<sub>2</sub> Jacobian (Brandenburg Gate)

$d(XCO_2)/d(emission)$  w.r.t. influx from northern, 2008-07-03T110000  
XCO<sub>2</sub>-location=13.3777/52.5163, min/max=0.000E+00/1.411E-15

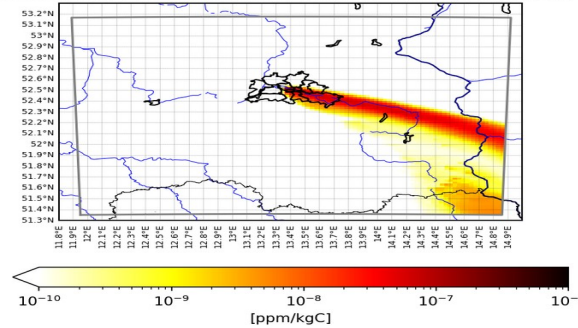


And with lateral inflow

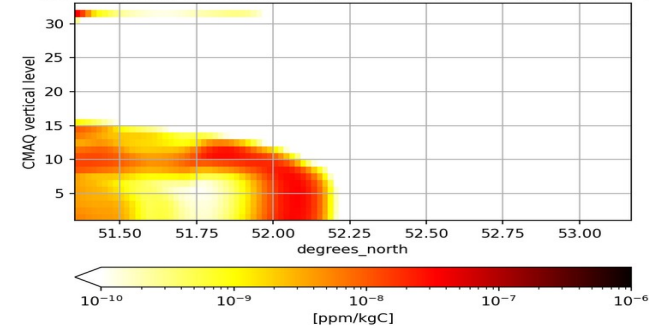
$d(XCO_2)/d(emission)$  w.r.t. influx from western, 2008-07-03T110000  
XCO<sub>2</sub>-location=13.3777/52.5163, min/max=0.000E+00/4.016E-08



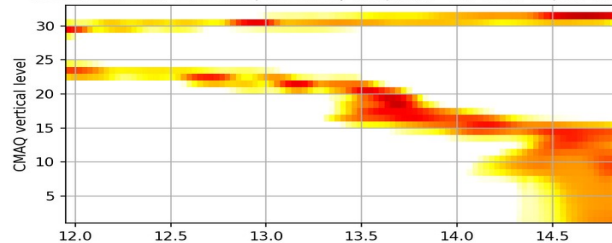
$d(XCO_2)/d(emission)$  w.r.t. surface emissions, 2008-07-03T110000  
XCO<sub>2</sub>-location=13.3777/52.5163, min/max=0.000E+00/1.214E-07



$d(XCO_2)/d(emission)$  w.r.t. influx from eastern, 2008-07-03T110000  
XCO<sub>2</sub>-location=13.3777/52.5163, min/max=0.000E+00/3.335E-08

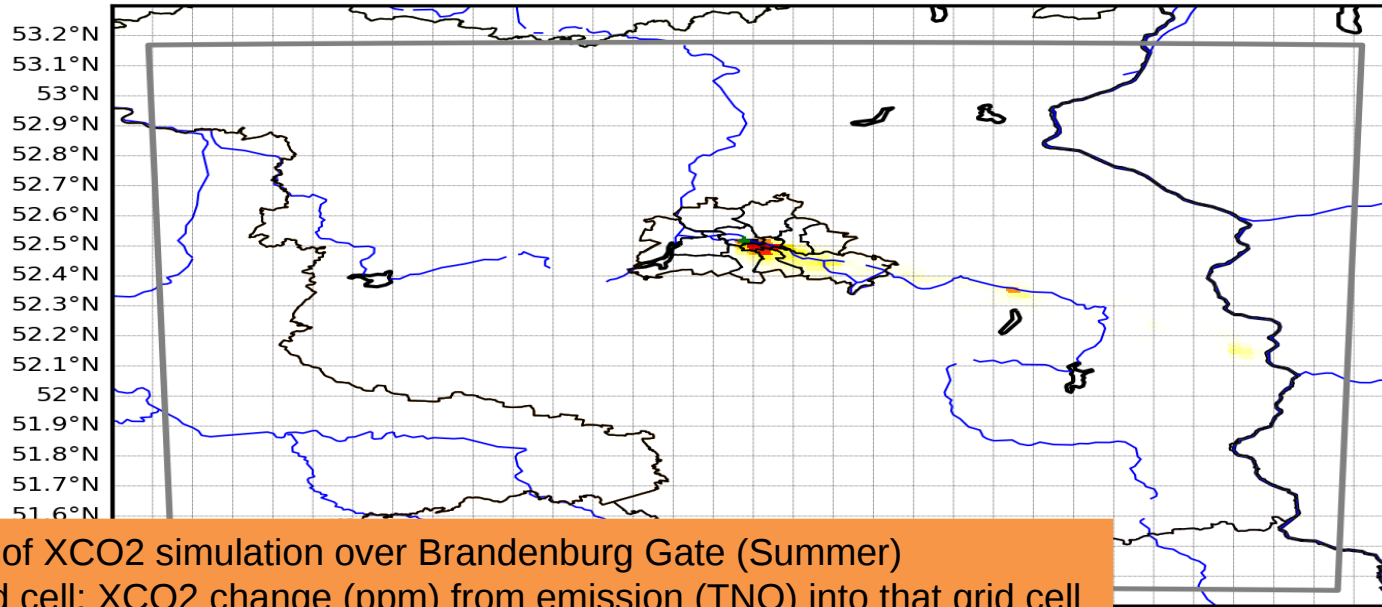


$d(XCO_2)/d(emission)$  w.r.t. influx from southern, 2008-07-03T110000  
XCO<sub>2</sub>-location=13.3777/52.5163, min/max=0.000E+00/7.578E-08



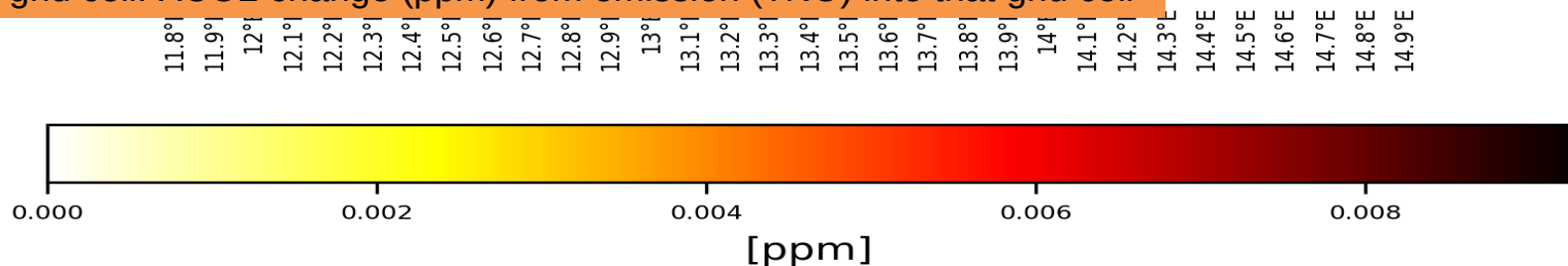
# Multiplied with TNO emission field: Decomposition of XCO<sub>2</sub> signal

OS emission contribution to XCO<sub>2</sub> at Brandenburger-Tor  
 $\Delta\text{XCO}_2 = 0.111\text{ppm}$ , 2008-07-03



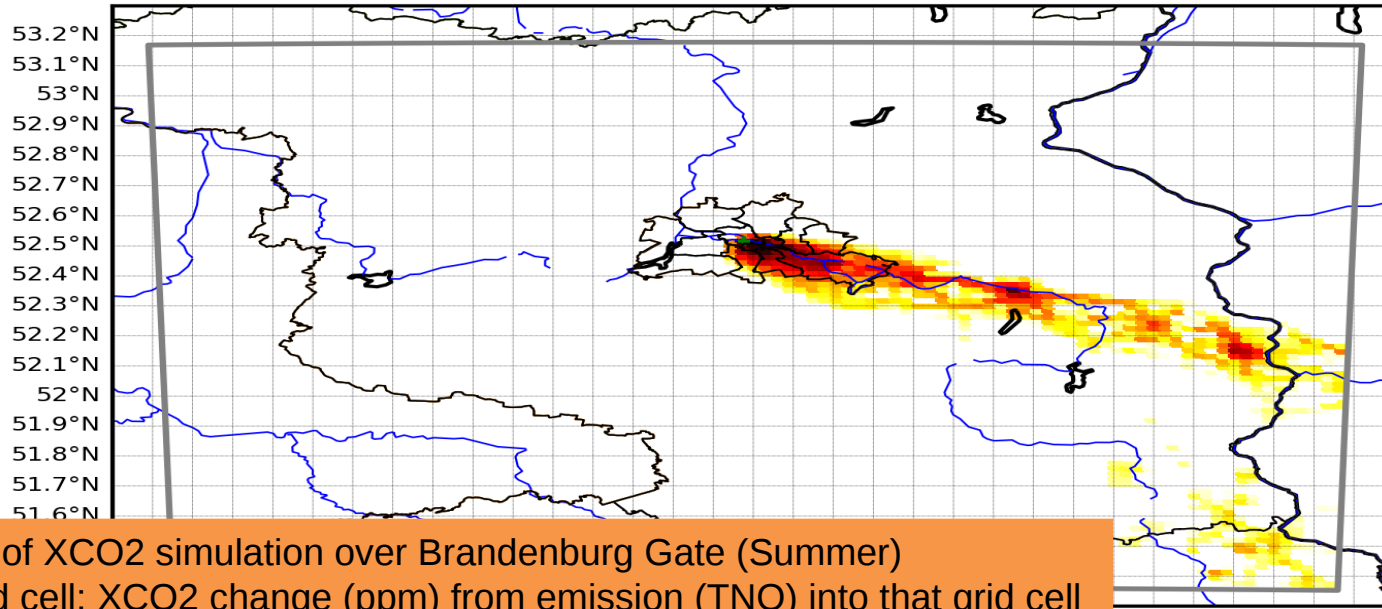
Decomposition of XCO<sub>2</sub> simulation over Brandenburg Gate (Summer)

- For each grid cell: XCO<sub>2</sub> change (ppm) from emission (TNO) into that grid cell



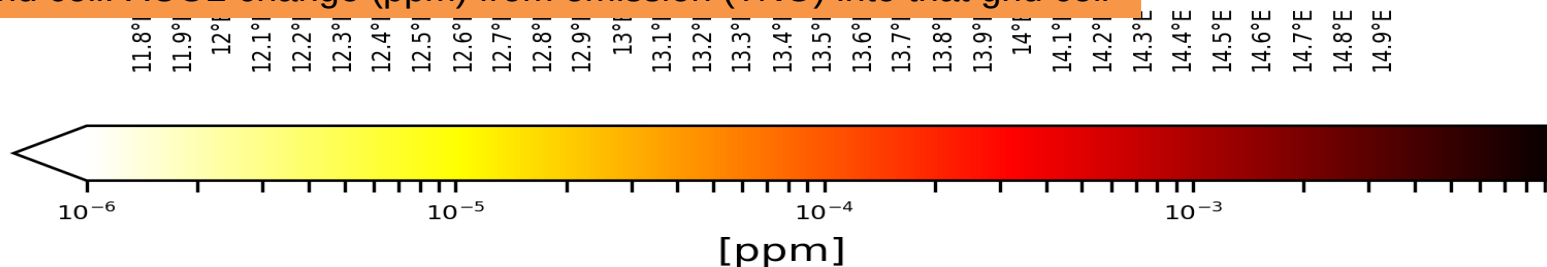
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OS emission contribution to XCO<sub>2</sub> at Brandenburger-Tor  
(2008-07-03)



Decomposition of XCO<sub>2</sub> simulation over Brandenburg Gate (Summer)

- For each grid cell: XCO<sub>2</sub> change (ppm) from emission (TNO) into that grid cell



# NO<sub>2</sub>

$$X_{CO_2} = T_{CO_2} e_{CO_2}$$

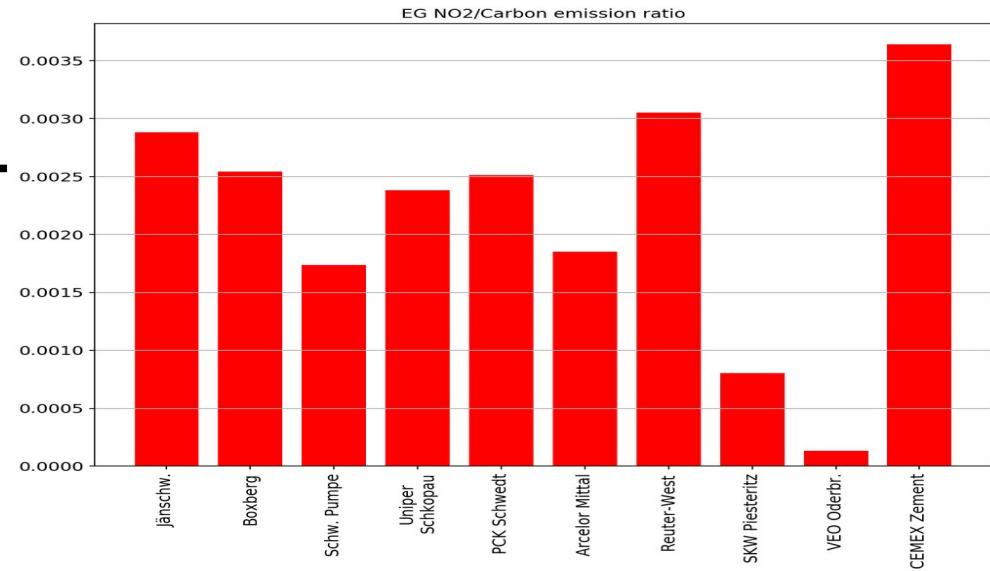
$$NO_2 = T_{NO_2} e_{NO_2}$$

$$e_{NO_2} = r e_{CO_2}$$

$$NO_2 = T_{NO_2} r e_{CO_2}$$

$r$ : emission ratio, provides link to CO<sub>2</sub>

- Combined use of XCO<sub>2</sub> and NO<sub>2</sub> 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 CO<sub>2</sub> and NO<sub>x</sub>
- provided by Ingrid Super (TNO)
- $r = \text{NO}_x/\text{CO}_2$  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)

	CO <sub>2</sub>		No <sub>x</sub>		No <sub>x</sub> /CO <sub>2</sub>
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			



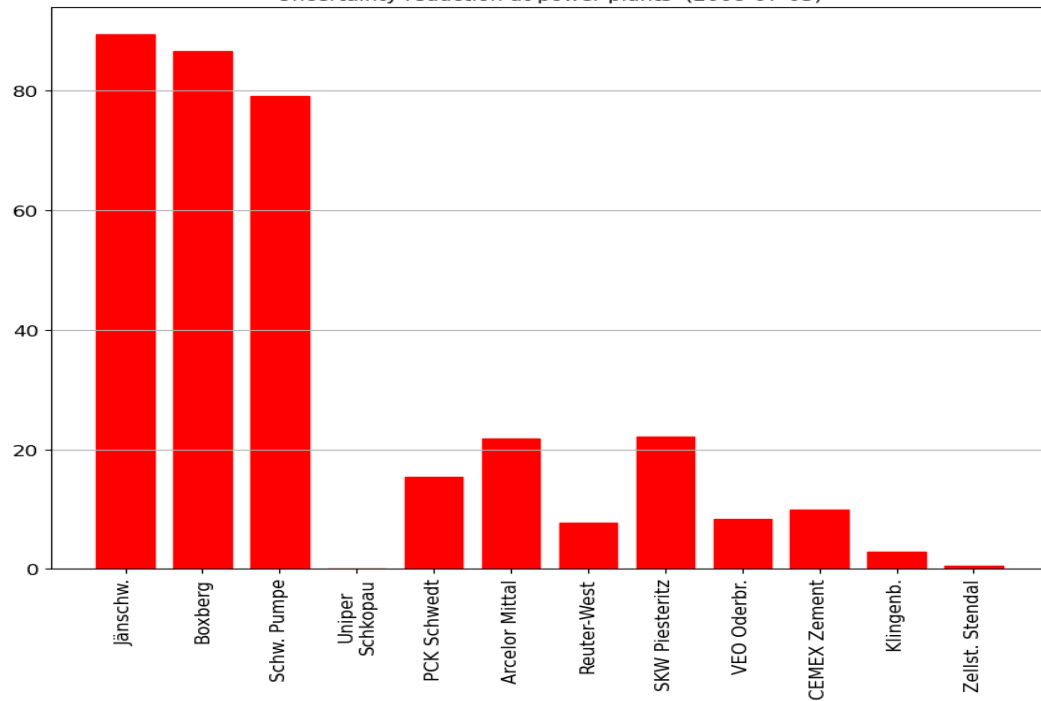
# Setup Default Experiment

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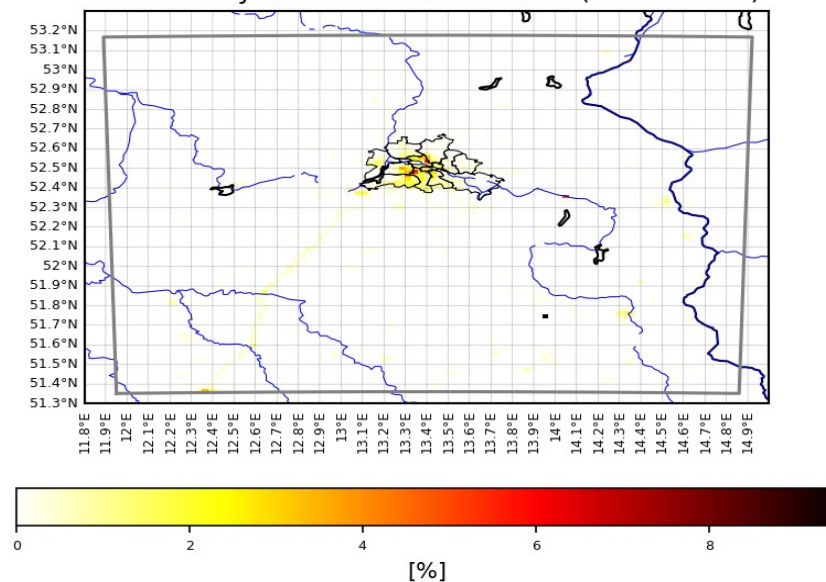
- XCO<sub>2</sub> retrieval uses MAP
- no NO<sub>2</sub>
- 20% prior uncertainty for each power plant
- 20% prior uncertainty for each natural flux parameter
- 20% prior uncertainty of other sector for Berlin (52.8% at pixel level)
- 1 ppm uncertainty of lateral inflow, fully correlated at 10 km horizontally, otherwise uncorrelated

# Default Experiment Summer

Uncertainty reduction at power plants (2008-07-03)

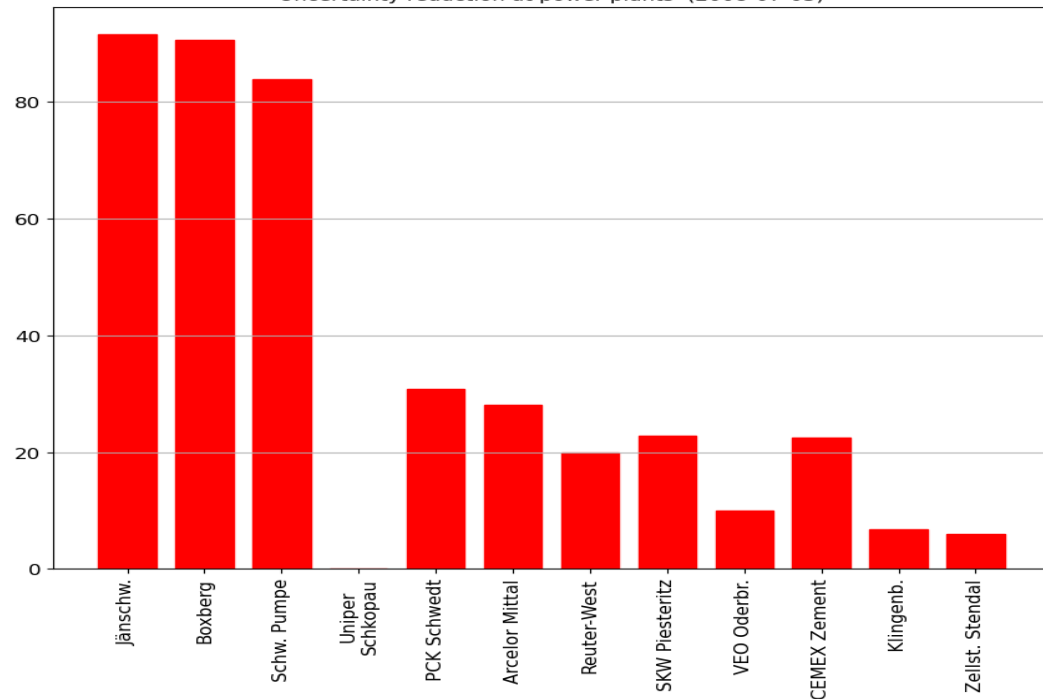


Uncertainty reduction other sector (2008-07-03)

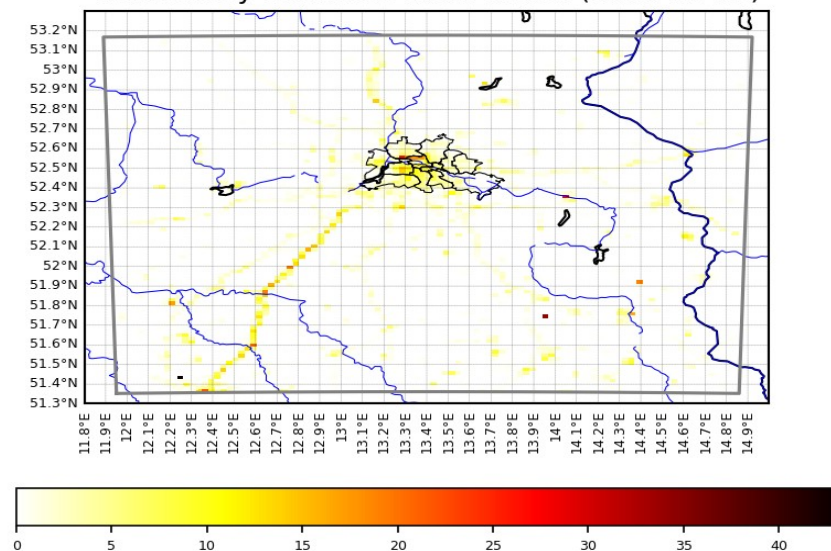


# Experiment NO2 (uniform) Summer

Uncertainty reduction at power plants (2008-07-03)

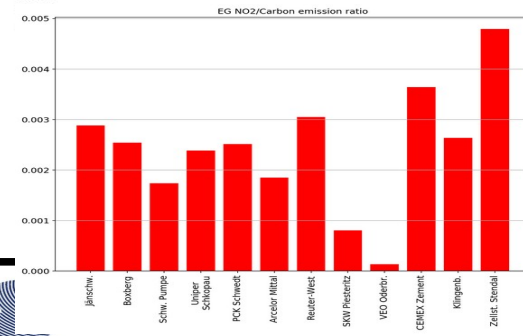


Uncertainty reduction other sector (2008-07-03)



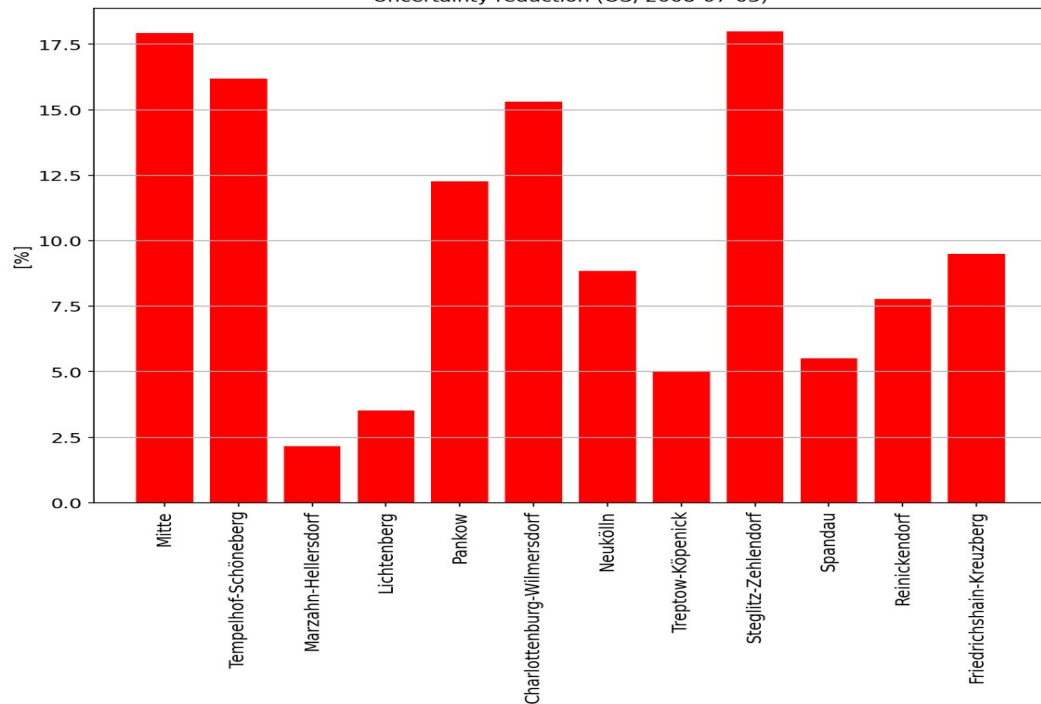
## Adding NO2:

- 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

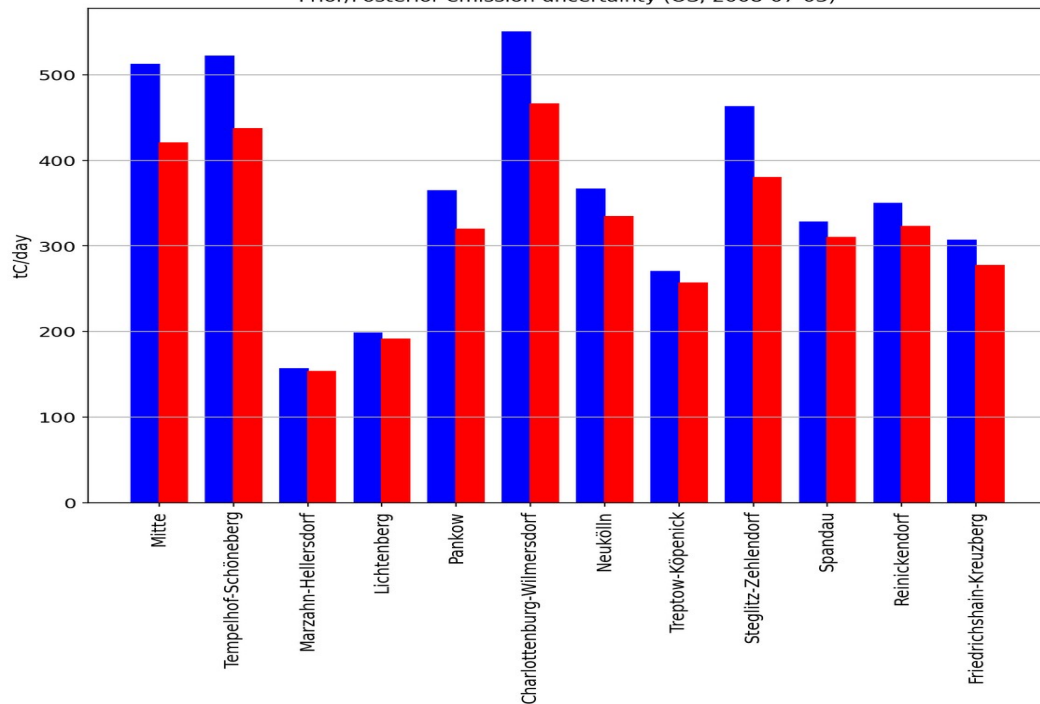


# Default Experiment Summer

Uncertainty reduction (OS, 2008-07-03)



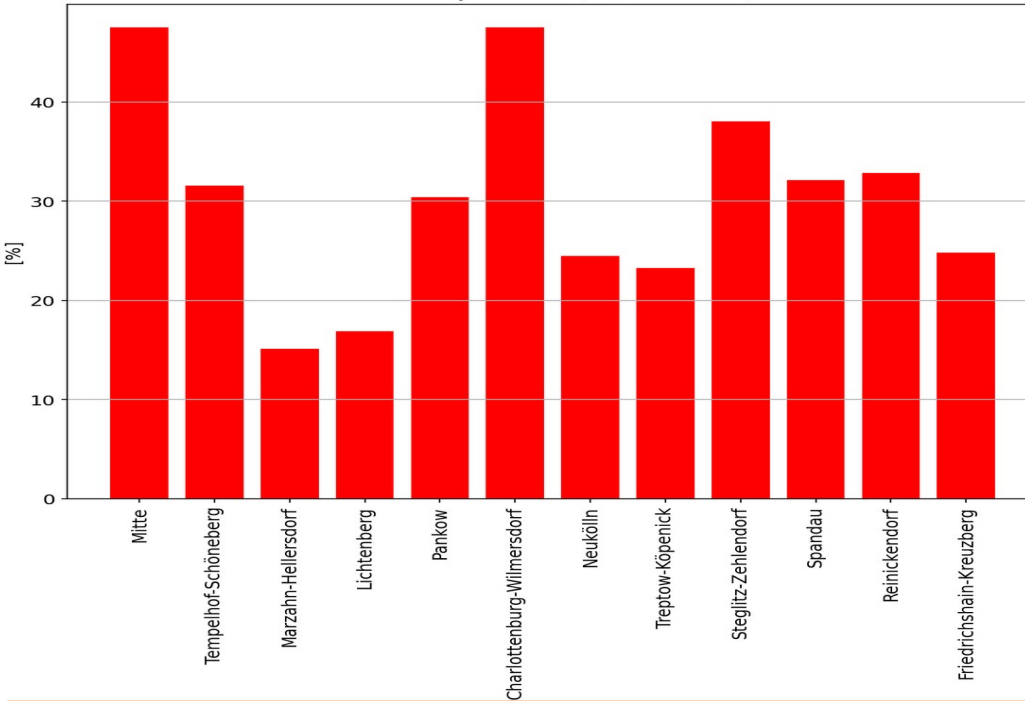
Prior/Posterior emission uncertainty (OS, 2008-07-03)



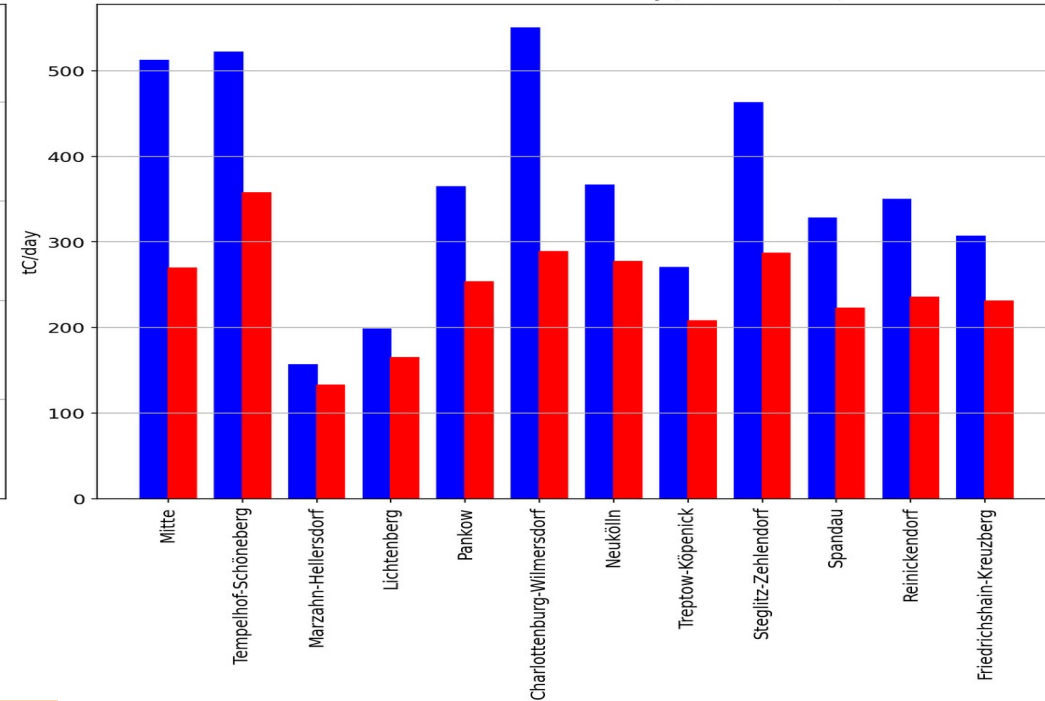
Other Sector emissions from Berlin districts

# Experiment NO2 (uniform) Summer

Uncertainty reduction (OS, 2008-07-03)



Prior/Posterior emission uncertainty (OS, 2008-07-03)



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

- Stronger where emissions are large



# Experiments

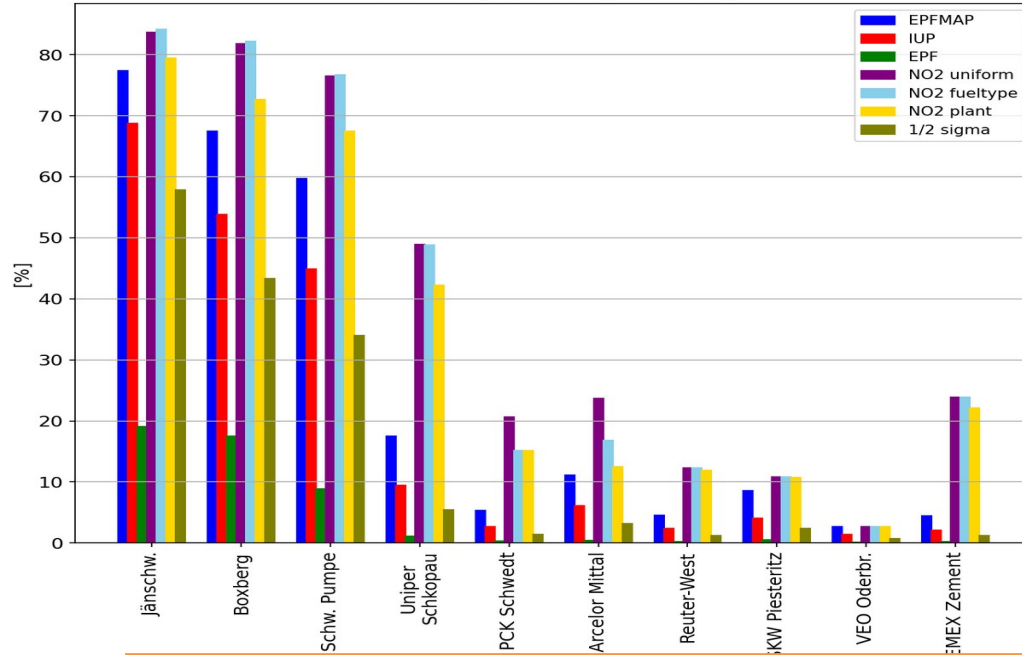
Table 3: List of experiments

#	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	$\sigma_r$ per fuel type	-
5	NO2 per plant	NN w/ MAP	$\sigma_r$ per plant	-
6	NO2 uniform	NN w/ MAP	$\sigma_r$ uniform	-
7	1/2 plant prior $\sigma$	NN w/ MAP	-	-

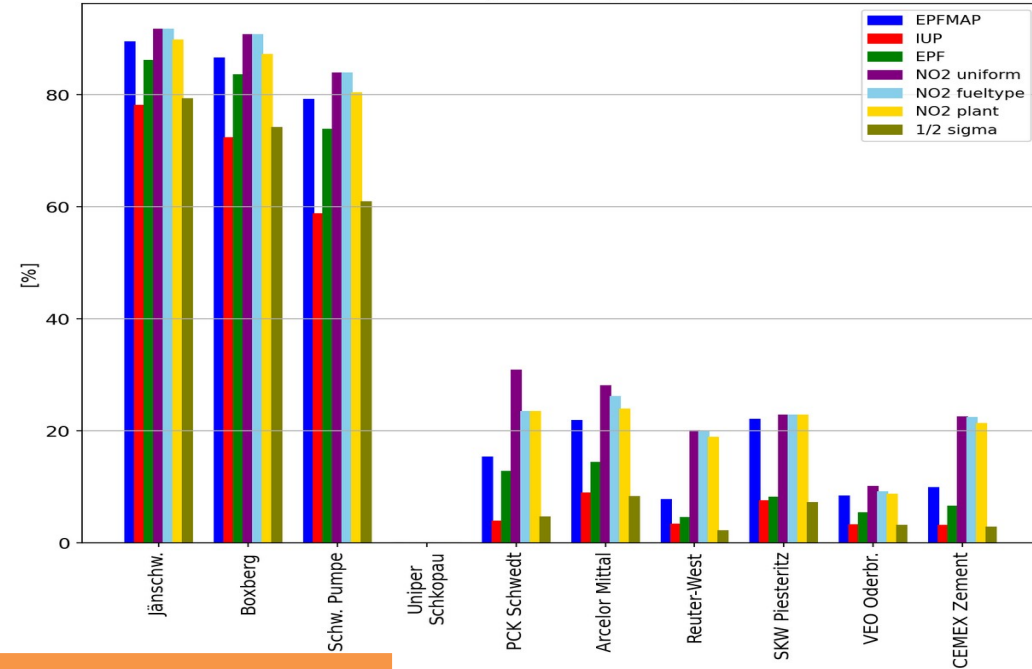
We have seen experiments 1 and 6

# Results Overview power plants

Uncertainty Reduction (2008-02-03)

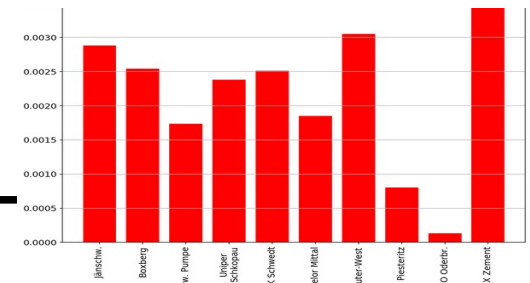


Uncertainty Reduction (2008-07-03)

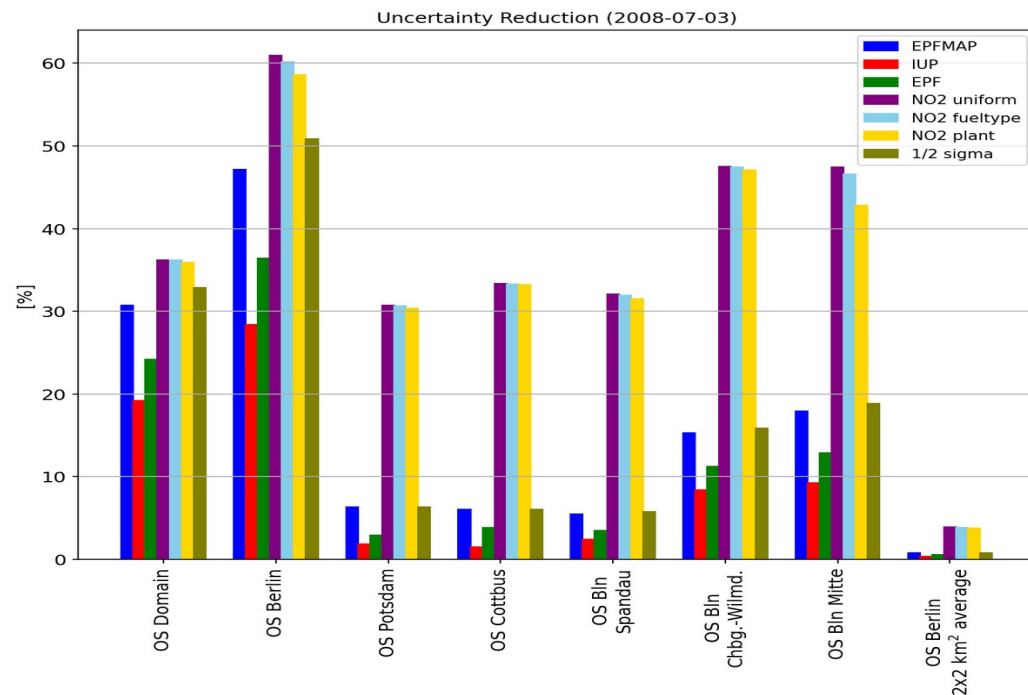
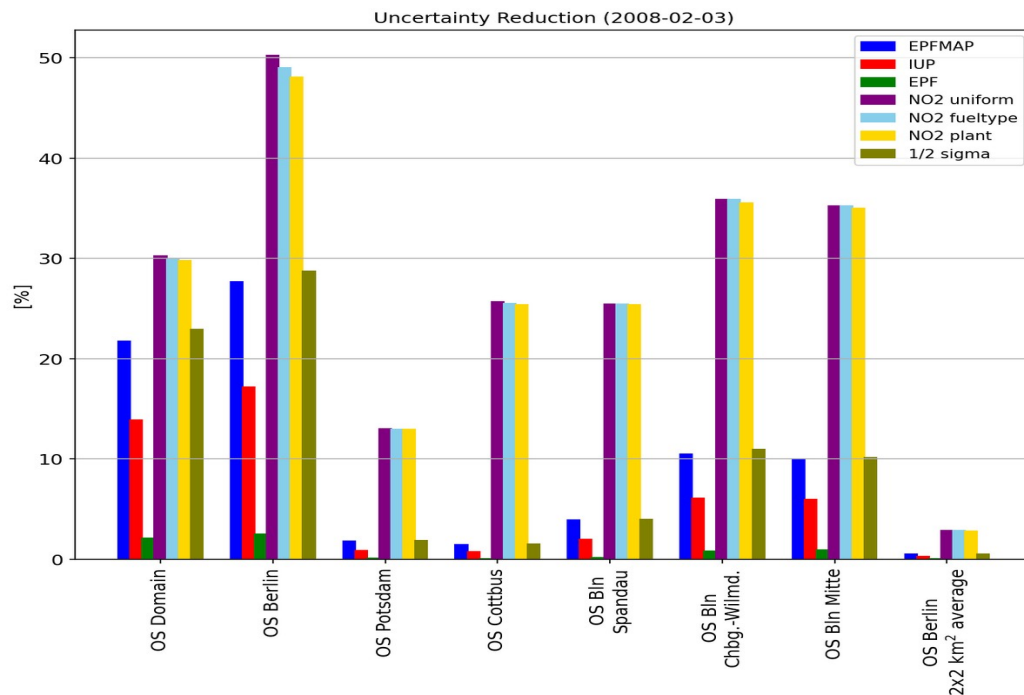


## Performance for power plants:

- 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 XCO<sub>2</sub> w/ and w/o MAP
- Developed modelling chain from parameters to XCO<sub>2</sub> and NO<sub>2</sub> observations
- Full Jacobian allows
  - decomposition of XCO<sub>2</sub> column in terms of spatial emission impact
  - rigorous uncertainty propagation (Quantitative Network Design approach) to assess CO<sub>2</sub>M observation impact
- Assessments include temporal and spatial scales typically not covered by inventories
- High XCO<sub>2</sub> constraint on emissions from larger power plants
- XCO<sub>2</sub> 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 XCO<sub>2</sub> 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 XCO<sub>2</sub> impact for large plants (in particular in winter) and slightly higher impact on the other sector
- NO<sub>2</sub> powerful additional constraint for power plants and other sector
- Adding NO<sub>2</sub> has particularly high impact
  - in winter when XCO<sub>2</sub> leaves more scope for improvement and lifetime is longer
  - on other sector on smaller scales and on smaller plants where XCO<sub>2</sub> leaves more scope for improvement
  - where emission ratio is high
- Overall best performance for combination of XCO<sub>2</sub> and NO<sub>2</sub> in summer
- Correlations in the uncertainties of NO<sub>2</sub>/C emission factors of plants have a moderate effect on added value of NO<sub>2</sub>

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