Monitoring the CO$_2$ emissions from cities using space-borne images of CO$_2$ and co-emitted species

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with contributions by
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Why are we interested in CO₂ emissions from cities?

Cities account for ~70% of global CO₂ emissions and have a large reduction potential.

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

Sources: IPCC, World Resources Institute, World Bank

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?

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\textsubscript{2} satellite versus existing satellites

Future CO\textsubscript{2} satellite must have

- **Dense sampling**
  imaging of CO\textsubscript{2} plumes

- **High spatial resolution**
  capture emission hotspots and avoid clouds

- **High accuracy**
  because atmospheric column XCO\textsubscript{2} gradients are small

- **Global coverage**
  Support for Paris Agreement requires a global scope

Adapted 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 CO₂ 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 NO₂ and CO satellite measurements for quantifying CO₂ emissions using high-resolution OSSEs
- PMIF: Investigate capability of Sentinel-CO₂ for quantifying emissions from clumps (e.g. cities) using simple, efficient Gaussian plume modeling
- AEROCARB: Study influence of aerosols on ability to retrieve XCO₂ 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 CO₂ 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

$\sigma = 0$ ppm

$\sigma = 0.5$ ppm (low noise)

$\sigma = 1.0$ ppm (high noise)

Parameterization of random noise following Buchwitz et al. 2013
Detection of plumes against noise & background variability

**Berlin plume peak signal**

- **CO₂**
  - XCO₂ (ppm)
  - Signal
  - Uncer.
  - High noise
  - Medium noise
  - Low noise
- **NO₂**
  - NO₂ (10^15 molec. cm⁻²)
  - Signal
  - Uncer.

**Spatial variability of background**

- Total
- Only (local) biosphere
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

**CO₂** (σ_{ref} = 0.5 ppm)

- 137 detected pixels (PPV = 0.93)
- Thin cloud prevents CO₂ retrieval

**NO₂** (σ_{ref} = 2×10^{15} cm⁻²)

- 1086 detected pixels (PPV = 0.88)
- NO₂ retrieval still possible

Cloud fraction > 1%
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
### Summary of SMARTCARB emission estimates

<table>
<thead>
<tr>
<th>$\sigma_{\text{VEG50}}$ (ppm)</th>
<th>Mean bias</th>
<th>Standard deviation</th>
<th>Root mean square deviation of mean</th>
<th>Number of plumes*</th>
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<tbody>
<tr>
<td></td>
<td>Mt yr$^{-1}$</td>
<td>%</td>
<td>Mt yr$^{-1}$</td>
<td>%</td>
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<td><strong>Mass balance approach using CO$_2$ for plume detection with $n_s = 37$ and $q = 0.99$</strong></td>
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* constellation of 6 satellites
LOGOFLUX case study for Berlin by IUP Bremen

Pillai et al., ACP, 2016

Tracking city CO₂ emissions from space using a high-resolution inverse modelling approach: a case study for Berlin, Germany

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XCO₂ simulations using EDGAR & IER

A priori & a posteriori errors

• Case study for Berlin for year 2008
• Satellite data: Simulation for CarbonSat (2x2km², swath width 240 km & 500 km)
• Model: WRF-GHG, 10x10km² resolution
• Bayesian inversion

Summary:
• Number of “good” overpasses per year: 17 (240 km) - 27 (500 km)
• Single overpass random error: typ. 9 MtCO₂/year
• Systematic: typically 6-10 MtCO₂/year depending on assumptions
Satellite XCO₂ & NO₂ imaging of localized CO₂ sources

Towards monitoring localized CO₂ emissions from space: co-located regional CO₂ and NO₂ enhancements observed by the OCO-2 and S5P satellites  
*Reuter et al., ACP (submitted)*

Maximilian Reuter¹, Michael Buchwitz¹, Oliver Schneising¹, Sven Krautwurst¹, C.W. O’Dell², Andreas Richter¹, Heinrich Bovensmann¹, and John P. Burrows¹

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**Example:**

Baghdad, 31-July-2018

- Satellite data: OCO-2 XCO₂ and S5P NO₂
- NO₂ primarily for emission source identification
- Cross-sectional CO₂ flux via integration of Gaussian plume XCO₂ 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 XCO₂ retrievals using the FOCAL algorithm“
Satellite XCO₂ & NO₂ imaging of localized CO₂ sources

Moscow on 25-August-2018:

Estimated emission: 78±34 MtCO₂/year

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$^{-1}$)

7 Oct 2010, 11:00

- 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 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 NO₂ 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!