Quantifying CO_2 emissions of power plants with the CO_2M mission

Gerrit Kuhlmann (gerrit.kuhlmann@empa.ch)[1], Stephan Henne[1], Yasjka Meijer[2], Lukas Emmenegger[1] and Dominik Brunner[1]

[1] Empa, Swiss Federal Laboratories for Materials Science and Technology
[2] European Space Research and Technology Centre (ESTEC), European Space Agency (ESA)

Copernicus CO_2 monitoring (CO2M) satellite mission

- The Copernicus CO_2 Monitoring satellite mission is a constellation of CO_2 and NO_2 imaging satellites, which is currently prepared by the European Commission, ESA, EUMETSAT and ECMWF.
- CO2M is envisioned as the space component of the European CO_2 emissions monitoring and verification support capacity.
- A main goal of the CO2M mission is the quantification of the annual CO_2 emissions of megacities, power plants and other large facilitates.
- In this study, we investigate how well point source emissions can be quantified with combined CO_2 and NO_2 images using a data-driven mass-balance approach.
- The data-driven approach does not require performing expensive atmospheric transport simulations, which allows it to be applied globally to large amounts of satellite observations.

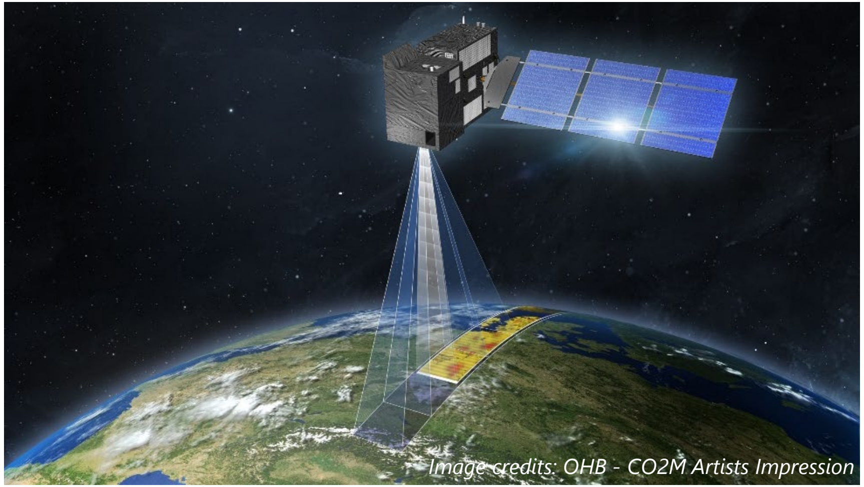


Image credits: OHB - CO2M Artists Impression

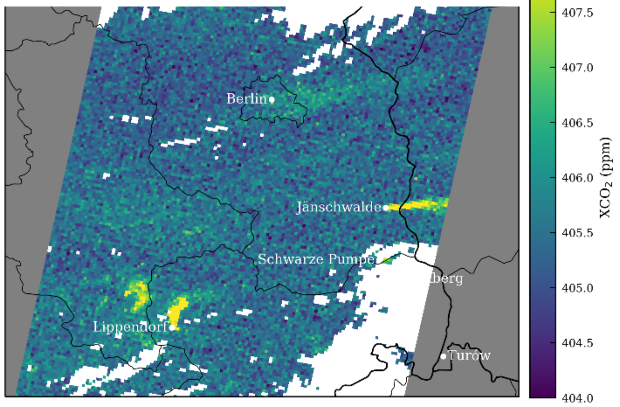
Copernicus CO_2 monitoring (CO2M) satellite mission

The CO2M imager will sample CO_2, CH_4 and NO_2 along a 250-km wide swath with a pixel size of 4 km². In addition, the satellite will carry support instruments for measuring aerosols and clouds.

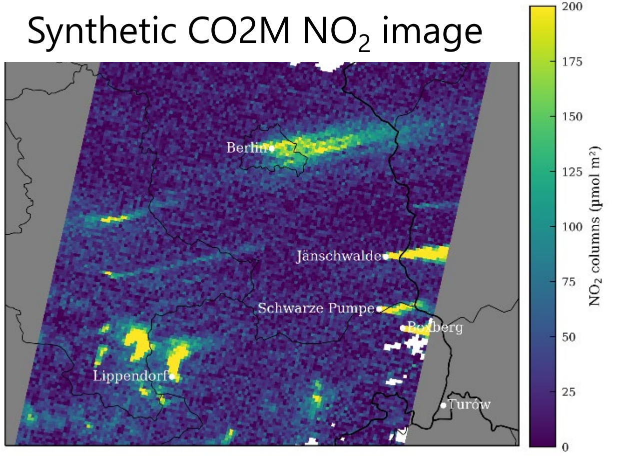
CO2M products	Spatial resolution
XCO_2	4 km²
XCH_4	4 km²
NO_2	4 km²
Vegetation solar-induced chlorophyll fluorescence (SIF)	4 km²
Aerosol optical depths (AOD) and layer height	16 km²
Water clouds and cirrus	400 m

VIS band also covers glyoxal
VIS & SWIR bands also cover water vapor

Synthetic CO2M CO_2 image



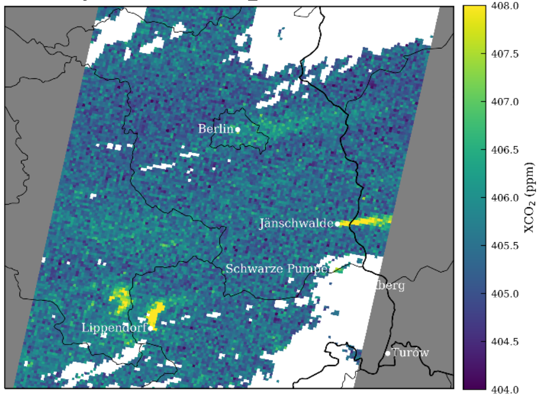
Synthetic CO2M NO_2 image



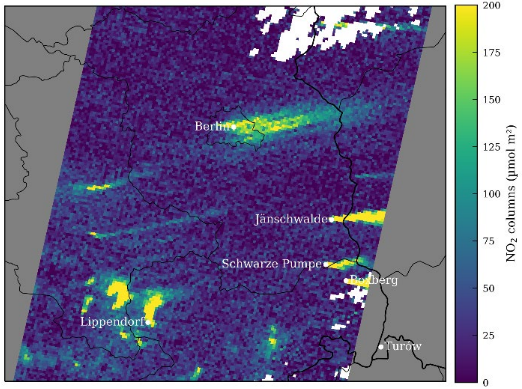
- Our study uses synthetic CO_2 and NO_2 observations for a constellation of up to six CO2M satellites that were generated in the SMARTCARB project [1] from high-resolution "nature runs" for a domain covering several point sources in parts of the Czech Republic, Germany and Poland (right figure).

- We used uncertainty scenarios for low- and high-noise CO_2 and NO_2 observations.

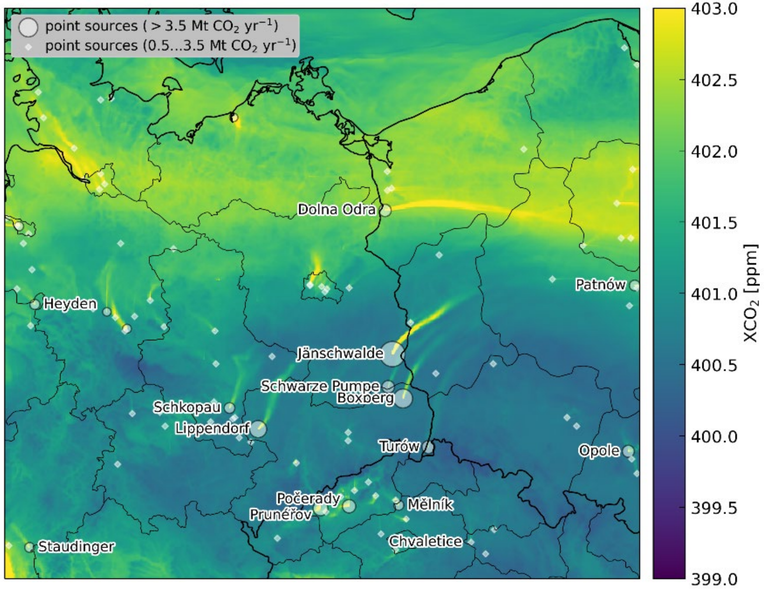
Synthetic CO_2 observations



Synthetic NO_2 observations



Spatial distribution of the largest point sources in the COSMO-GHG domain (white dots). The largest 15 point sources are labelled with their names. The image shows an XCO_2 model field on 2 Nov. 2015.



[1] Kuhlmann et al. (2020), Synthetic XCO_2, CO and NO_2 observations for the CO2M and Sentinel-5 satellites, doi: https://doi.org/10.5281/zenodo.4048227.

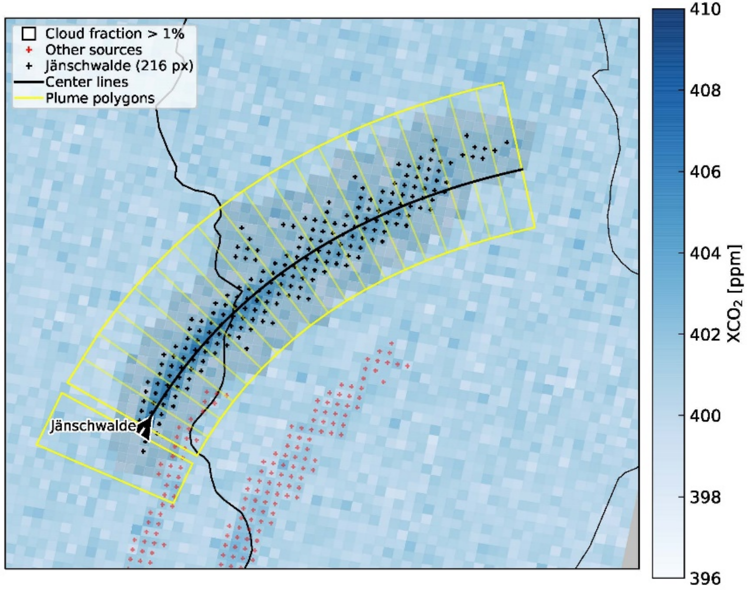
Data-driven emission quantification

- To identify the emission plumes, we developed a plume detection algorithm that identifies the location, orientation and extent of multiple plumes from CO2M's NO_2 observations.

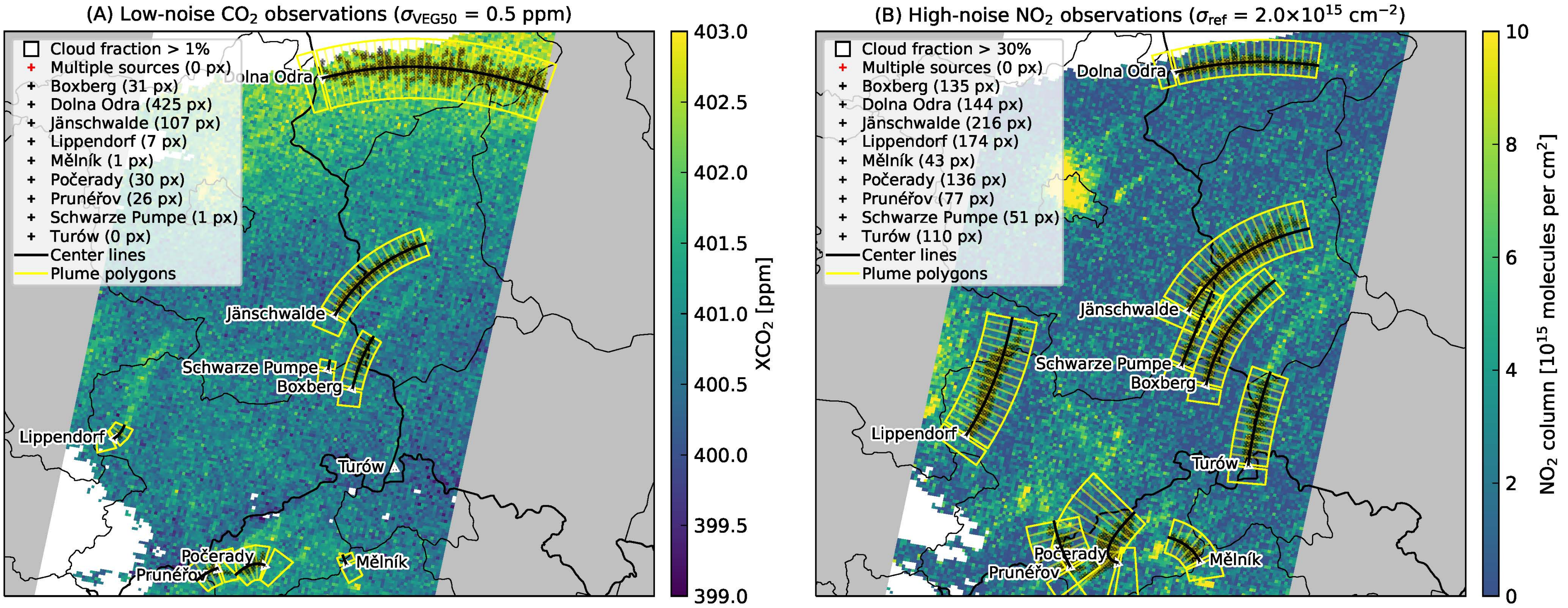
- A mass-balance approach was applied to individual plumes to estimate CO_2 and NO_x emissions by fitting Gaussian curves to the across-plume signals.

- Annual emissions were obtained by interpolating the temporally sparse individual estimates applying a low-order spline fit.

Sketch of detected CO_2 plume with detected pixels, center line, and the polygons up- and downstream of the source



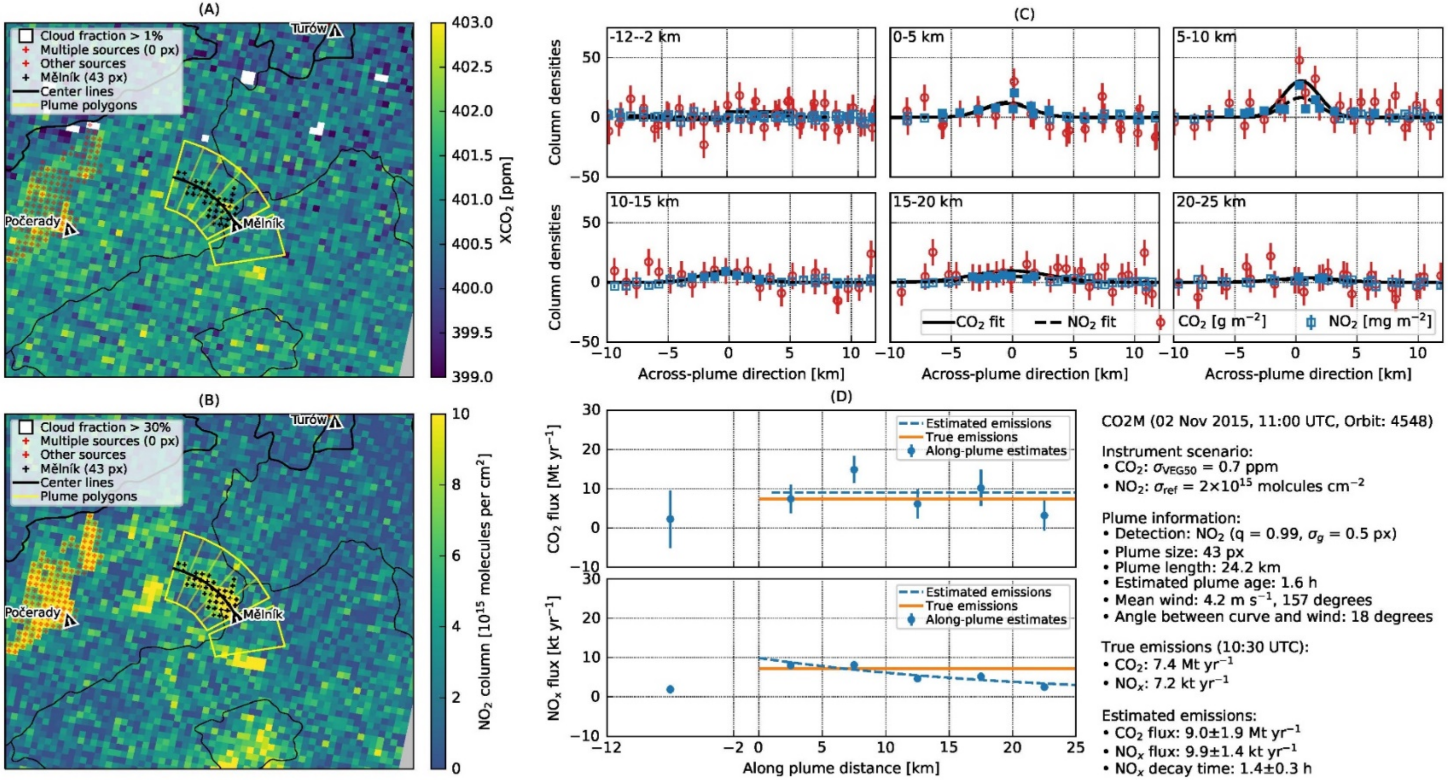
Example for plume detection algorithm



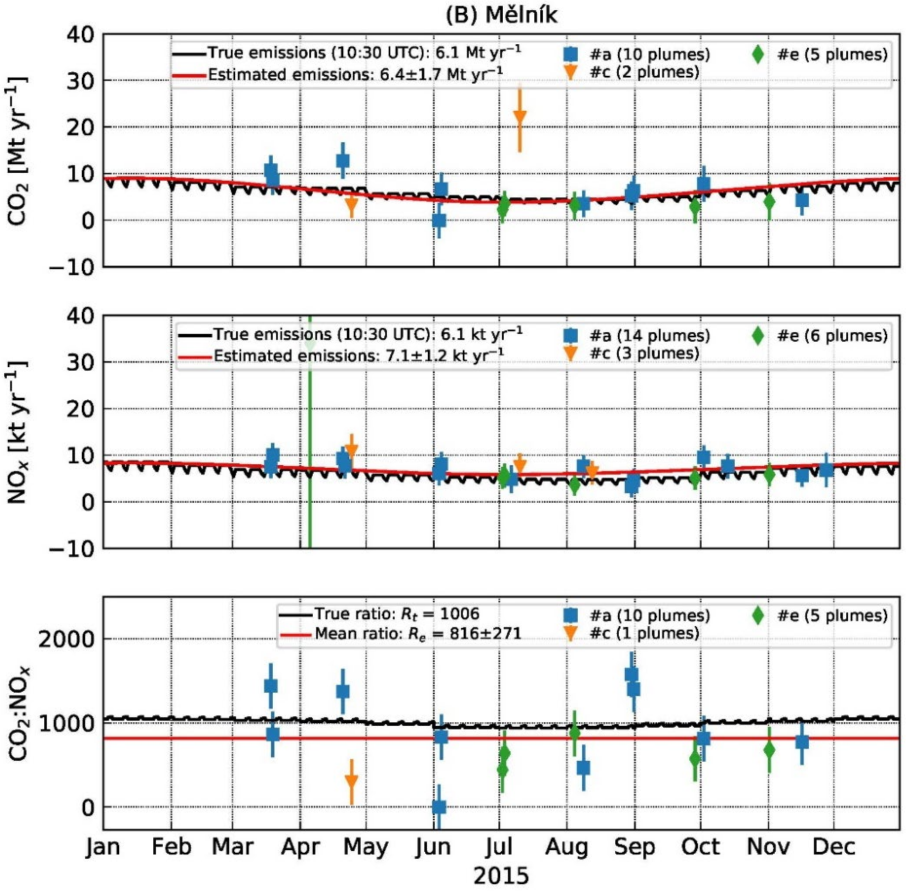
Comparing plume detection using (A) CO_2 observations with low noise scenario (σ_{VEG50}= 0.5 ppm) and (B) NO_2 observations with high noise scenario (σ_{ref} = 2×10^{15} cm^{-2}). For each detected plume, the figure shows detected pixels, plume center line and polygons used in the mass-balance approach. The triangular marker shows the location of the source and the wind direction in the model field.

Example for mass-balance approach

Application of the mass balance approach to a single CO2M overpass for the point source near Mělník. (A) CO_2 and (B) NO_2 satellite image with detected plumes and polygons for computing line densities. (C) Across plume CO_2 and NO_2 values for the six polygons with fitted Gaussian curves. (D) CO_2 and NO_x fluxes along the centerline and estimated CO_2 and NO_x emissions.



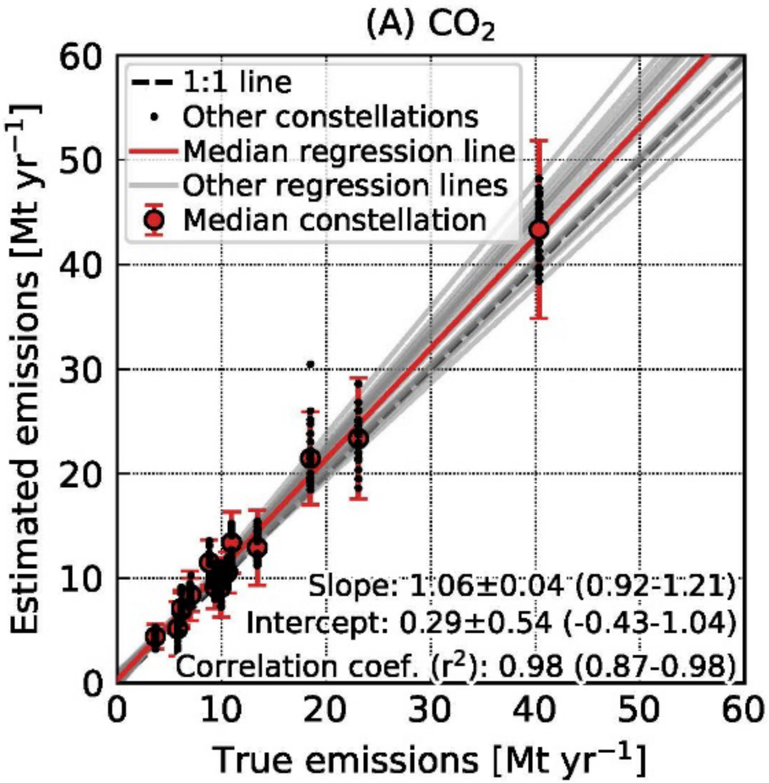
Example of time series of individual estimates



Time series of estimated CO_2 and NO_x emissions and CO_2:NO_x emission ratios for the point source near Mělník (CZ) for a constellation of three satellites using high-noise CO_2 observations (σ_{VEG50}= 0.7 ppm) and high-noise NO_2 observations (σ_{ref} = 2×10^{15} cm^{-2}).

Annual CO_2 and NO_x emissions are obtained by fitting a low-order spline with periodic boundary conditions to the individual estimates.

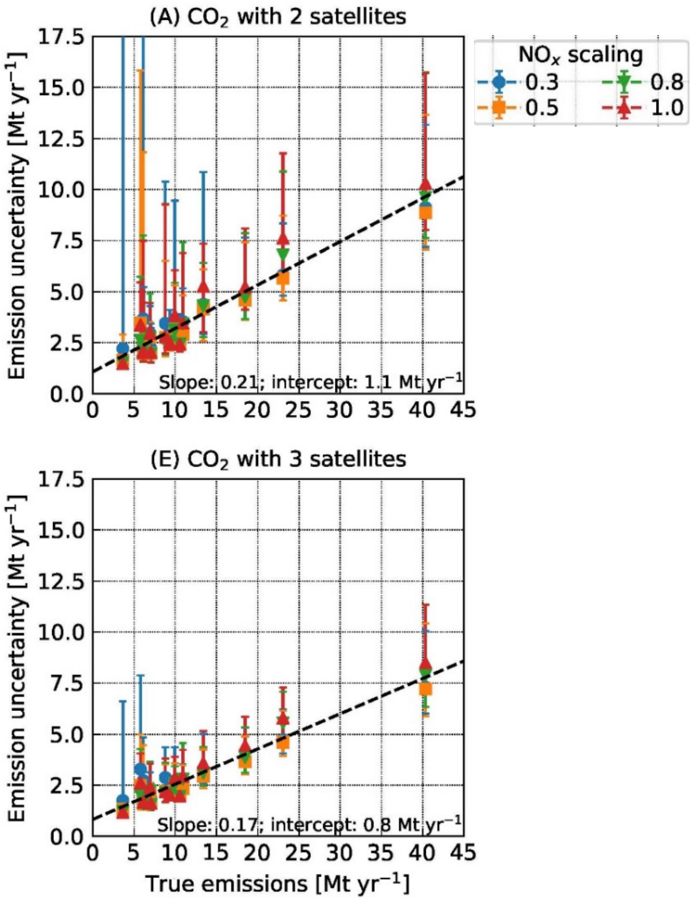
Annual CO_2 emissions of 15 power plants



Annual estimates of CO_2 emissions for a constellation of three satellites for the 15 largest point sources in the model domain using high-noise CO_2 observations (σ_{VEG50} = 0.7 ppm) and high-noise NO_2 observations ($\sigma_{ref} = 2\times10^{15}\ cm^{-2}$). Large markers show the median constellation and small markers the 20 possible combinations of 3 satellites that could be constructed as permutations of the six simulated satellites. Regression lines were fitted to the median as well as to the individual constellations. Slope, intercept and Pearson correlation coefficient r^2 are displayed for the median and for the range of the 20 constellations. True emissions correspond to emissions at satellite overpass at 10:30 UTC.

Uncertainty of annual emissions

- Estimated uncertainty of annual mean of emissions of CO_2 in for a constellation of two and three CO2M satellites.
- Uncertainties were computed using uncertainties in CO_2 and NO_2 observations, wind speed, diurnal and annual cycles of emissions, and accounted for additional uncertainties in mass-balance approach by comparing with true emissions.
- The markers denote the median uncertainties and the bars the range obtained for the individual constellations. The different marker denote scaling applied to NO_x emissions that is expected due to more stringent air quality regulations in the future.
- The uncertainties increase linearly with the source strength (slope and intercept of linear fit is shown in figures) and are clearly larger for two CO2M satellites than for three satellites.

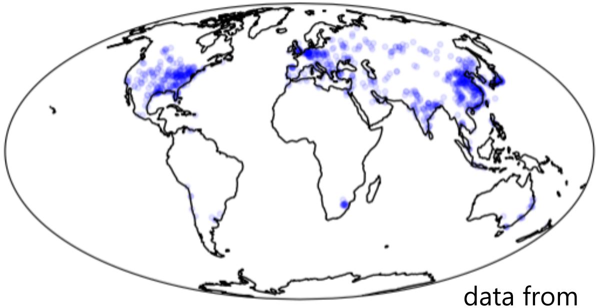


Application at the global scale

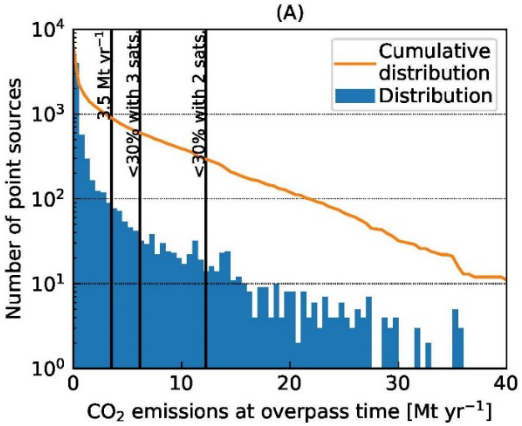
- The linear fit to uncertainties (previous slide) is applied to compute uncertainties of annual CO_2 emission estimates for ~900 point sources in global map of emissions clumps (Wang et al., 2019, see map). Figure A shows the distribution of CO_2 emission strengths for these point sources.

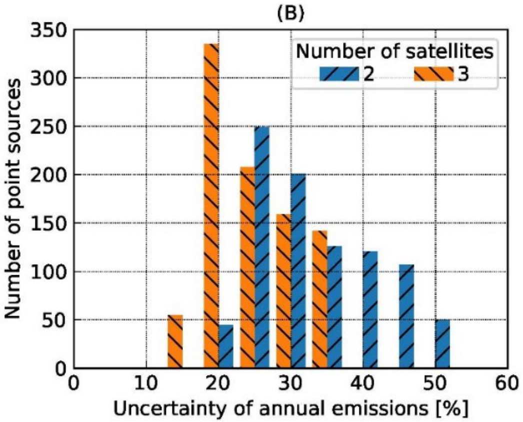
- Figure B shows the distribution of uncertainties showing that two satellites would be able to quantify the emissions of up to 300 point sources with <30% uncertainty, while adding a third satellite would double the number to about 600 point sources.

Location of ~900 point sources with emissions >3 Mt CO_2 yr^{-1}



data from Wang et al. (2019)





Summary

- We developed an improved algorithms for data-driven emission quantification of point sources that applies a mass-balance approach to plumes obtained from a plume detection algorithm. The mass-balance approach has the advantage that it can be applied worldwide without expensive atmospheric transport simulations.

- CO2M should be able to quantify annual CO_2 emissions of point sources using the data-driven approach with an uncertainty of 30% or smaller.

- Two CO2M satellites should be able to quantify 300 point sources with <30% accuracy, while three CO2M would double this number to 600 due to better spatial and temporal coverage.

- Further reducing the uncertainties will require the development of advanced atmospheric inversion systems for emission plumes and an improved constraint on the temporal variability of emissions using additional sources of information such as other satellite observations or energy demand statistics.

References

The results presented here are from the second phase of the study on the use of satellite measurements of auxiliary reactive trace gases for fossil fuel carbon dioxide emission estimation (SMARTCARB-2).

The synthetic CO2M observations used have been published at:
https://doi.org/10.5281/zenodo.4048227

The code for detecting and quantifying emissions of point sources is available on Gitlab upon request:
https://gitlab.com/empa503