The potential of a constellation of LEO satellite imagers to monitor worldwide fossil fuel CO_2 emissions from large cities and point sources

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1. Introduction

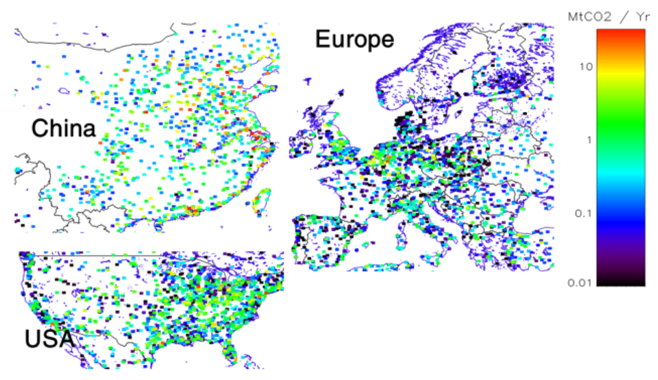
Reducing the emissions of the greenhouse gases (GHG) is one of the most important environmental challenges of the 21st century to keep global warming below 2°C with respect to pre-industrial times. Meeting this objective will benefit from independent observation to accurately monitor GHG anthropogenic emissions at spatial scales relevant to carbon policy. In this context, satellites offer an unparalleled global spatial coverage since they can provide long-term, spatial high-resolution observations.

Here we present a new atmospheric inversion framework to provide a quantitative evaluation of the potential of future satellite XCO2 imagery to estimate anthropogenic emissions from point sources, cities, regions and countries OVER THE ENTIRE GLOBE. The Observing System Simulation Experiments (OSSE) results shown below focus on resolving CO2 emissions from groups of emitting pixels that form a XCO2 plume (clumps) using high spatial resolution space-borne imagery data, with a simple atmospheric transport (Gaussian). This version of the OSSE relies on realistic sampling of satellite data taking into account a single LEO imager, and constellations of up to four such imagers, but assumes no changes in XCO2 around clumps due to natural fluxes.

2. Identification of sources (clumps) with detectable CO_2 plumes

A high-resolution map of fossil fuel CO2 emissions (ODIAC) with hourly temporal profiles associated with an aggregation method based on spatial consistency was used to identify the major anthropogenic emission sources that can be detected from space -> clumps

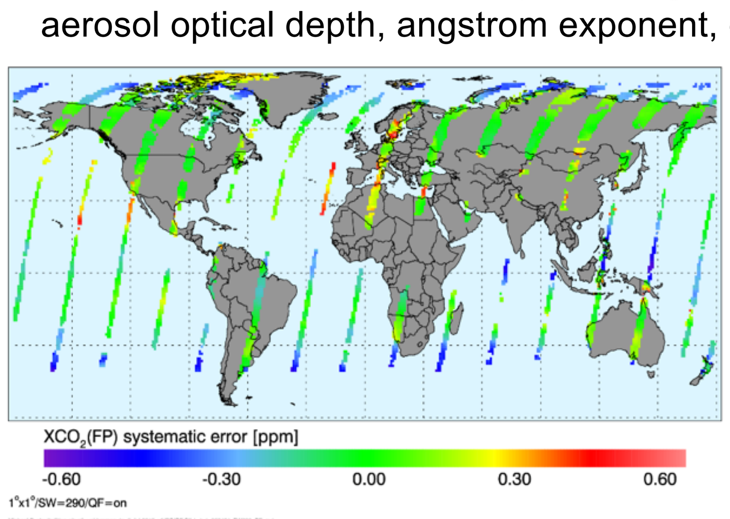
A total of 8242 clumps were delineated globally:
- **3458 urban areas**
- **4784 power plant/industrial sites**



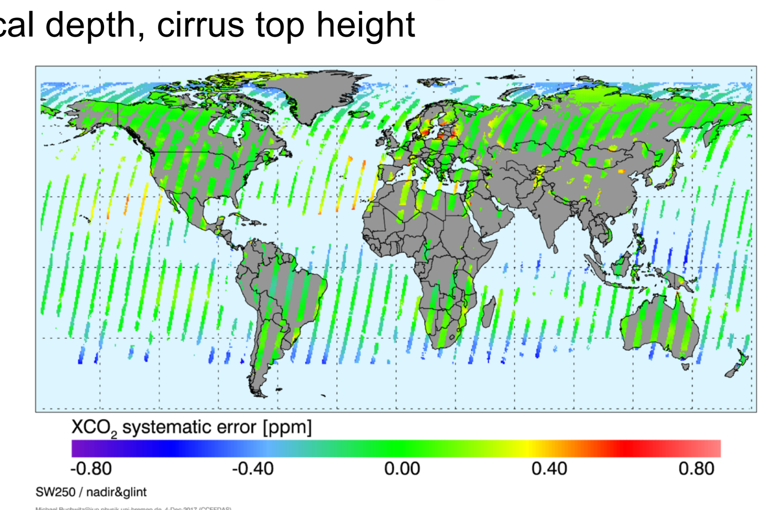
Spatial distribution of the identified clumps and their annual emissions in China, Europe and US

3. Simulate atmospheric measurements by LEO imagers ESA Sentinel CO_2

- Ground pixel size: 2x2 km²; Maximum swath width: 350 km; Individual sounding precision < 1 ppm
- Account for cloud occurrence
- XCO2 error parameterization: Regression-based formula to compute for each "cloud-free" single ground pixel XCO2 random error (1-sigma), systematic error, averaging kernel and quality flag
  -> Input parameters for nadir (i.e., non-glint mode) observations: Solar zenith angle, surface albedo, aerosol optical depth, angstrom exponent, cirrus optical depth, cirrus top height



One satellite



Constellation of three satellites

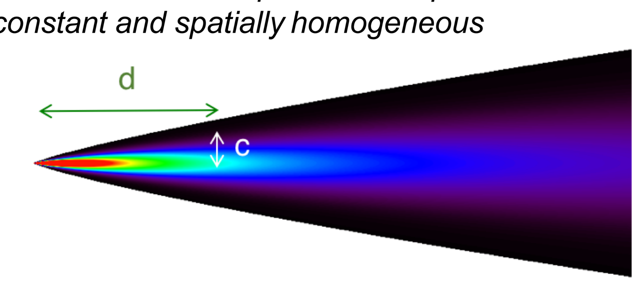
4. Atmospheric transport modeling : application of a Gaussian plume model to each clump

Each clump generates a XCO_2 concentration plume whose intensity and direction depends on wind vector. A simple transport model is used to compute the plume of each emitting pixel within the clump. These plumes are then aggregated in order to obtain a full plume for the considered clump. This represents a total of 100 billion plumes over a year.

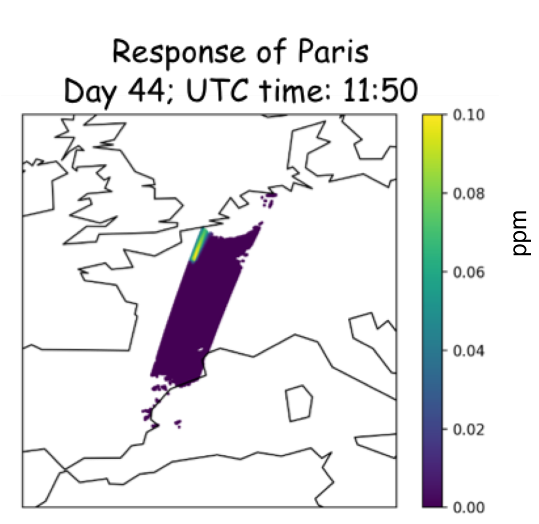
$$XCO2(d,c) = \frac{F\alpha}{\sqrt{2\pi}\sigma(d)U} \exp\left(-\frac{1}{2}\left(\frac{c}{\sigma(d)}\right)^2\right)$$

U: Wind speed
σ: Plume width

Wind fields are extracted from ECMWF at the clump location for the 3 hours before the satellite overpass. Wind speed and direction are assumed constant and spatially homogeneous



General shape of the Gaussian plume model



Example of the computation of the response function for Paris on a specific day

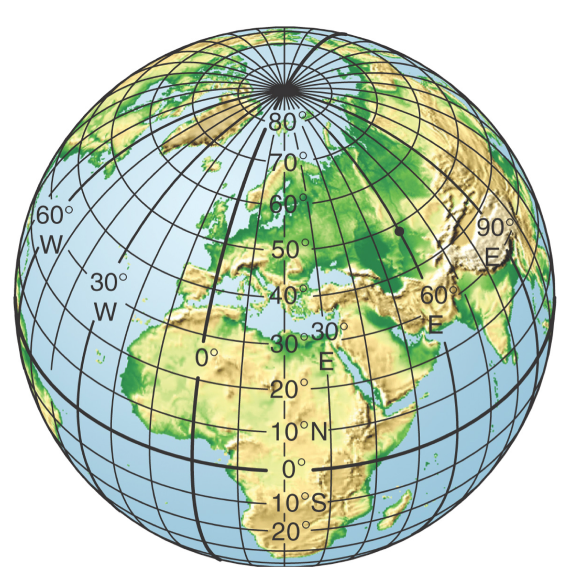
5. Inversion methodology

Inversion is made day by day following these steps:
1. Reading of all satellite observations
2. Computation of the full plumes for all clumps (see section 4)
3. Aggregation of the full plumes for all the clumps located in a inversion window in order to build H matrix (see below).
4. Inversion – the control vector is the number of clumps

The steps 3 and 4 are repeated for 10° x 10° spatial windows covering the globe.

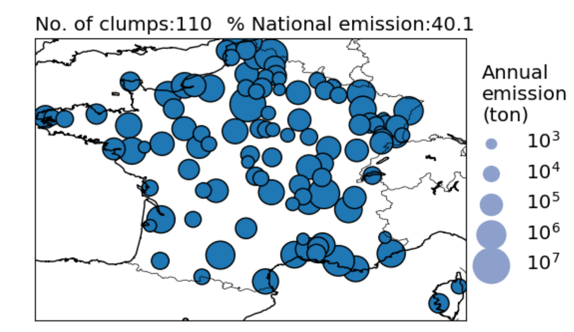
Mathematical formulation of the inversion:
The posterior uncertainty A is derived from the prior uncertainty B
$\mathbf{A = (B^{-1} + H^T R^{-1} H)^{-1}}$
B : Covariance matrix of prior uncertainty
R : Covariance matrix of observations (diagonal)
H : Response of observation space to space of control variables
A : Covariance matrix of posterior uncertainty

Uncertainty Reduction: $UR = 1 - \frac{A}{B}$


Schematic representation of the 10°x10° inversion windows

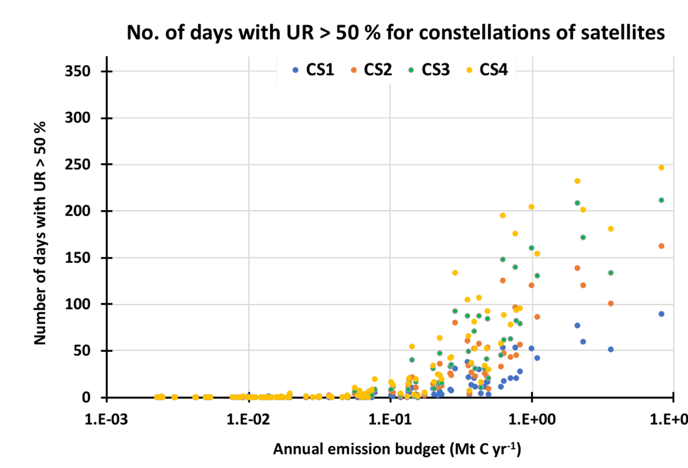
6. Results over France as an example

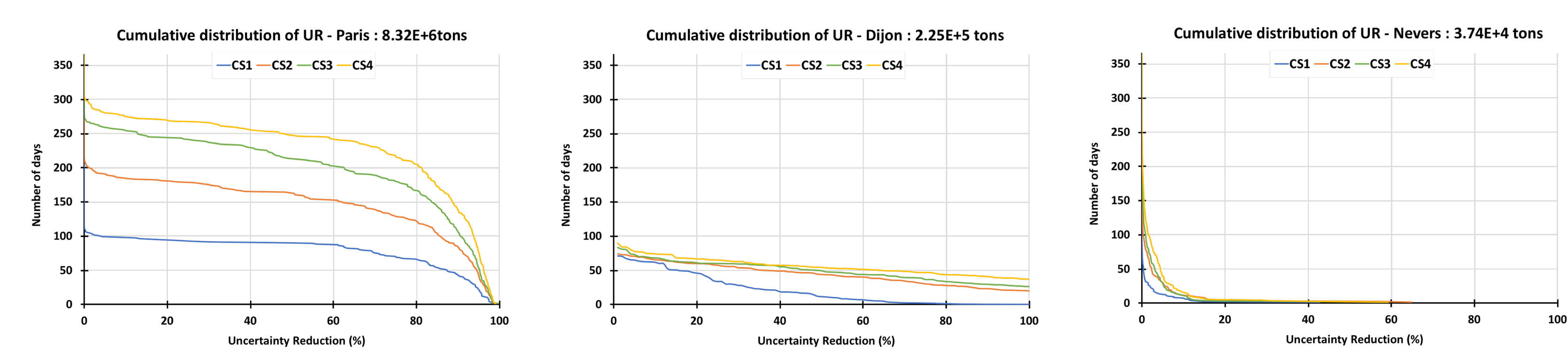
- Prior uncertainty = 100%
- Maximum length of each plume (H_{max}) = 500 km.
- Results are shown for 110 clumps located in France.
  -> These clumps account for 40.1% of national emissions
- Computations are made for the 366 days of the year 2008



Spatial distribution of the 110 clumps located in France

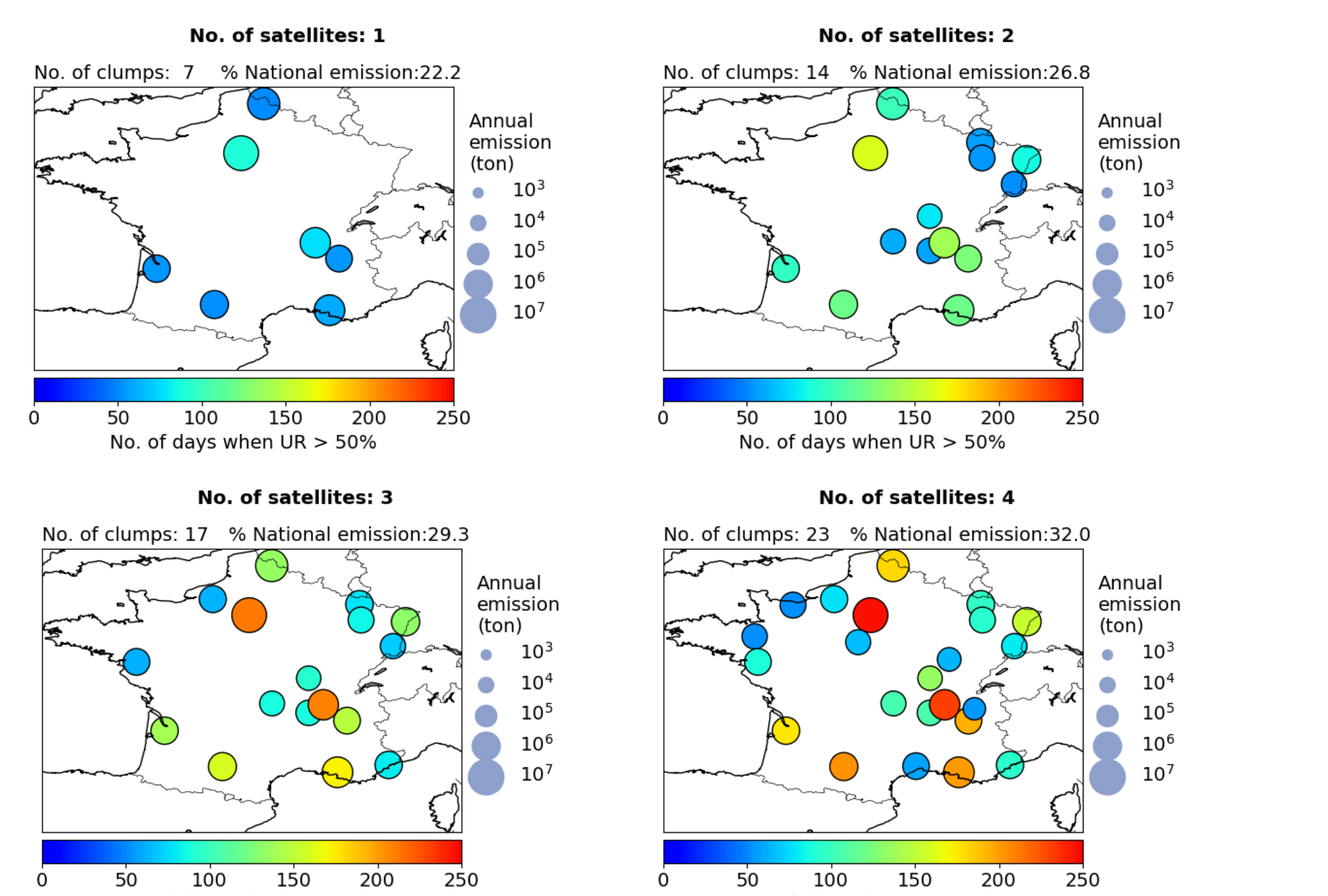
- Clumps can be monitored by satellite observations only if their annual emissions exceed 0.1 M t C yr⁻¹
- Number of days with Uncertainty Reduction (UR) > 50 % increases as a function of the emission budget of clumps
- Small and cloudy cities have a very low UR
- Increasing number of days with UR > 50 % when increased the number of satellites from one to four



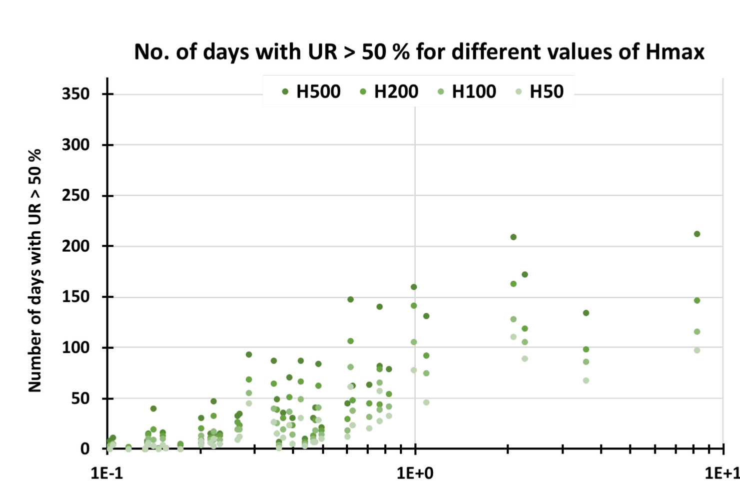


Number of days (y-axis) for which the UR values are larger than an UR threshold in % (x-axis)

-> The shape of the distribution of the number of days with UR larger than 50% (*N*) depends on clumps emission budget. Increase of *N* between 2 and 3 imagers is marginal for small and cloudy cities in France



French clumps and number of days with UR>50% for 1 to 4 satellites



- H_{max} is the maximum length of each plume along the wind direction
- The impact of different values of H_{max} on the number of days with UR > 50% was tested for one (CS1) up to four satellites (CS4). Here the results are shown for three satellites (CS3).

7. Results over the globe

% clumps covered

Number of days with UR > 50%	CS1	CS2	CS3	CS4
100	0.2	10.9	19.2	24.0
50	11.4	24.3	31.6	35.6
30	21.9	32.8	39.0	42.7
10	39.2	47.0	52.1	55.2

% of global emission covered

Number of days with UR > 50%	CS1	CS2	CS3	CS4
100	3.5	40.8	58.9	69.4
50	42.3	72.3	82.2	88.4
30	66.6	85.6	91.4	93.2
10	91.3	94.7	96.0	96.5

7. Conclusions / Perspectives

First results suggest that only fossil fuel CO2 emissions from clumps larger than 0.1 MtC yr-1 can be monitored by LEO imagers representing ESA's Sentinel CO2 planned missions. There is a significant positive impact of the number of satellites, and assuming shorter plumes decrease the performances of satellites.

Further work is needed in order to assess realism of the simulations through comparisons to detailed studies with more complex modeling framework for specific cities. There are also many ways to refine the OSSE through assessing the impact of swath, spatial resolution, precision, include vegetation fluxes, and spatial and temporal errors of clumps emissions. This system has the advantage to invert fluxes from pseudo data of satellite imagers at their native high resolution. It can therefore be applied to test the performances of other imagers like GEOCARB and OCO-3 and from constellations of different satellites.