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Plume detection and characterization from XCO_2 imagery: methodology and expected uncertainties on derived point source fluxes

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CONTENT

Generation of realistic synthetic imagery data

Methodology: Gaussian plume modelling and Optimal Estimation Method

Plume characterization: fitting Gaussian parameters

- Validation with MicroCarb City Mode simulations
- Favorable/complex observation cases
- Parameter constraints and uncertainties

Point source emission retrieval: exploiting wind information

Synthesis and further work

- MicroCarb City Mode imagery
- Geostationary imagery
- OCO-2 case measurements
- Further methodology developments

SYNTHETIC DATASET: XCO_2 FIELDS

- **Simulations over Western Europe of daily fields of column averaged dry air carbon dioxide mixing ratio (XCO_2), July 2016**
  - IER 1 km emission inventories, 8 km VPRM vegetation flux model, 15 km CAMS XCO_2 boundary conditions
  - CHIMERE transport model at 2 km resolution (forced by ECMWF meteorological fields at ~9 km) to represent realistic atmospheric signatures of emissions

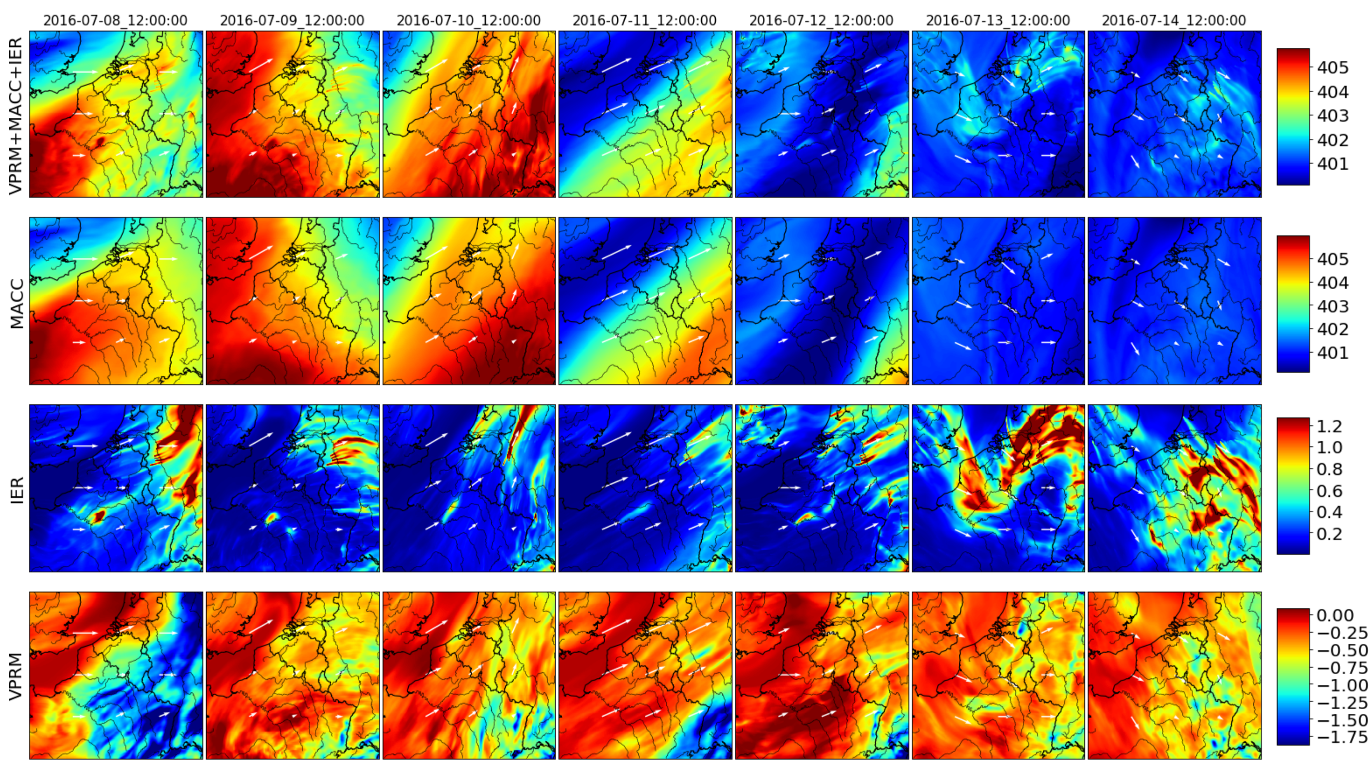
XCO_2 (ppm) from *day 8 to 14*

Overall XCO_2

CAMS boundary conditions

IER anthropogenic emission

VPRM biogenic fluxes

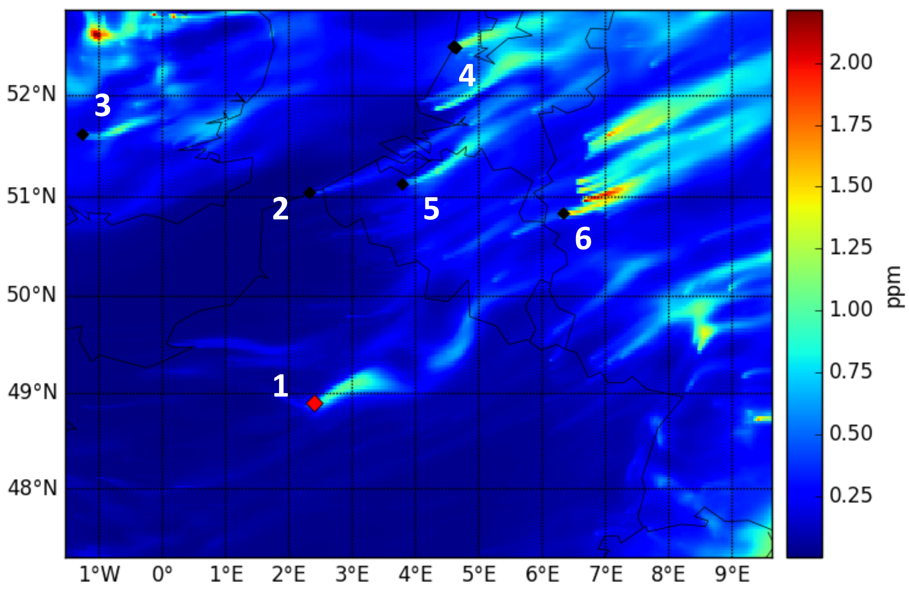


SYNTHETIC DATASET: POINT SOURCES IMAGERY

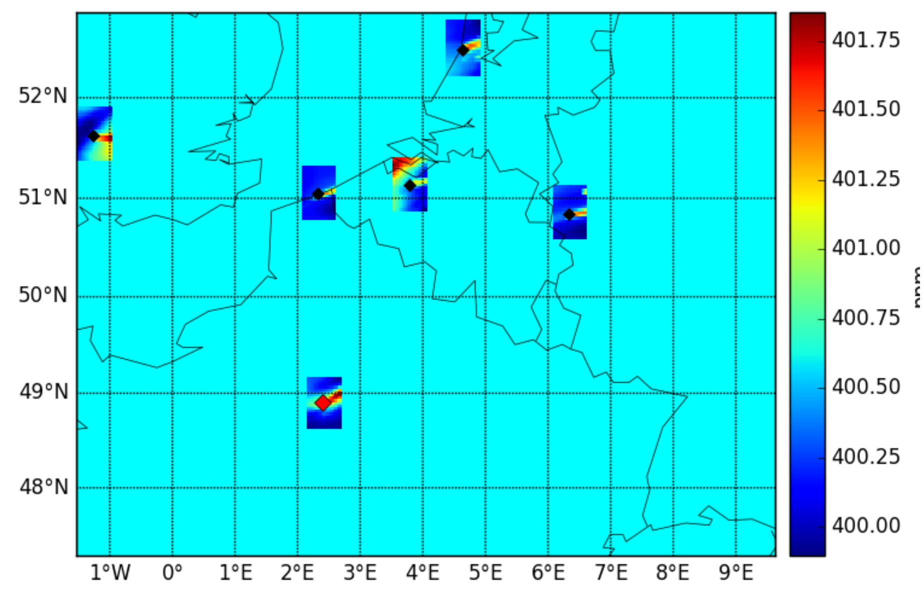
Six typical European sites covering power plants in France, Belgium, Germany, Great-Britain and the Netherlands plus one megacity (Paris) have been selected as targets for generating synthetic images

Country	France	France	UK	The Netherlands	Belgium	Germany
Name	**Paris**	**DK6 Dunkerque**	**Didcot A**	**Velsen & Ijmond**	**Rodenhuize**	**Weisweiler**
Source	City	Gas power plant	Coal power plant	Gas power plants	Thermal power plant	Coal power plant
Lat		51,04816	51,62363	52,4723 & 52,4758	51,1337	50,8387
Lon		2,32547	-1,26757	4,6331 & 4,6048	3,7759	6,3219
FOV form	Rectangle	Rectangle	Rectangle	Rectangle	Rectangle	Rectangle
FOV size	3.11×2.05 km²	3.12×1.96 km²	3.12×1.94 km²	3.12×1.90 km²	3.12×1.96 km²	3.11×1.97 km²

Position of the sites of selected anthropogenic emission sources



Example of synthetic images generated from the total XCO_2 fields
Simulations for the MicroCarb City Mode, a SPECIFIC mode of the MicroCarb mission designed for providing pseudo-imagery over a limited number of targets



Methodology: Gaussian plume modelling

- **Plume: reformulation of the classic** (e.g., Bovensmann et al., 2010) **Gaussian model**

$$\Delta \mathrm{XCO_2}(x,y) = \mathrm{XCO_2}(x,y)_{\mathrm{plume}} - \mathrm{XCO_2}(x,y)_{\mathrm{background}} = C_0 \frac{\sigma_0}{\sigma_y(x)} e^{\frac{-1}{2}\left(\frac{y}{\sigma_y(x)}\right)^2}$$

expressed in the plume coordinates system xOy, Ox is the direction of the plume axis, Oy the direction perpendicular to the plume axis. For x>0, the plume spreads in the transverse direction Oy, as:

$$\sigma_y(x) = \sigma_0\left(1 + \frac{x}{x_0}\right)^b$$

with $C_0 = Ucoeff \frac{F}{\sqrt{2\pi}\sigma_0 u}$ and $x_0 = \left(\frac{\sigma_0}{a}\right)^{1/b}$

- ✓ XCO_2 is the CO_2 dry air column averaged mole fraction in ppmv (integrated over the image pixel)
- ✓ **4 controlling parameters**: C_0 = f(F,u), σ_0, x_0, b
  - o $C_0 = Ucoeff \frac{F}{\sqrt{2\pi}\sigma_0 u}$, in ppmv. $Ucoeff = \frac{Mmol_{air}\, g(x,y)}{Mmol_{co2} P_S(x,y)}$; F : flux in gCO_2/s; u : wind component in the x direction, in m/s
  - o σ_0 : plume spread in the y direction at x = 0, in km; a : parameter characterizing the plume width
  - o x_0 : offset distance in the x direction (avoid singularity in x=0), in km
  - o b : parameter characterizing the plume dynamics

- **Background CO_2 field, in the image coordinate system XOY** (rotation of angle Φ_0 of the plume axis)

$$\mathrm{XCO_2}(X,Y)_{\mathrm{background}} = \mathrm{XCO_2}(0,0) + X\,p_X + Y\,p_Y$$

- ✓ **3 controlling parameters** for the background: $\mathrm{XCO_2}(0,0)$, p_X, p_Y
- ✓ **1 parameter** for the plume direction, Φ_0 : plume direction angle in the XOY reference system

METHODOLOGY: OEM RETRIEVAL

Retrieval scheme

- 1 dimensional Optimal Estimation formalism (Rodger, 2000) using observation and *a priori* values of the state vector together with respective uncertainty figures
  - Numerical computation of Jacobian based on finite differences
  - Levenberg-Marquardt convergence scheme
- A preprocessing is implemented for the image analysis
  - Detecting the presence of one (or several) plume(s)
  - Characterizing the plume(s): extension, amplitude, source position
  - Providing *a priori* estimate of background and direction parameters for the main plume

State vector

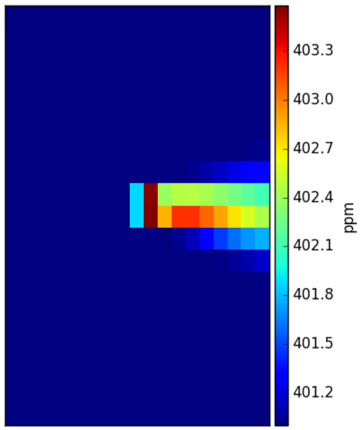
- All the 8 parameters controlling Gaussian plume, background and plume direction are considered in the state vector
- *Ad hoc* estimate of state vector *a priori* uncertainty: variance from the literature, no error correlations

Observation vector

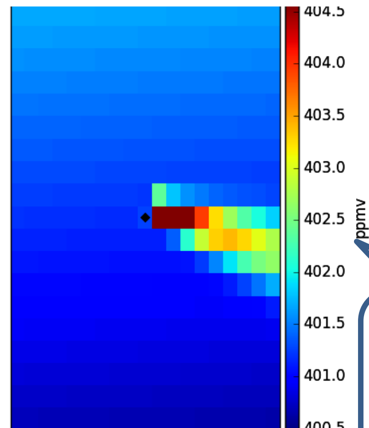
- XCO_2 image for the case of MicroCarb simulations: 20x20 = 400 pixels
- Observation error covariance matrix: diagonal, values depend on the configuration (for MicroCarb, tests with 1, 2 and 3 ppm have been done)

RESULTS: PLUME CHARACTERIZATION (1/5)

➢ Validation with MicroCarb City Mode simulations: Weisweiler, 18/07/18

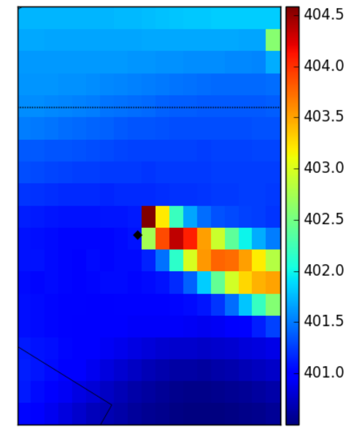


GUESS



ANA

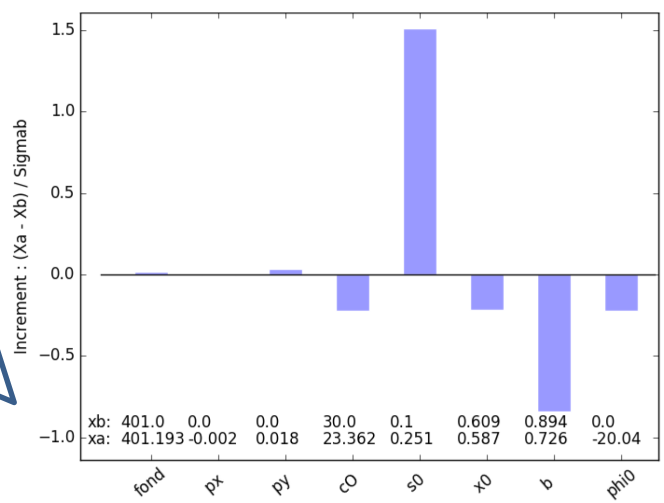
Solution fitted to the obs (small residual)



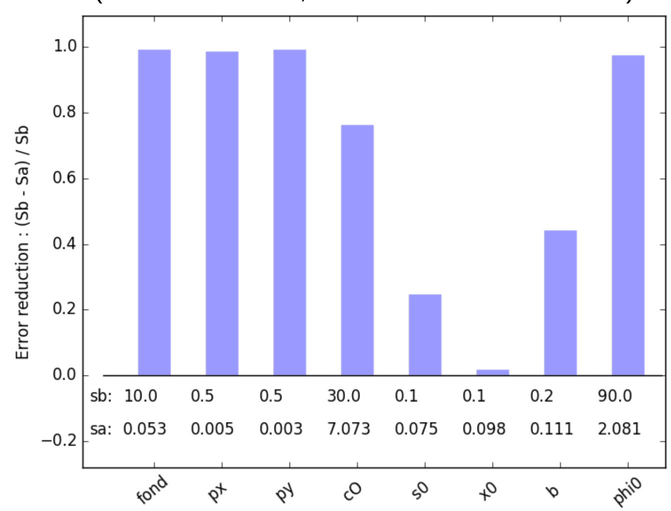
OBS

Fitting 8 parameters: background and wind direction well constrained. More than 2 pieces of information (over 4) on Gaussian model parameters

Retrieval increment of Gaussian parameters
(relative increment wrt guess value)

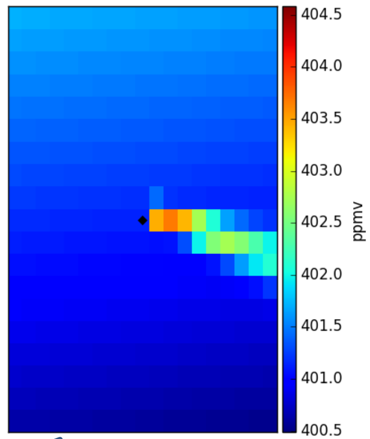


Error reduction on Gaussian parameters
(0 = no constraint; 1 = full constraint from obs)

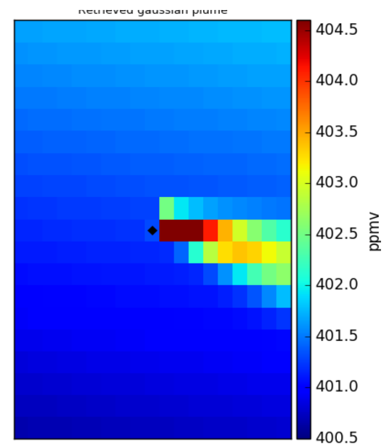


RESULTS: PLUME CHARACTERIZATION (2/5)

➢ Validation with MicroCarb City Mode simulations: Weisweiler, 18/07/2018

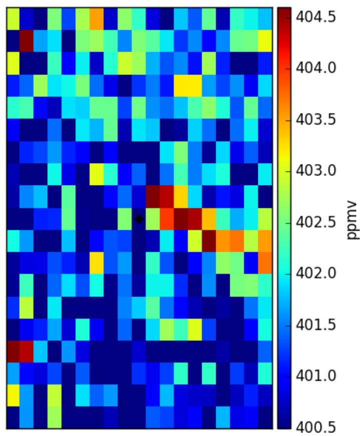


GUESS +



ANA

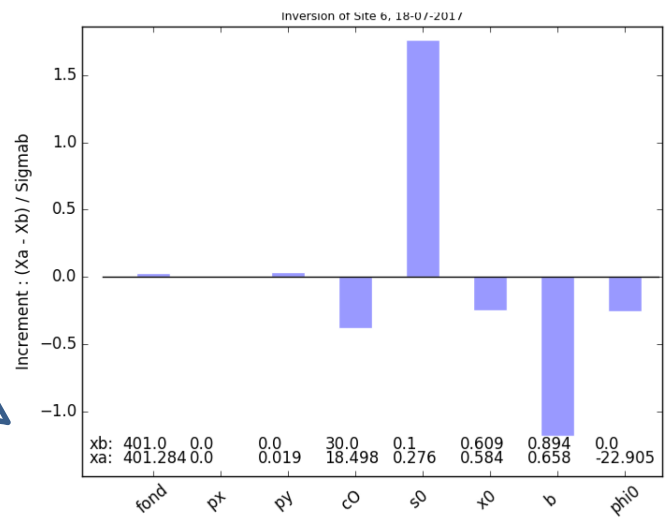
1 ppm random noise



OBS

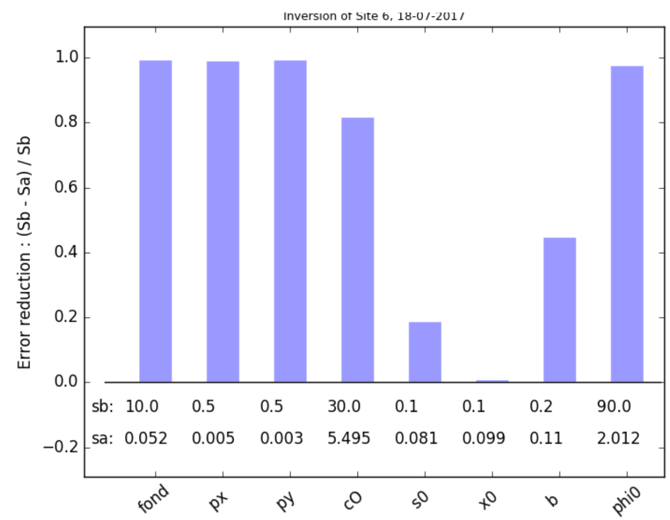
Image pre-processing: *A priori* estimate of direction and background

Retrieval increment of Gaussian parameters
(relative increment wrt guess value)

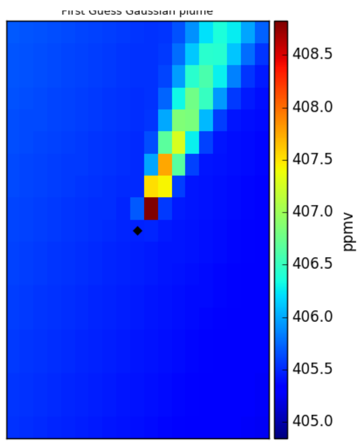


Solution remains stable with noisy observations

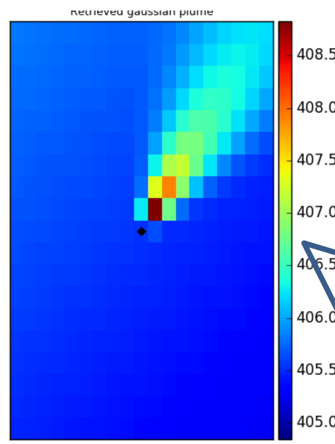
Error reduction on Gaussian parameters
(0 = no constraint; 1 = full constraint from obs)



➢ Validation with MicroCarb City Mode simulations: Rodenhuize, 04/07/2017



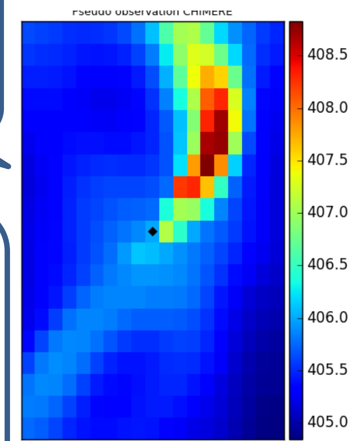
GUESS +



ANA

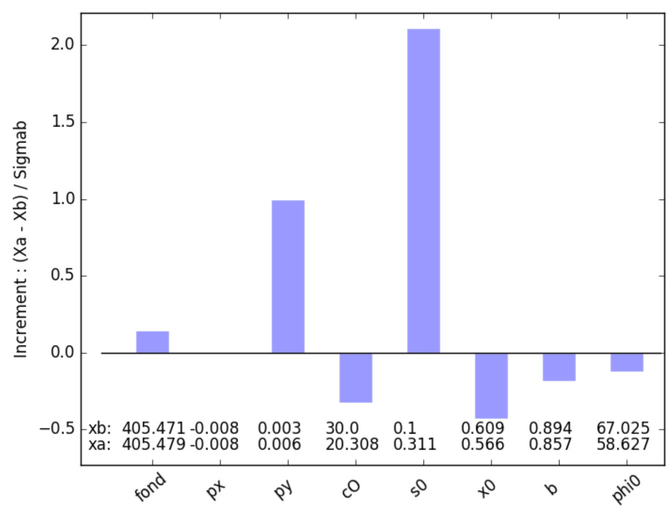
Non Gaussian structure of the plume

Solution found, but with large residual
NON FAVORABLE CASE

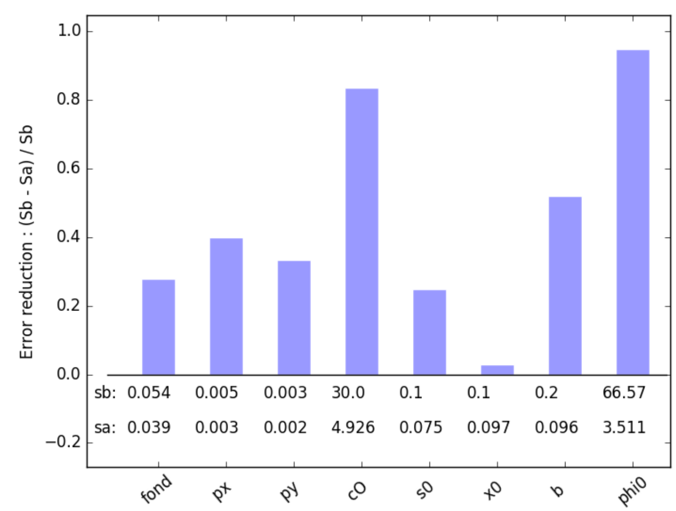


OBS

Retrieval increment of Gaussian parameters
(relative increment wrt guess value)



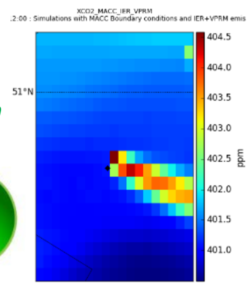
Error reduction on Gaussian parameters
(0 = no constraint; 1 = full constraint from obs)



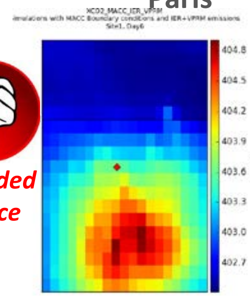
RESULTS: PLUME CHARACTERIZATION (4/5)

➢ **Validation with MicroCarb City Mode simulations: Processing of 180 noisy images (6 sites x 30 days). How does Gaussian model fit realistic observations ?**

Isolated source with contrast

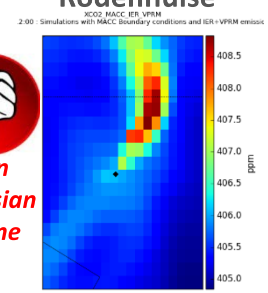


Paris



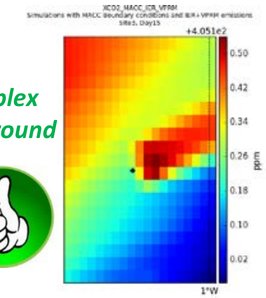
Extended source

Rodenhuise



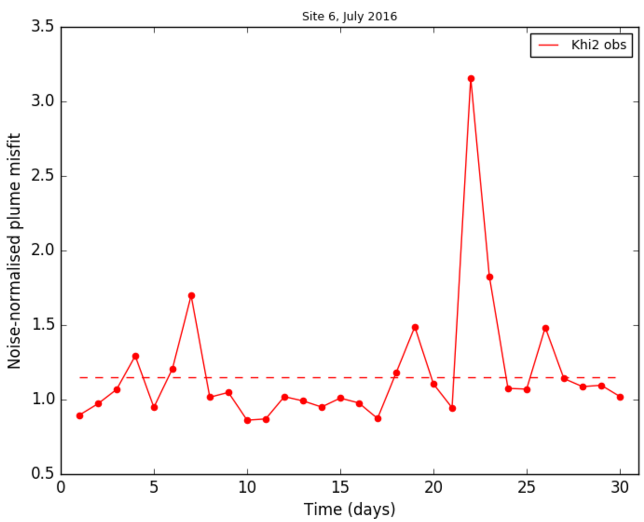
Non Gaussian plume

Complex background

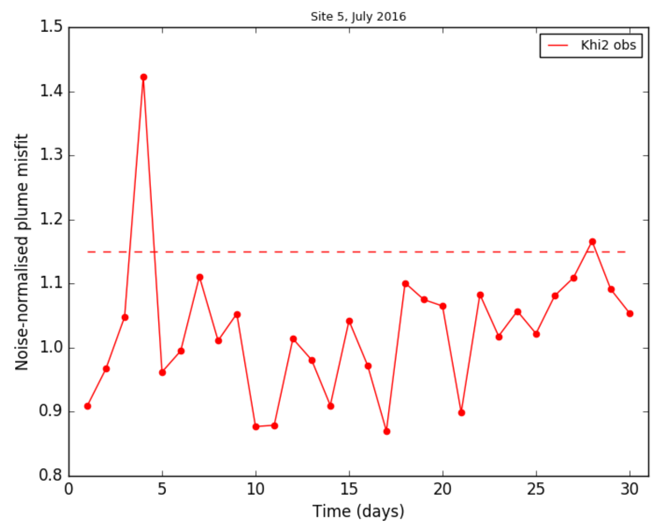


Identify cases well-fitted with our Gaussian retrieval : $\chi^2_{y\,(red)} = \frac{(y_{obs}-y_{OEM})^T S_y^{-1} (y_{obs}-y_{OEM})}{N_{obs}}$ *close to 1 (threshold: 1.15)*

Weisweiler (strong source: ~19 MT CO_2/year)
73 % of favorable cases



Rodenhuise (weaker source: ~2 MT CO_2/year)
50 % of favorable cases



Over the 6 sites and 30 days, 60 % of cases are identified as favorable

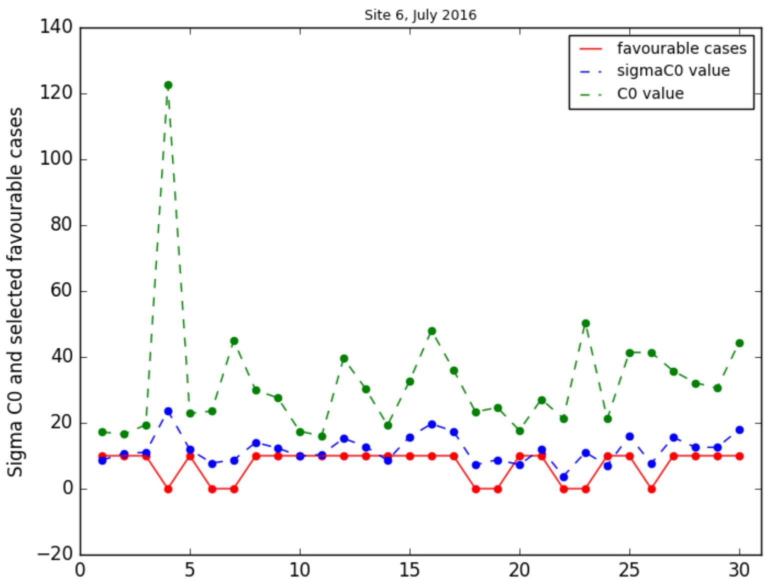
- ➢ Well fitted
- ➢ Detectable (good SNR)
- ➢ Retrieval convergence and stability with noise

(1 ppm noise, no clouds)

RESULTS: PLUME CHARACTERIZATION (5/5)

- **Validation with MicroCarb City Mode simulations: processing of 180 noisy images (6 sites x 30 days). Which accuracy on Gaussian constrained parameters ?**

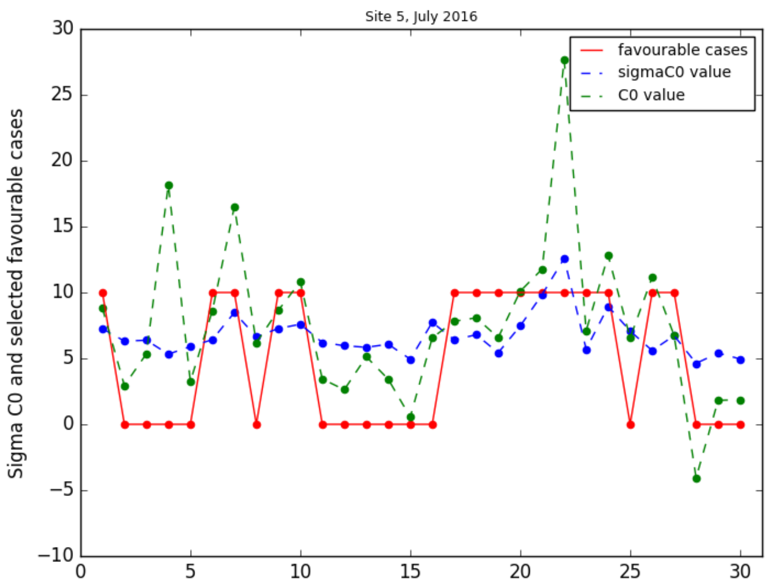
Weisweiler (strong source: ~19 MT CO_2/year)
Error on retrieved C_0 : 46 % (~12 ppmv)



Days of the month

10 = favorable case

Rodenhuise (weak source: ~2 MT CO_2/year)
Error on retrieved C_0 : 74 % (~7.5 ppmv)



Days of the month

10 = favorable case

Over the 6 sites and 30 days

- Error on C_0 (plume amplitude, which directly depends on flux and wind) is of 63% in average (~8.6 ppmv)
- C_0 values vary between 10 ppmv and 100 ppmv

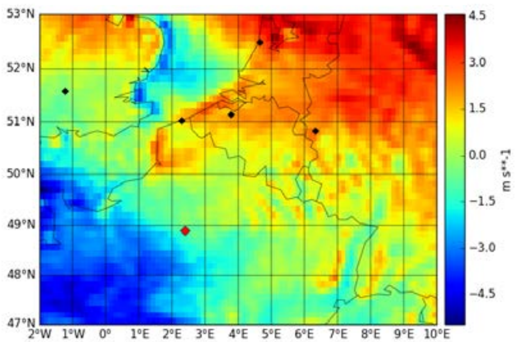
(1 ppm noise)

Point source emission retrieval: exploiting wind information

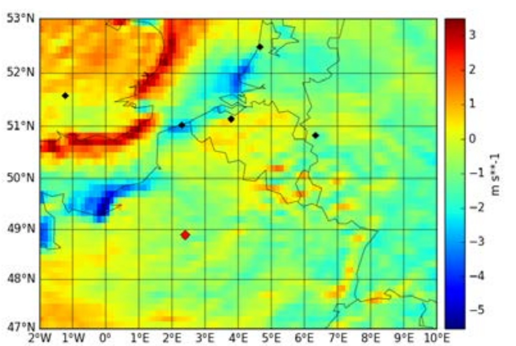
- Point source emission F is estimated from C_0 and given an « effective » wind $u = u_{eff}$
  - u_{eff} is estimated from the ECMWF wind profile, plus some rule to choose the wind effectively acting on the CO_2 plume: u_{eff} is taken as the average of the 3 estimators below
    - Wind at the altitude of the source
    - Wind averaged in the mixed boundary layer
    - Wind with the closest direction to the plume direction

- ECMWF wind profile: 12:00 analysis, 137 levels, 0.125 ° resolution. Boundary layer height available

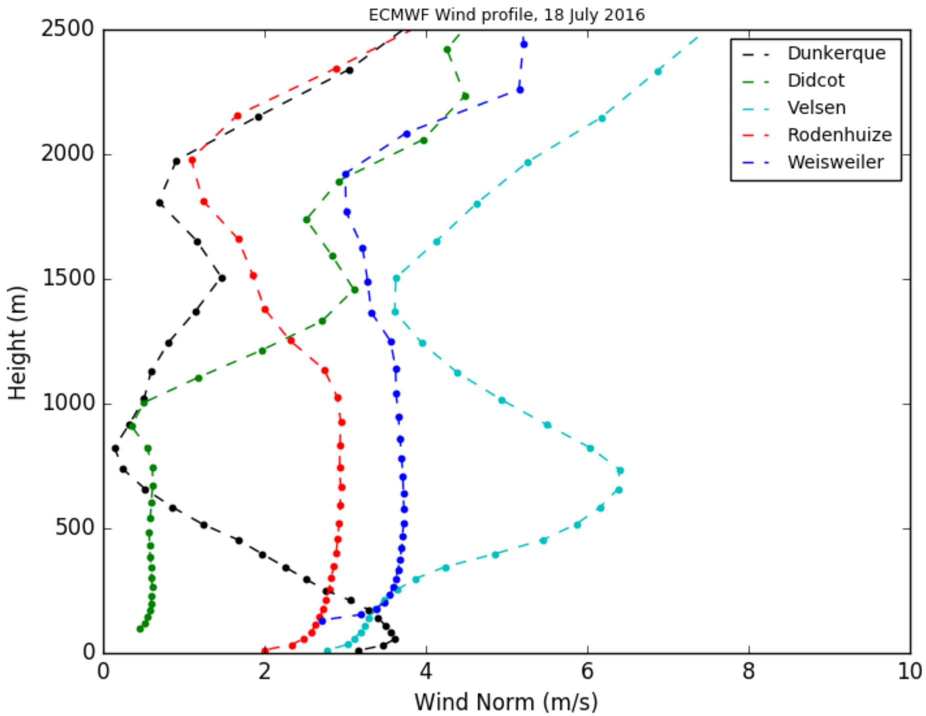
U component of the surface wind



V component of the surface wind



Profile of the wind module for the selected sites



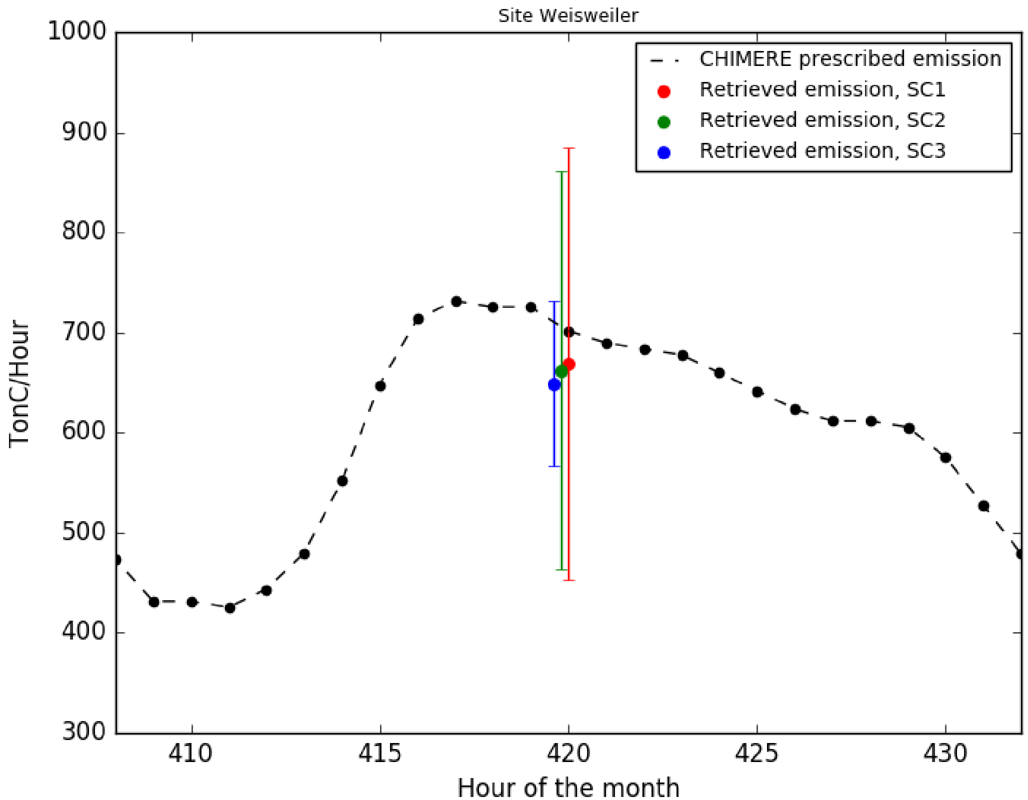
Point source emission retrieval: test for Weisweiler, 18/07/2016

- Site emission F (Ton C per hour) are computed from retrieved plume parameters (C_0, σ_0) and u_{eff} (estimated at 3.5 m/s with 0.2 m/s uncertainty)
- F uncertainty standard deviation (σ_F) results from u_{eff} uncertainty estimate (variability in the boundary layer) and from plume parameter retrieval uncertainty (3 scenarios SC1, SC2, SC3 presented below)
- Retrieved F is compared with hourly site emission prescribed in CHIMERE simulation. Retrieved plume dynamic parameters are discussed with respect to Pasquill stability classes

SC1: Fit of the 8 parameters with weak *a priori* constraints
σ_F = 32%
x_0 offset distance maintained to subpixel size (1 km)
The *a posteriori* uncertainties on plume amplitude C_0 and spread σ_0 result in a **large *a posteriori* uncertainty on F**
Stability parameters **a** and **b** are fitted, but values not consistent with the Pasquill classification (retrieved value of **a** = 0.211 suggests lower u_{eff} than that derived from ECMWF)

SC2: b stability parameter fixed to 0.894 as in Bovensmann et al. (2010) and Nassar at al. (2017)
σ_F = 30%
Slightly improved *a posteriori* error on plume amplitude C_0, plume spread σ_0 and **F**
The fitted stability parameters **a** remains not fully consistent with the Pasquill classification as in SC1

SC3: the stability parameter a is fixed (via σ_0) consistently with Pasquill class A-B (a = 0.185, classified from wind speed and solar radiation)
σ_F = 13%
Significant improvement of *a posteriori* error on plume amplitude C_0 and **F**



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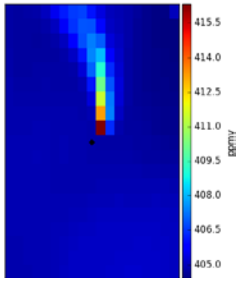
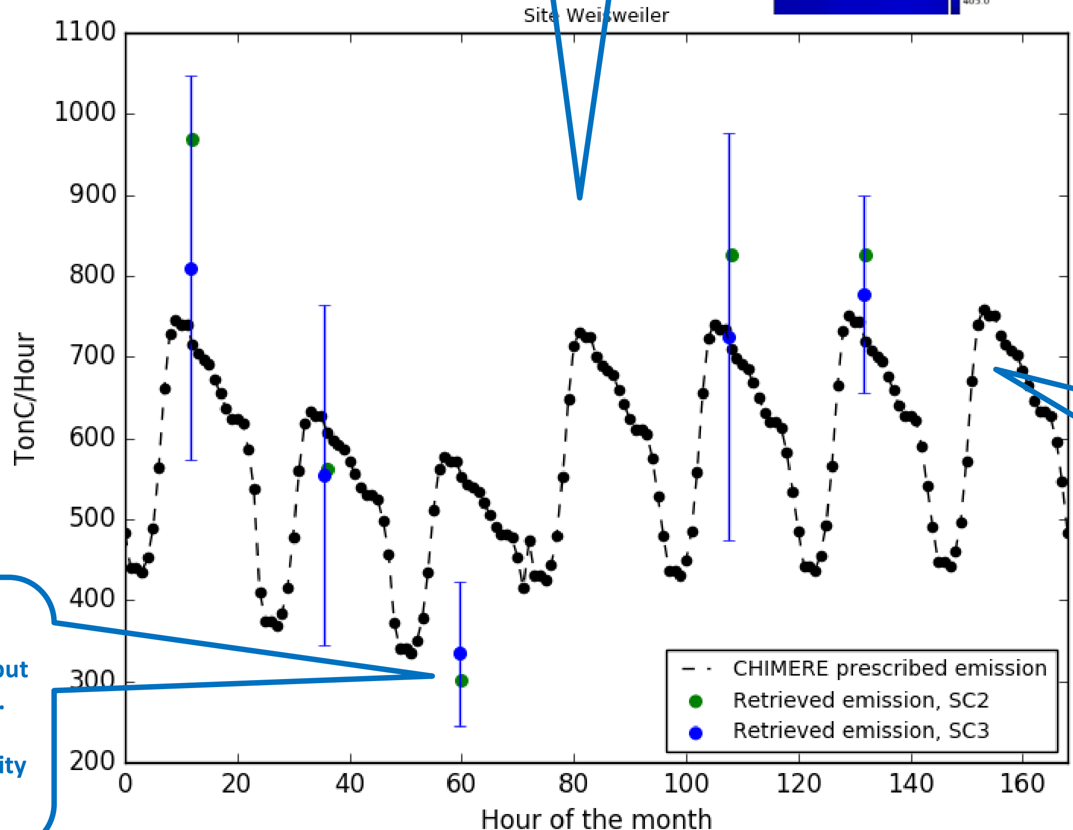
Point source emission retrieval: test for Weisweiler, from days 1 to 7

- **Site emission F (Ton C per hour) and corresponding error are computed using the SC2 and SC3 approaches**

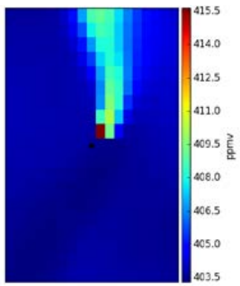
OBS, Day 4



Day 4 (Hour 84) identified as non favorable case: Non Gaussian form of the plume



OBS, Day 7



Day 7 (Hour 156) identified as non favorable case: Non Gaussian form of the plume

Day 3 (Hour 60) emission is significantly under-estimated, but identified as a favorable case. To be further investigated (effective wind estimate, stability parameters, …)

SYNTHESIS AND FURTHER WORK

- **A complete retrieval scheme has been implemented**
  - Gaussian model with simulation/integration of different instrument FOV sizes and forms
  - OEM inversion scheme fitting all Gaussian parameters in the state vector consistently with characterized *a priori* values and uncertainties. An effective wind speed is derived from ancillary data and used for emission estimate
  - Image preprocessing for plume characterization

- **The retrieval process includes the «objective» identification of favorable observation cases for robust estimate of source emissions and their uncertainty**
  - Identification of the Gaussian character of simulated/observed plumes (which could be processed with other retrieval/assimilation schemes), for a proper use of this simple Gaussian method
  - Also based on characterization of plume contrast (exploiting image noise), and on consistency between image and plume characteristic scales (exploiting image resolution and sampling)

  Allows the identification of potential sites that can be monitored by a given mission configuration (e.g., applied on the specific MicroCarb City Mode for characterization of candidate target sites)

  Allows to perform systematic data screening and filtering on synthetic/measured images

- **The method has been tested on realistic synthetic images for the specific MicroCarb City mode**
  - Capability and expected performances for retrieving emission from point sources
  - Characterization of favorable cases and configurations for target sites

Further work (1/3): analysis of instrument configurations

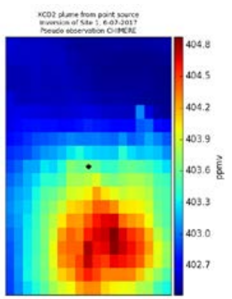
- MicroCarb like & GEO like: qualitative comparison of configurations

Images are at the same spatial scale

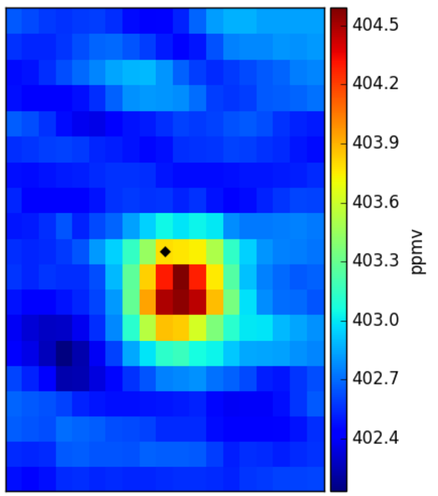
City (Paris)

***GEO** provides the required extension, spatial resolution is not critical*

MicroCarb



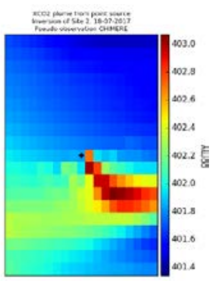
GEO



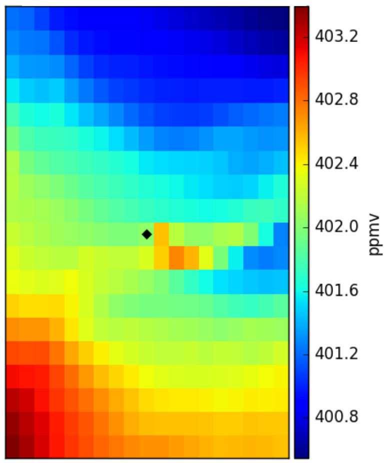
Power point (Dunkerque)

***MicroCarb** provides the required extension and spatial resolution*

MicroCarb



GEO



- On going work: analysis with GeoCARB image configuration

In the frame of the CNES/CNRS GeoCARB-Fr activities driven by LSCE in collaboration with Univ. Oklahoma and JPL

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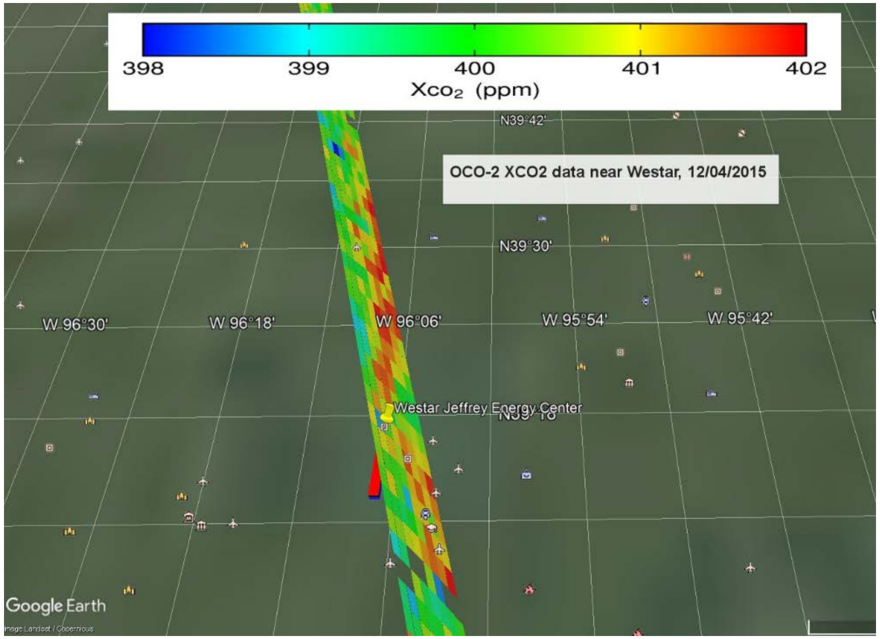
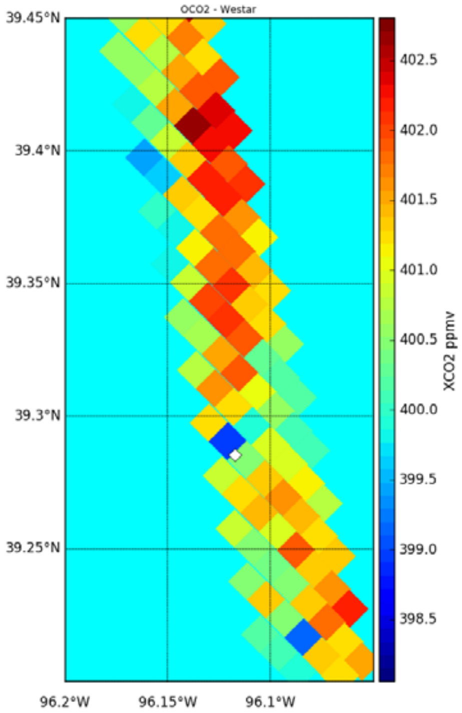
Further work (2/3): tests with real OCO-2 data

- On going tests for retrieving point source emissions from OCO-2 XCO_2 data already exploited by Nassar et al. (2017)





OCO-2 data near Westar Jeffrey Energy Center, 12/04/2016 (Nassar, pers. comm.). Google Earth view (left) and plotted image considered for the retrieval (right). The Gaussian model and retrieval scheme will consider the diamond form of pixels with their actual dimensions

- Image preprocessing for plume characterization and analysis of retrieval feasibility
- Tests with different hypotheses on *a priori* constraints, for a robust estimate of retrieved emission uncertainty

Further work (3/3): further methodology development

- **Consolidation of the Gaussian approach: modelling and retrieval**
  - Exploit the capability of the scheme to fit stability parameters i.e. $\boldsymbol{\sigma_0}$ (or **a**) and **b** for constraining the plume dynamics from the observations
  - Test different formulations of σ_y(x) plume spread for a better exploitation of available auxiliary information on the plume dynamics (temperature gradient, fluctuation of the wind direction, Richardson number, Monin-Obukhov length, …)
  - Consolidate the theoretical analysis with synthetic data for characterizing error sources

Thank you for your attention

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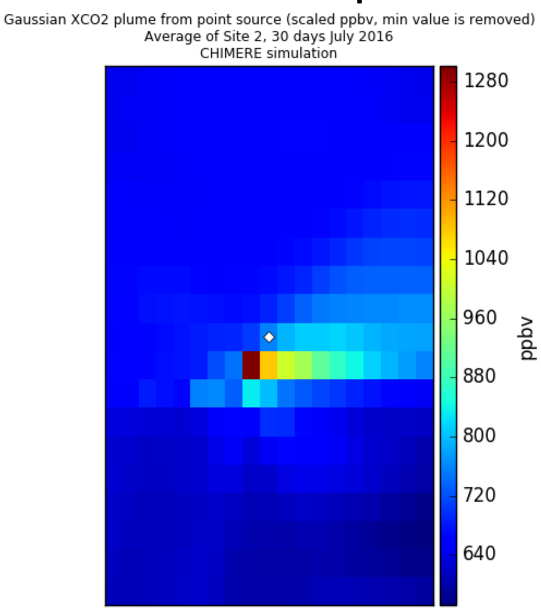
Additional slides

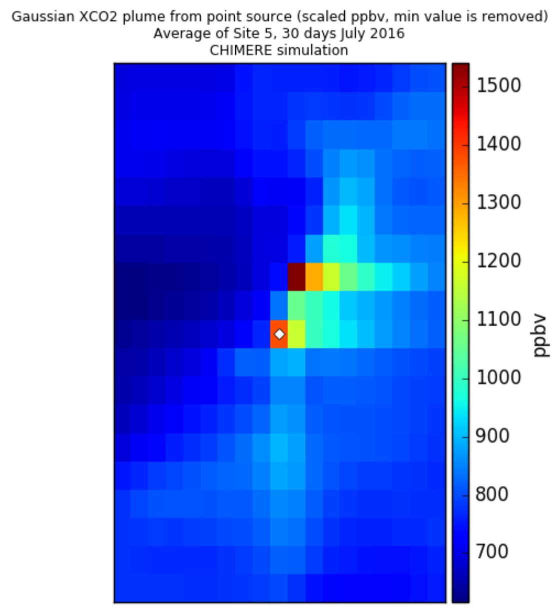
Exploitation of image averaging over a significant period of time (here CHIMERE simulation averaged over 1 months), for sources identification

Detection and processing (with improved Gaussian model) of several sources in the image

Site 2: Dunkerque



Site 5: Rodenhuize



Site 6: Weisweiler