SPASCIA LSCE

Plume detection and characterization from XCO_2 imagery: potential of Gaussian methods for analysing and estimating plant and city fluxes

SPASCIA/LSCE/IPSL

Pascal Prunet, **Claude Camy-Peyret**, Olivier Lezeaux

François-Marie Bréon, Grégoire Broquet, Diego Santaren

Work supported by CNES

15th IWGGMS

3-5 June 2019, Sapporo, Japan

- **A new method for point source plume characterization and emission inversion from the atmospheric XCO_2 images has been developed and tested :**
  - Exploiting 2D image information of the plume
  - Based on **Gaussian modelling of the plume**, adapted for single/multiple point sources and for extended sources
  - Image preprocessing for the plume characterization (direction, background)
  - 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 the emission estimate.

- **Objective criteria allows the identification of favorable observation cases for the quantification of the emissions :** good fit of the Gaussian plume(s), characterization of the plume contrast in the image, OEM convergence and χ^2 criteria. This allows:
  - Data filtering and flagging.
  - Identification of potential sites that can be monitored by a given mission configuration (applied to the MicroCarb City Mode for the characterization of candidate target sites in support of the mission strategy)

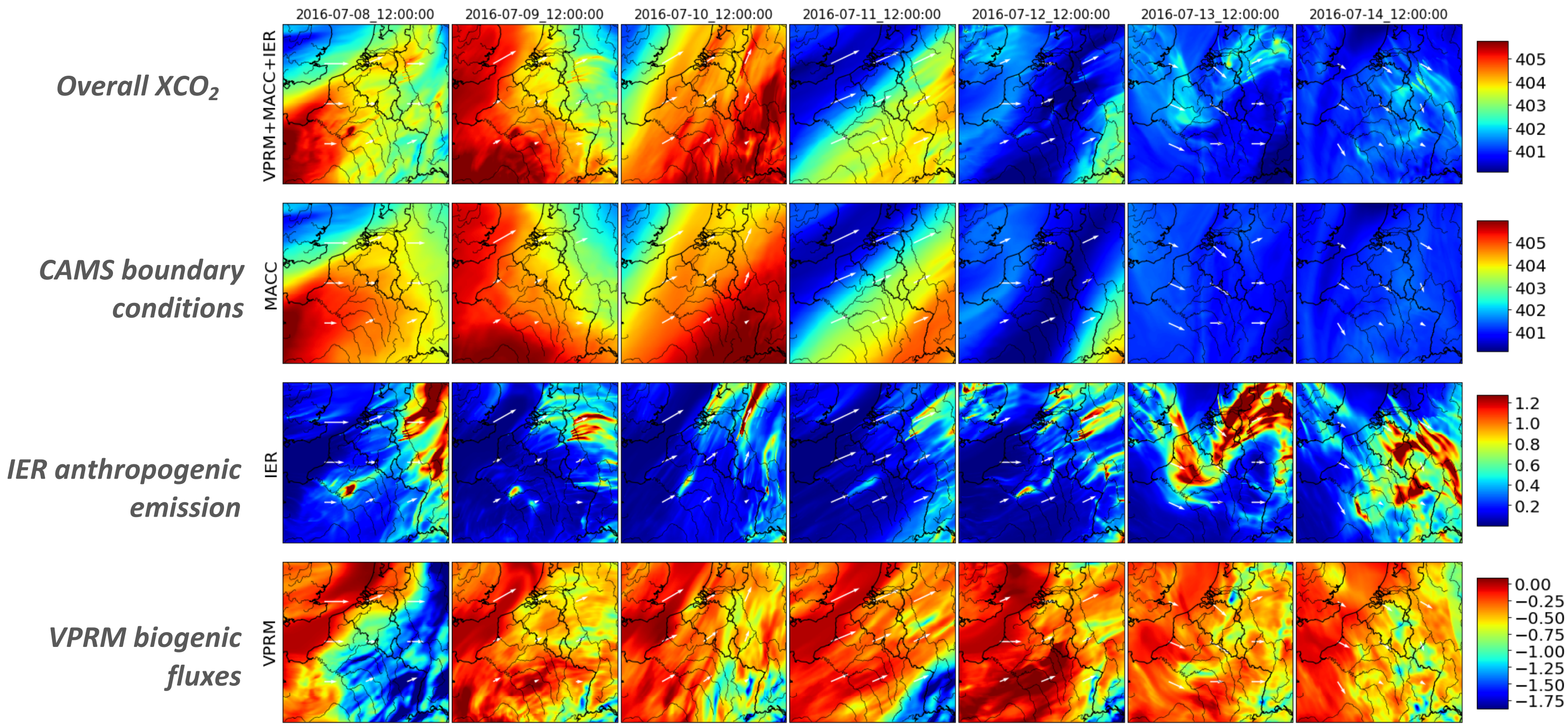
- **Validation with realistic synthetic XCO_2 images provided by CHIMERE simulations (LSCE) for a representative set of city/power plant sites, including :** high resolution emission inventories, realistic atmospheric dynamics and boundary conditions, simplified instrumental configuration for MicroCarb City Mode and GeoCarb**.**

Synthetic datasets and sites selection

SYNTHETIC DATASET: XCO_2 FIELDS

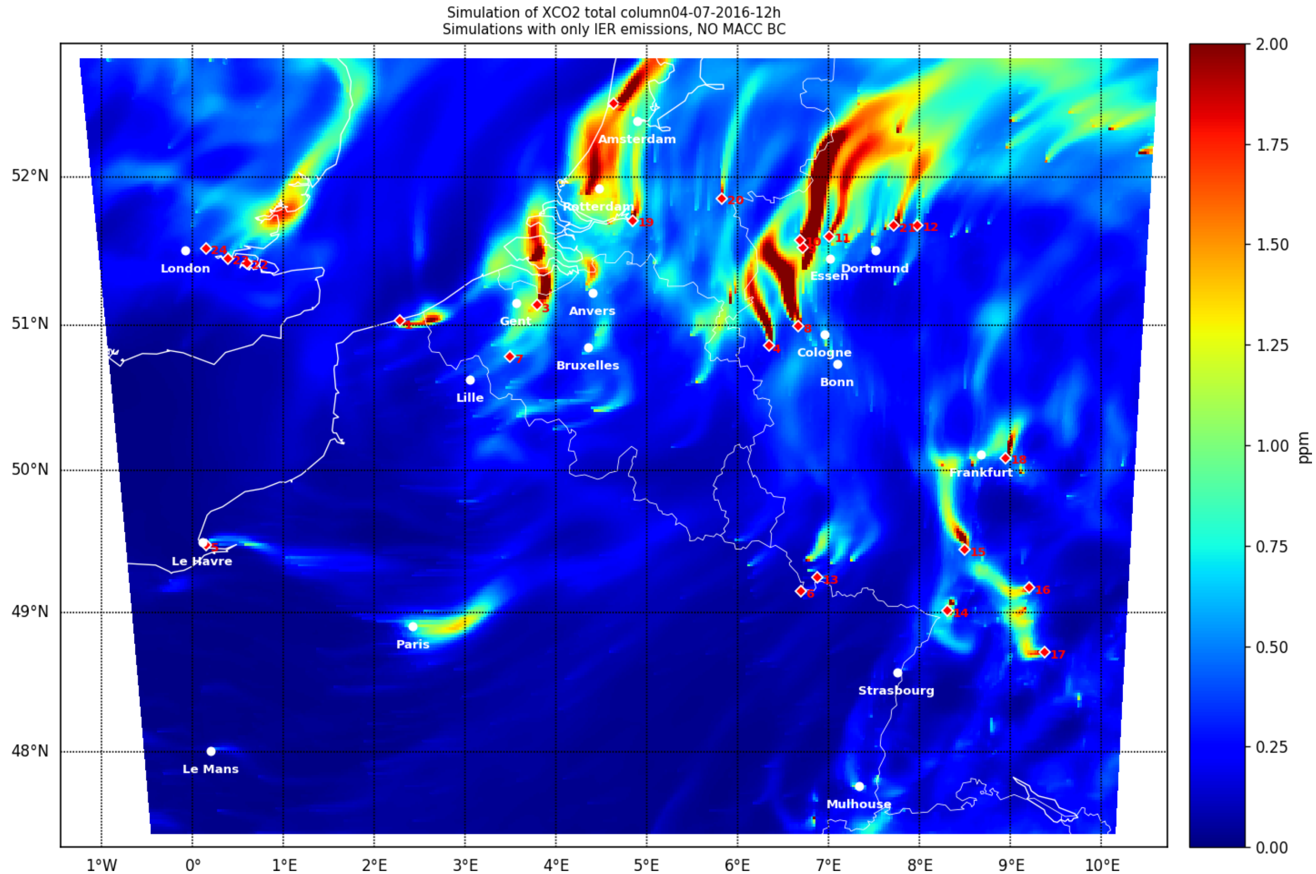
- **Simulations over Western Europe of daily fields of column averaged dry air carbon dioxide mixing ratio (XCO_2) for July 2016**
  - IER 1 km emission inventories, 8 km VPRM vegetation flux model, 15 km CAMS XCO_2 boundary conditions
  - CHIMERE transport model at 2 km resolution (forced by ECMWF meteorological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

XCO_2 (ppm) from *day 8 to 14*



CONSIDER A MORE REPRESENTATIVE SET OF SITES (CITIES, PP)

Pre-selection of European sites covering various typical power plants and cities in France, Belgium, Germany, Great-Britain and the Netherlands, as targets for generating synthetic images : cities (white points and names) and power plants (red points and table).



Power plant	Number
Dunkerque	1
Velsen	2
Rodenhuize	3
Weisweiler	4
EdF Le Havre	5
Emile-Huchet	6
Ruien	7
Nedieraussemn	8

Power plant	Number
Duisburg	9
Voerde	10
Scholven	11
Westfalen	12
Völklingen	13
Karlsruhe	14
Mannheim	15
Heilbronn	16

Power plant	Number
Altbach	17
Großkrotzenburg	18
Amer	19
Gelderland	20
Werne	21
Kingnorth	22
Tilbury	23
Barking	24

Sites positions (red points) and numbering (table on the left) for power plants (PP), white points and names (for cities) in the CHIMERE domain (XCO_2 from IER emission only are shown, for the 4^{th} of July 2016 at 12:00)

CONSIDER A REPRESENTATIVE SET OF SITES (CITIES, PP)

Selection of 16 sites in the CHIMERE domain

Plants	Emission [MtC/yr]	$\overline{X_{CO2}\ max}$ [ppmv]
Dunkerque	1.8	1.0
Weisweiler	6.9	5.1
Niederaussem	10.5	4.5
Duisburg	6.4	4.5
Völklingen	1.0	1.5
Karlsruhe	1.8	1.9
Großkrotzenburg	1.5	2.2
Amer	1.6	1.8

Cities	Emission [MtC/yr]	$\overline{X_{CO2}\ max}$ [ppmv]
Paris	12.2	1.2
Rotterdam	11.9	1.1
Anvers	3.7	1.0
Strasbourg	0.9	0.60
Mulhouse	0.62	0.70
Bonn	1.2	1.2
Lille	0.97	0.40
Le Mans	0.37	0.35

List of 8 power plants (upper table) and 8 cities (lower table) selected as representative of different types of source configurations in terms of plume and emission intensity and of site extension and isolation. ($\overline{X_{CO2}\ max}$: monthly mean value of maximum concentration of the plume).

Method

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:

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

with $C_0 = Coeff \frac{F}{\sqrt{2\pi}\sigma_0 U}$ 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 any single image pixel)
- ✓ **4 control parameters**: C_0 = f(F,U), σ_0, x_0, b
  - $C_0 = Coeff \frac{F}{\sqrt{2\pi}\sigma_0 U}$, in ppmv. $Coeff = \frac{Mmol_{air}\, g(x,y)}{Mmol_{co2} P_s(x,y)}$; F : flux in gCO_2/s; U : wind component in the x direction, in m/s
  - σ_0 : plume spread in the y direction at x = x_0, in km; a : parameter characterizing the plume width
  - x_0 : offset distance in the x direction (avoid singularity in x=0), in km
  - b : parameter characterizing the plume dynamics or transverse plume widening

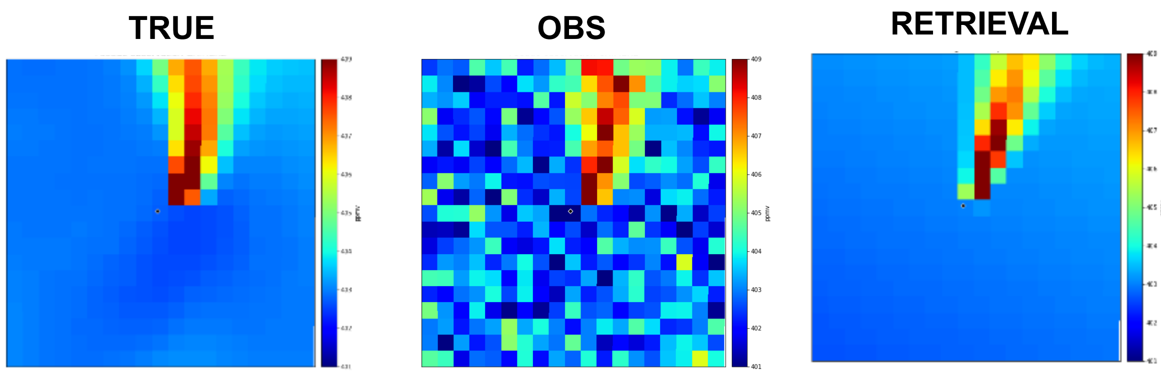
- **Background CO_2 field, in the image coordinate system XOY** (rotation of angle Φ_0 of the plume axis)

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

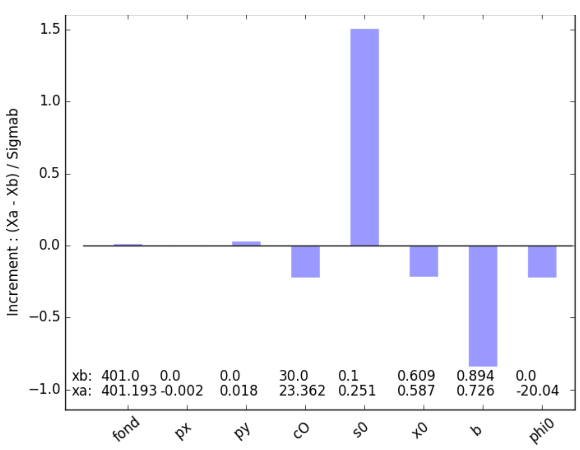
- ✓ **3 control parameters** for the background: $XCO_2(0,0)$, p_X, p_Y
- ✓ **1 parameter** for the plume direction, Φ_0 : plume direction angle in the XOY reference system

METHODOLOGY : PLUME INVERSION

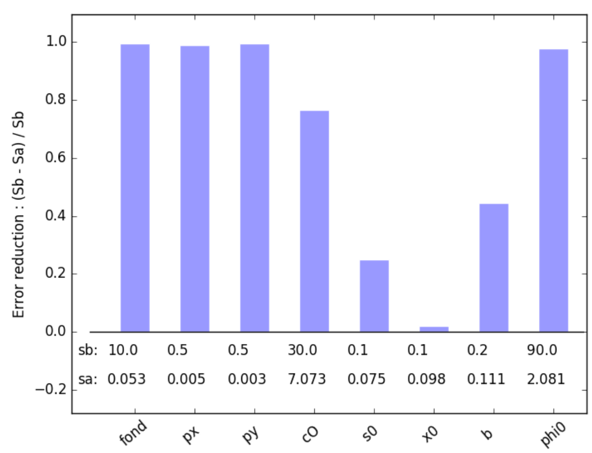
Weisweiler, 07/07/16 : MicroCarb configuration



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



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



OEM retrieval scheme adjusting the 8 parameters of the Gaussian model from noisy pseudo-observations (1 ppm error stdv)

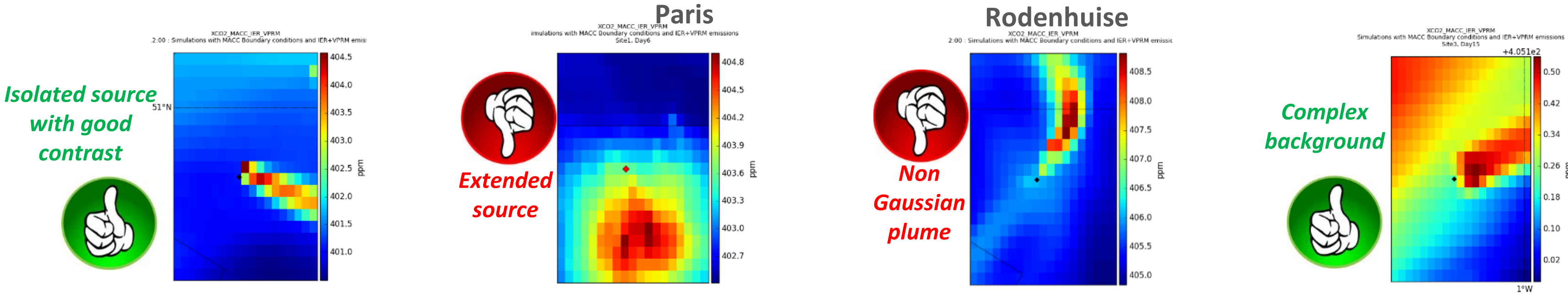
A preprocessing is implemented for the image analysis: detecting the presence of one (or several) plume(s), characterizing the plume (extension, amplitude, source position), and providing a *first* estimate of background and direction parameters.

Fitting 8 parameters:

- background and wind direction well constrained.
- More than 2 pieces of information (over 4) on Gaussian model parameters.
- C_0 (proportional to F/U) is constrained by the data

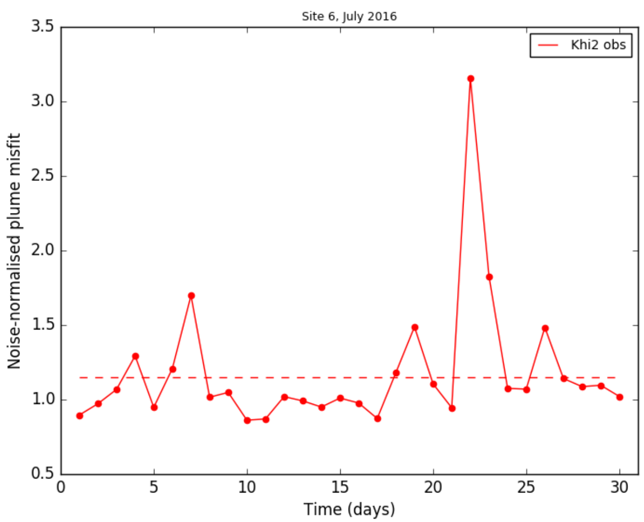
RESULTS: PLUME CHARACTERIZATION

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

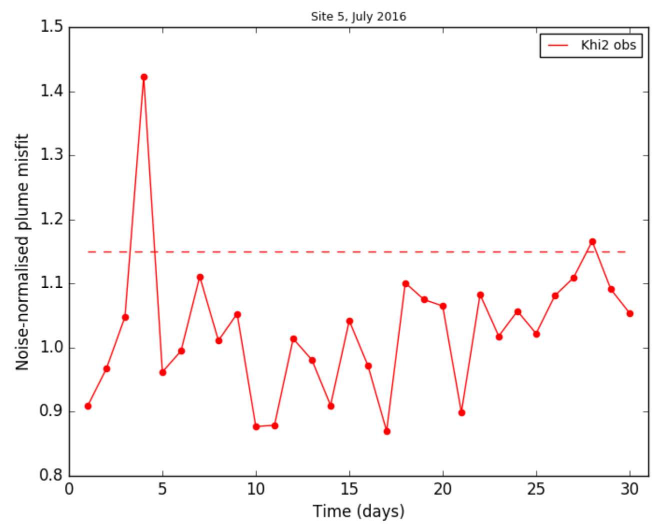


Identify cases well-fitted with our Gaussian retrieval : $\chi^2_{y\,(red)} = \frac{(y_{obs}-y_{OEM})^T\, S_y^{-1}\,(y_{obs}-y_{OEM})}{N_{obs}}$ ***close to 1*** *(threshold: 1.15)*

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



Rodenhuise (weaker source: ~ 5 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

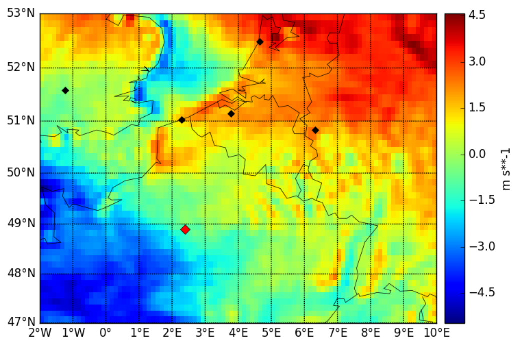
(1 ppm noise, no clouds)

From gaussian parameters to source emission retrieval (F): exploiting wind information for determining U

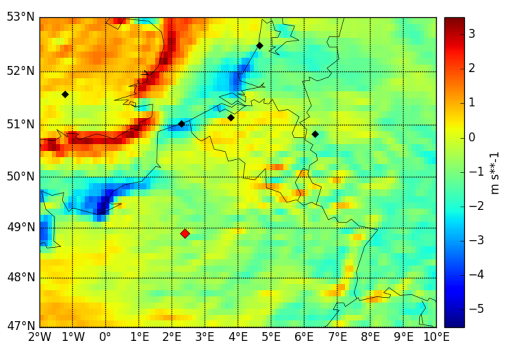
- Point source emission F is estimated from C_0 and given an « effective » wind $U = U_{eff}$
  - U_{eff} is estimated from the ECMWF wind profile, plus some rule to choose the wind effectively acting on the CO_2 plume: U_{eff} is taken as a combination of the 3 estimators below
    - Wind at the altitude 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

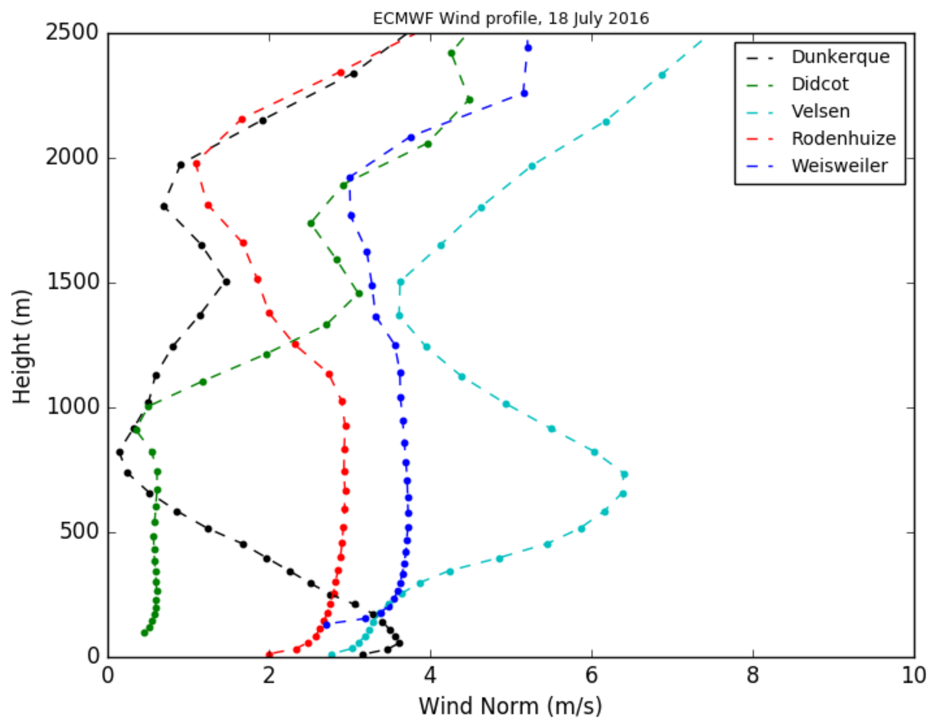
U component of the surface wind



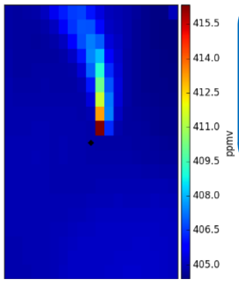
V component of the surface wind



Profile of the wind module for the selected sites

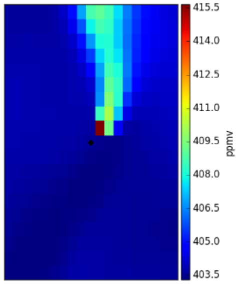


Test for Weisweiler, from days 1 to 7, MicroCarb configuration



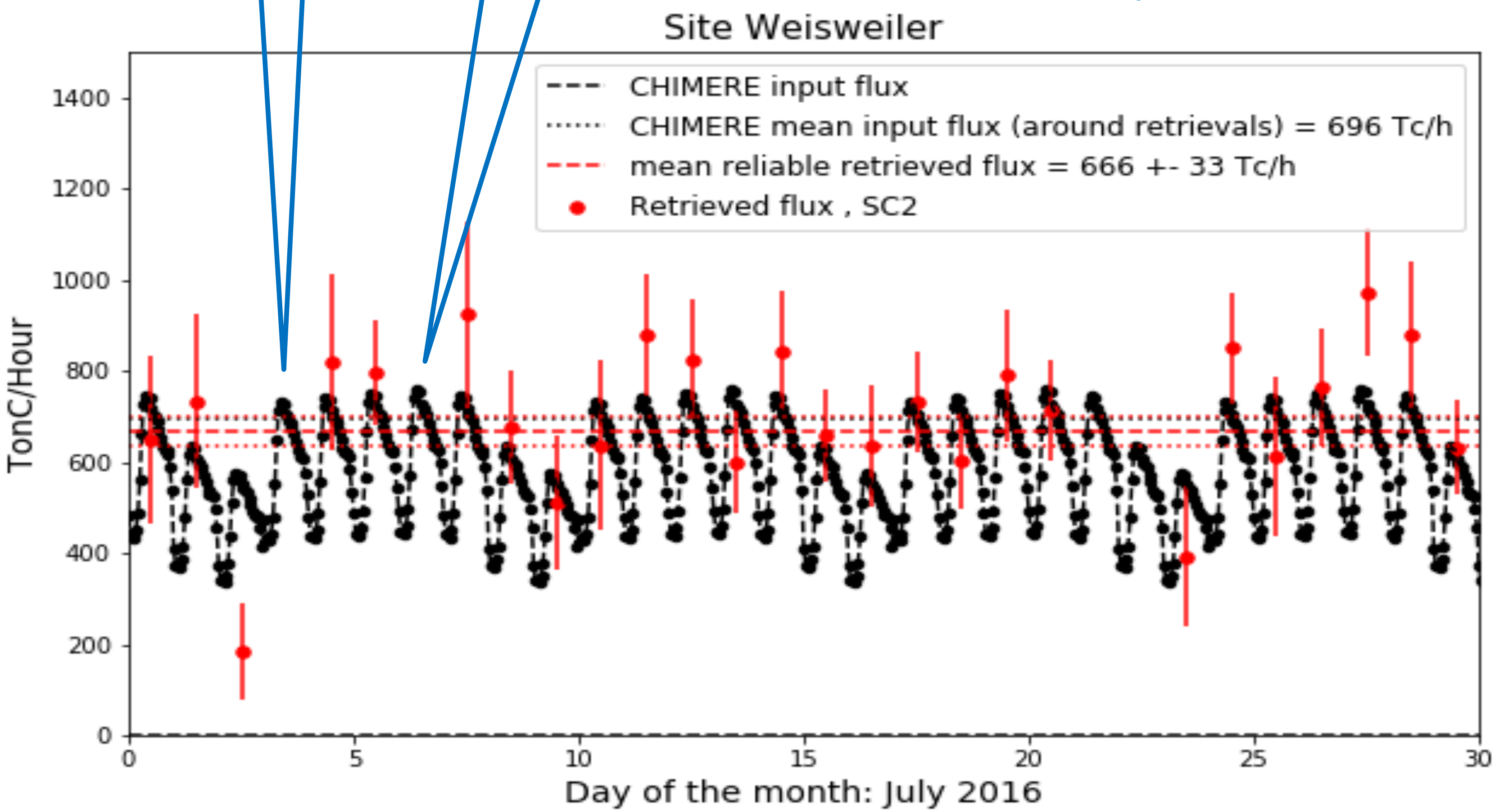
Day 4 (hour 84) flagged as non favorable case: non gaussian form of the plume

Day 7 (hour 156) identified as non favorable case: non gaussian form of the plume



Site emission F (ton of C per hour) and error are computed using different hypotheses of *a priori* constraint on gaussian parameters (SC1, SC2 and SC3 approaches), and given an « effective » wind $U = U_{eff}$

Retrieved F is compared with hourly site emission prescribed in CHIMERE simulation

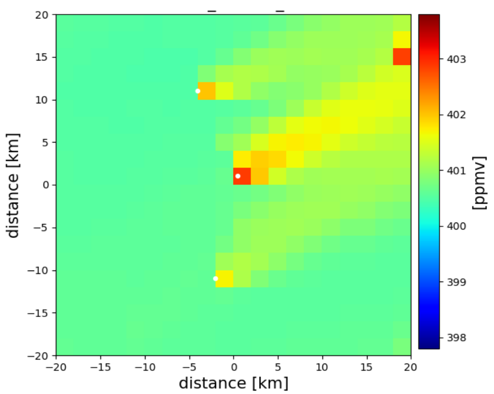


Necessity to deal with multiple and extended sources for addressing realistic scenes

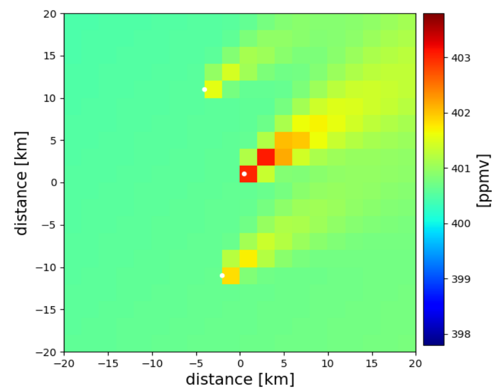
METHODOLOGY : PLUME INVERSION

Duisburg, 12/07/16 : MicroCarb configuration

TRUE

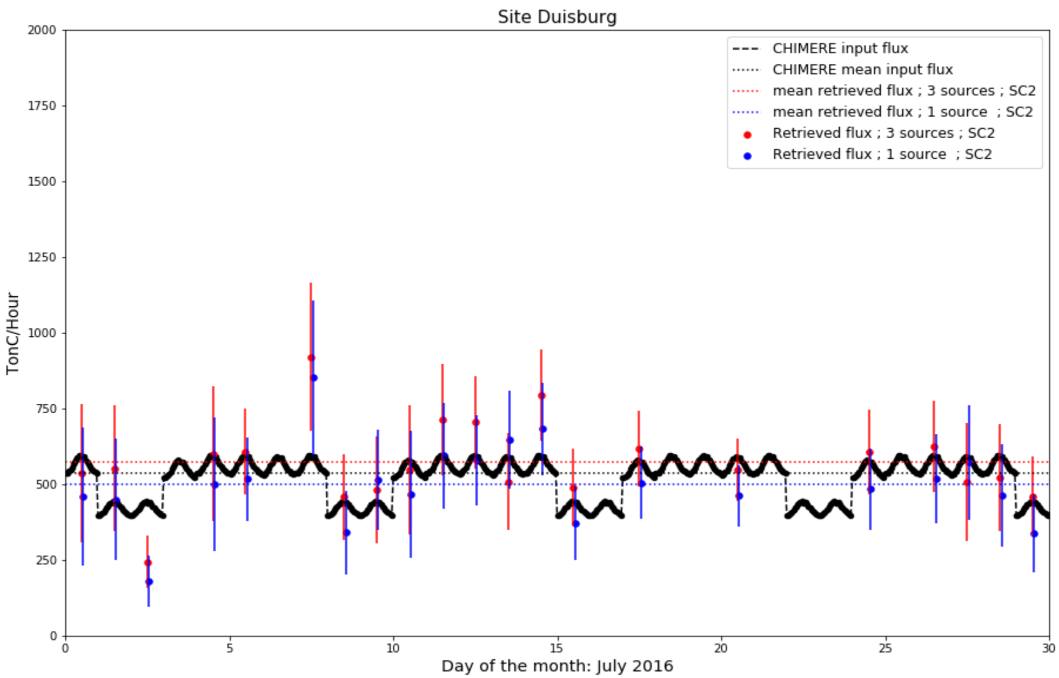


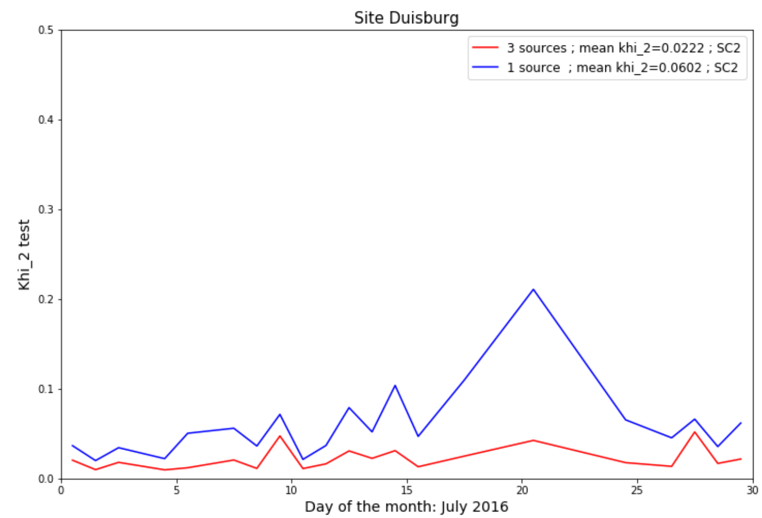
RETRIEVAL



3 sources must be considered to reproduce correctly the CHIMERE image with the Gaussian model.

The consideration of 3 sources improves only slightly the flux retrieval bias of the central source (if considered isolately). However, the residual in the observation space (χ^2) is significantly reduced, improving the quality of the image retrieval



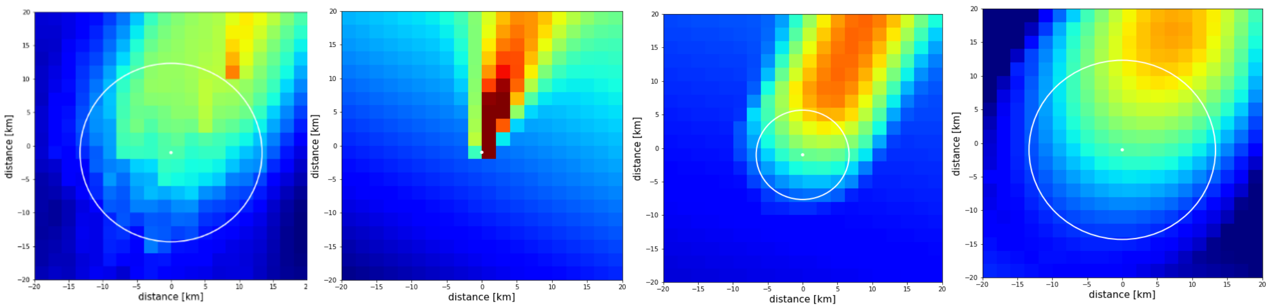


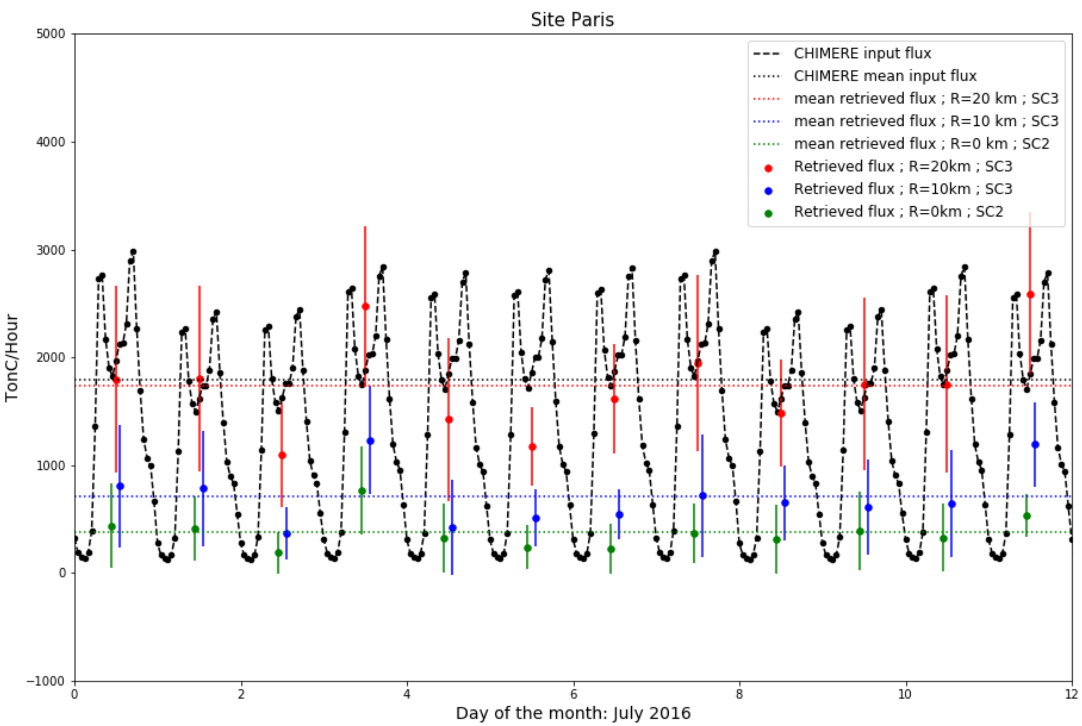
METHODOLOGY : PLUME INVERSION

SPASCIA LSCE

Paris, 03/07/16 : MicroCarb configuration

TRUE | RETRIEVAL Gaussian point source | RETRIEVAL Gaussian spread source R=10 km | RETRIEVAL Gaussian spread source R=20 km





A surfacic source (disk of radius R) is considered for properly reproducting the Paris plume with the Gaussian model.

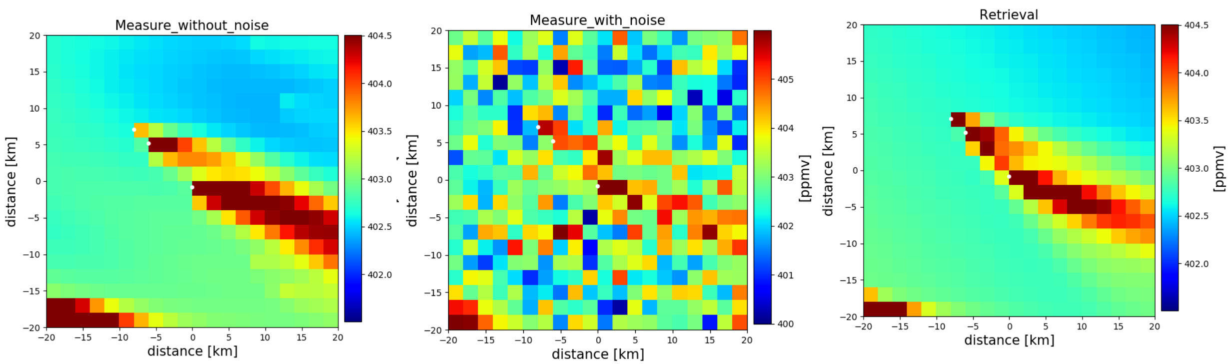
The consideration of a surfacic source significantly improves the flux retrieval. The proper adjustment of the size of the source (radius) is critical and allows a good retrieval of the flux, not possible if only a point source is considered.

Results : Power plants

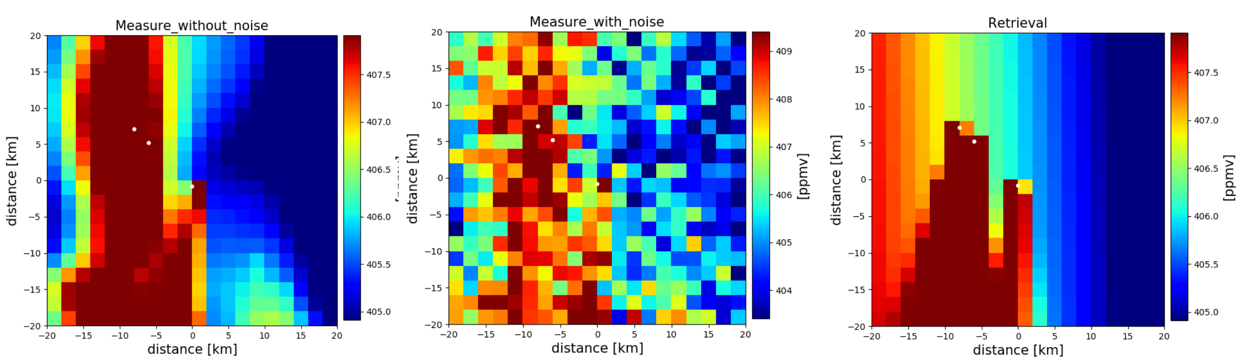
RESULTS: PLUME INVERSION

TRUE **OBS** **RETRIEVAL**

06/07/16 : Good fit of the image and good flux retrieval



22/07/16 : Complex scene, bad fit of the image and incorrect flux retrieval, but well identified case, flagged through the quality check (large χ^2)



Example of MicroCarb synthetic images over Niederaussem, 6^th and 22^th July 2016 at 12:00

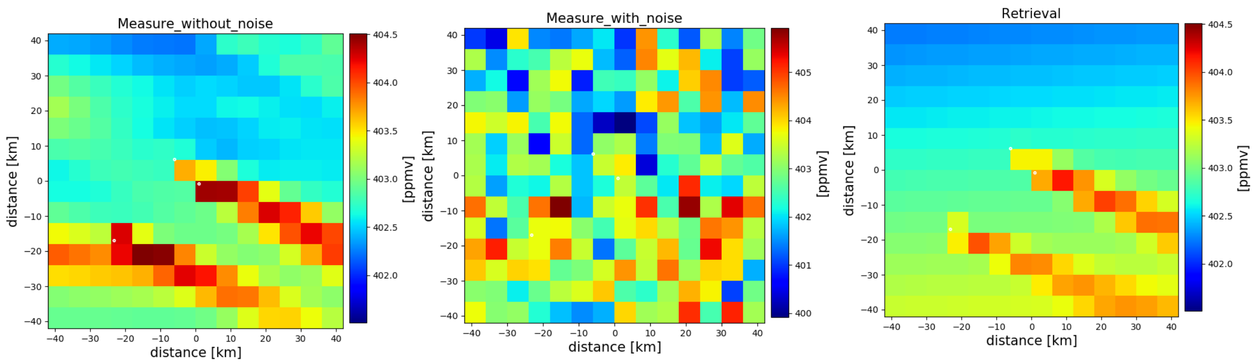
Image : 20 x 20 pixels (40 km x 40 km), with a 2 km x 2 km pixel

Multiple sources considered for this retrieval

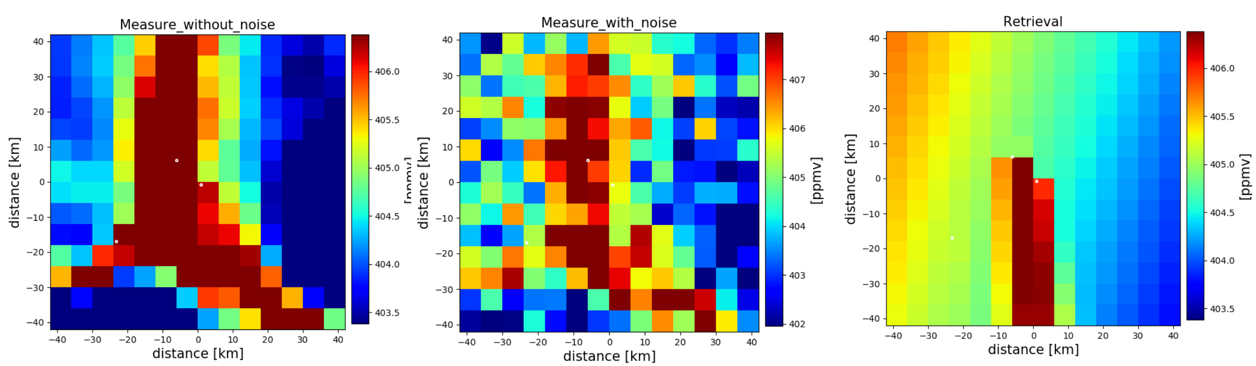
RESULTS: PLUME INVERSION

TRUE **OBS** **RETRIEVAL**

06/07/16 : Proper fit of the image and good flux retrieval, but flag resulting from a “parasitic” plume (source(s) on the left of the domain)



22/07/16 : Complex scene, bad fit of the image and improper flux retrieval, but well identified case, flagged through quality check (large χ^2)



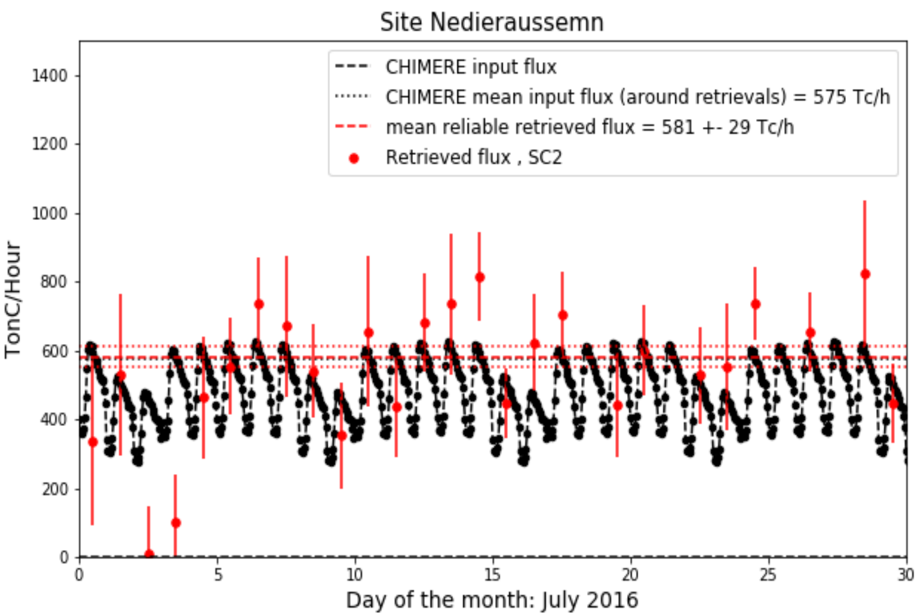
Example of GEO like synthetic images over Niederaussem, 6th and 22th July 2016 at 12:00

Image : 14 x 14 pixels (84 km x 84 km), with a 6 km x 6 km pixel

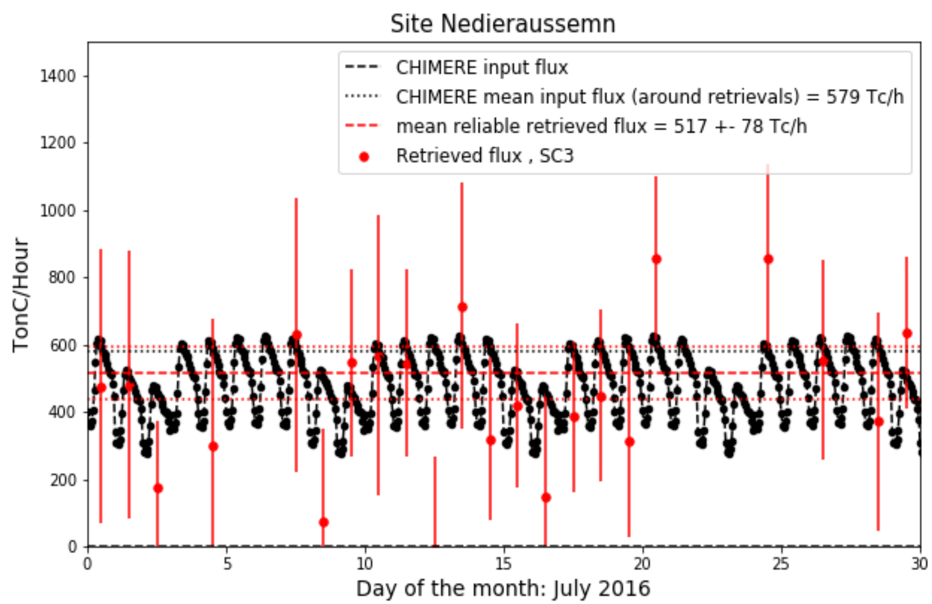
Multiple sources considered for this retrieval

Point source emission retrieval: test for Niederaussem, from days 1 to 30 : MicroCarb and GEO like configurations

MicroCarb



GEO like



In MicroCarb mode : bakground parameters $XCO_2(0,0), p_X, p_Y$**; wind direction** Φ_0**, atmospheric dispersion parameter** σ_0**, and flux** F **are constrained by the retrieval (SC2 scenario). In GEO mode, exploiting external information (e.g., Pasquill classification) to constrain the Gaussian parameter** σ_0 **is necessary (SC3 scenario).**

- Larger number of good retrievals in the MicroCarb mode (less days flagged), larger uncertainties on individual retrievals in GEO mode.
- In terms of monthly averaged flux : better performances for MicroCarb mode (1% bias, 5% noise). The retrieved values are consistent with CHIMERE reference flux in both cases.

MicroCarb/Geo mode differences, in terms of retrieval values and error, would be mainly due to the image resolution (i.e., number of pixels effectively capturing the plume and gradient information, capability to capture multiple point sources).

Plant emission retrieval: results on several sites

In MicroCarb mode : good performances for most of the sites, including "relatively small" plants like Dunkerque or Karlsruhe (averaged DOFS > 0.5). Error from 5% (large plants) to 10-25% (small plants) on monthly averaged flux retrieval.

Site	type	#	Scenario	Reference Flux [tC/h]	Retrieved Flux [tC/h]	Error [tC/h]	Error [%]	DOFS mean	χ^2 mean
Dunkerque	plant	1	SC2	150	148	24	16	0.58	1.00
Weisweiler	plant	2	SC2	690	662	35	5	0.79	1.16
Duisburg	plant	3	SC2	552	542	32	6	0.70	0.99
Niederaussem	plant	4	SC2	575	581	29	5	0.93	1.06
Karlsruhe	plant	6	SC2	91	79	18	23	0.62	0.99
Amer	plant	8	SC2	195	199	23	11	0.70	1.00

In GEO-like mode : degraded performances for "relatively small" plants, but good results for the largest plants, with errors from 8 to 15 % on monthly averaged flux retrieval

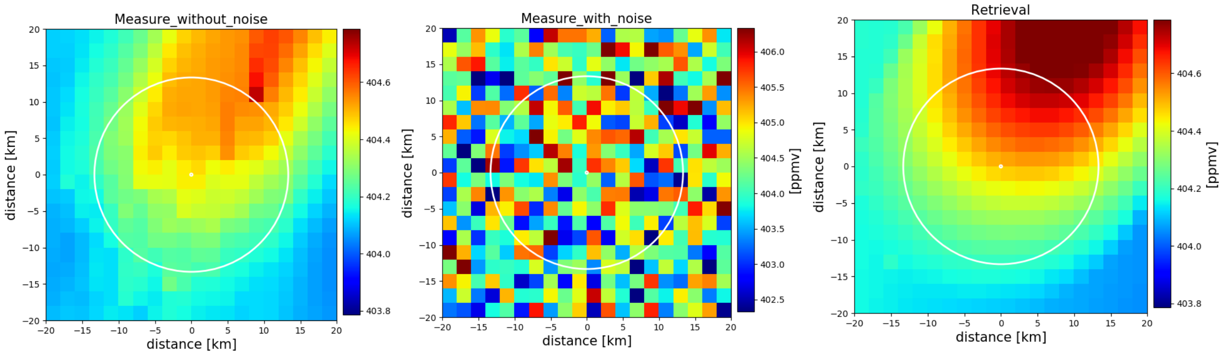
Site	type	#	Scenario	Reference Flux [tC/h]	Retrieved Flux [tC/h]	Error [tC/h]	Error [%]	DOFS mean	χ^2 mean
Dunkerque	plant	1	SC3	150	152	75	49	0.19	0.95
Weisweiler	plant	2	SC3	693	718	58	8	0.77	1.06
Duisburg	plant	3	SC3	546	581	85	15	0.62	1.05
Niederaussem	plant	4	SC3	579	517	78	15	0.73	1.18
Karlsruhe	plant	6							
Amer	plant	8	SC3	192	233	52	22	0.34	1.03

Results : City

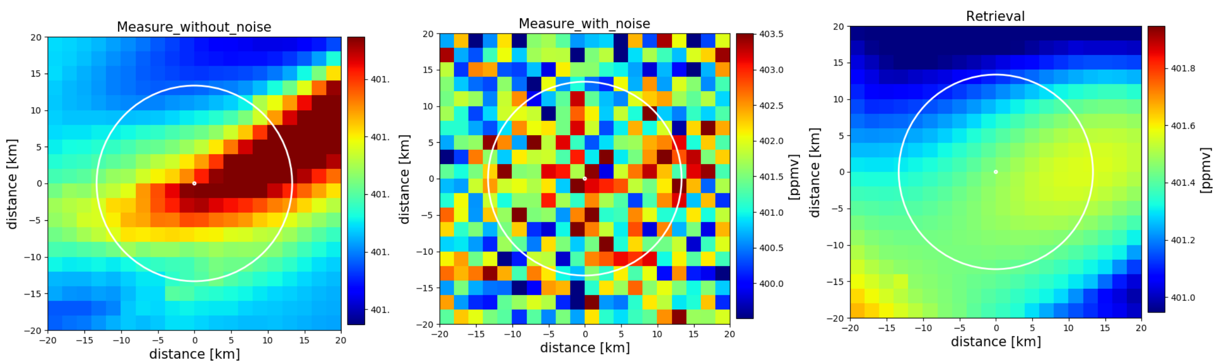
RESULTS: CITY PLUME INVERSION

TRUE **OBS** **RETRIEVAL**

03/07/16 : High DOFS, good fit of the image and correct flux retrieval



12/07/16 : High DOFS, correct fit of the image, overestimation of the flux despite a retrieved plume with low intensity : suggest some bias in effective wind estimate (retrieved plume with a larger spread and of lower intensity than the truth)



Example of MicroCarb synthetic images over Paris, 3rd and 12th July 2016 at 12:00

Image : 20 x 20 pixels (40 km x 40 km), with a 2 km x 2 km pixel

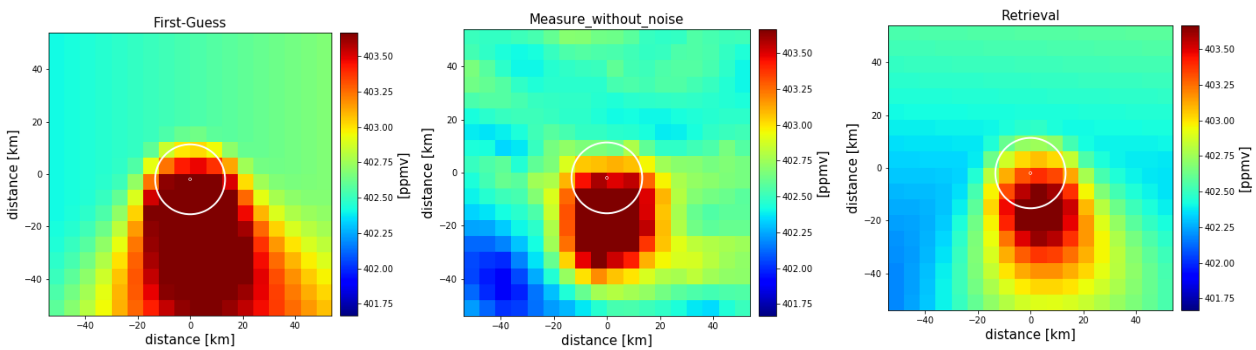
Extended source is considered

SPASCIA LSCE

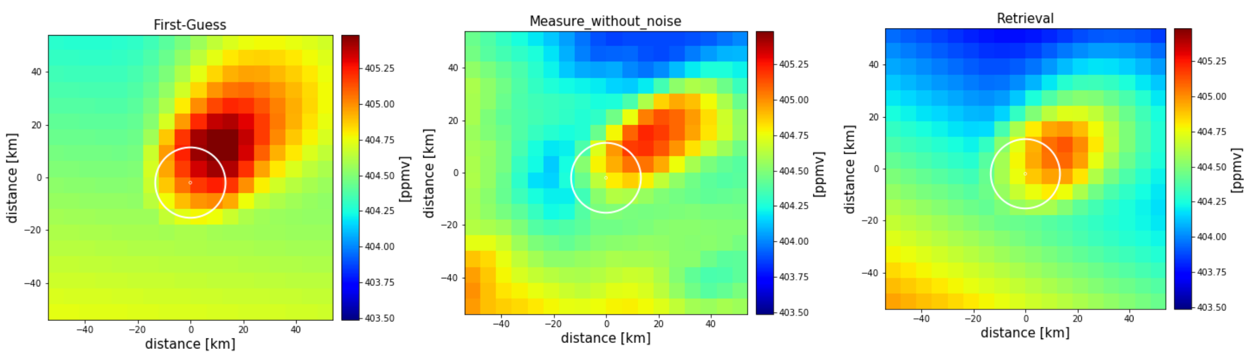
RESULTS: CITY PLUME INVERSION

FIRST GUESS **TRUE** **RETRIEVAL**

06/07/16 : Case of low wind, correct fit of the image and proper flux retrieval



09/07/16 : Correct fit of the image and proper flux retrieval, due to a good retrieval of σ_0

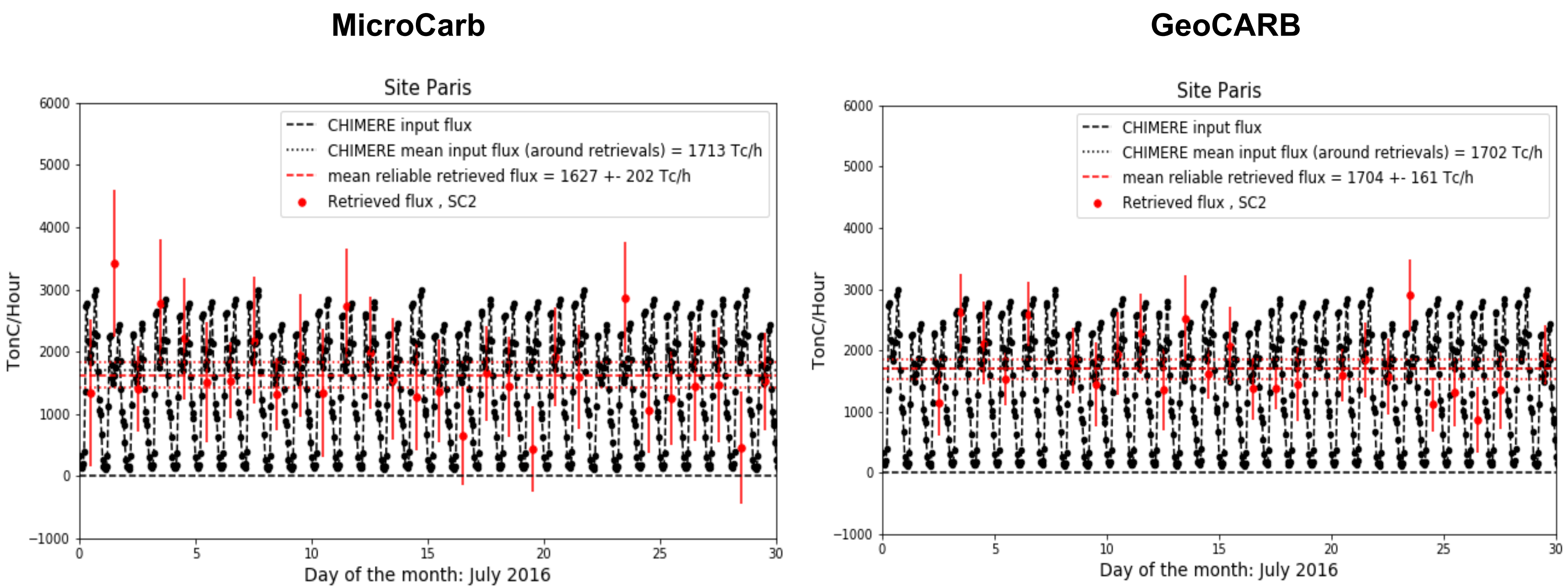


Example of GEO-like synthetic images over Paris, 6th and 9th July 2016 at 12:00

Image : 18 x 18 pixels (108 km x 108 km), with a 6 km x 6 km pixel

Extended source is considered for this retrieval

Point source emission retrieval: test for Paris, from days 1 to 7 MicroCarb and Geo-like configurations



In both MicroCarb and GEO mode : bakground parameters $XCO_2(0,0), p_X, p_Y$; wind direction Φ_0, atmospheric dispersion parameter σ_0, and flux F are constrained by the retrieval (SC2 scenario).

- Good performances in both modes : slightly larger number of good retrievals in the MicroCarb mode, slightly better accuracy on individual retrievals in the GEO mode.
- In terms of monthly averaged flux : better performances for the GEO mode (no bias, 9% noise). The retrieved values are consistent with the CHIMERE reference flux in both cases.

MicroCarb/GEO-like differences : MicroCarb mode is usable over Paris city (error 12 %), despite a limited image size, because of the good image resolution; good results are obtained in the GEO mode (error 9%) due to the image size which capture the whole panache and surrounding background.

City emission retrieval: Results on several sites

In MicroCarb mode : good performances for Paris (12 % error on monthly averaged flux retrieval), limited performances for the other (smaller) cities (from 22 to 39 % error). Atmospheric dispersion parameter σ_0 is not retrieved except for Paris.

Site	type	#	Scenario	Reference Flux [tC/h]	Retrieved Flux [tC/h]	Error [tC/h]	Error [%]	DOFS mean	χ^2 mean
Paris	city	1	SC2	1713	1627	202	12	0.78	1.00
Anvers	city	3	SC3	420	272	106	39	1.4/4	0.98
Mulhouse	city	5	SC3	71	76	17	22	0.42	1.00
Lille	city	7	SC3	111	101	33	33	0.39	0.98
Le Mans	city	8	SC3	42	46	11	24	0.54	0.99

In GEO-like mode : retrieval done only for Paris, other sites very complex in GEO mode. Good performances over Paris (9% errors) related to the capability of GEO mode to capture the whole plume.

Site	type	#	Scenario	Reference Flux [tC/h]	Retrieved Flux [tC/h]	Error [tC/h]	Error [%]	DOFS mean	χ^2 mean
Paris	city	1	SC2	1702	1704	161	9	0.63	1.00

SYNTHESIS AND FURTHER WORK

- **A complete retrieval scheme based on flexible Gaussian plume modelling and Optimal Estimation Method has been implemented and applied over a representative set of realistic synthetic XCO_2 images used for flux retrieval**

- **In the tested observation modes (MicroCarb and GEO-like, with 1 ppm noise on the XCO_2 L2 product), our results suggest that anthropogenic emissions from large power plants (> 4 MtC/year) and cities (> 10 MtC/year) should be retrieved, in terms of averaged flux (over month, season or year) :**
  - with 5-20% accuracy for power plants, and with 12% accuracy for Paris city, in the MicroCarb observation mode
  - with 10-50% accuracy for power plants, and with 9% accuracy for Paris city, in a GEO-like observation mode

- **The proposed Gaussian method, allowing flexibility for fitting the plume pattern, intensity and direction, and providing quality criteria for data filtering, appears suitable for XCO_2 image processing. Necessary improvements are :**
  - Proper estimation of the effective wind from ancillary information for unbiased retrieval
  - Image preprocessing for scene analysis, plume detection and characterization of wind direction
  - Better characterization of error sources related to non Gaussian plume behaviour (turbulence)

SPASCIA

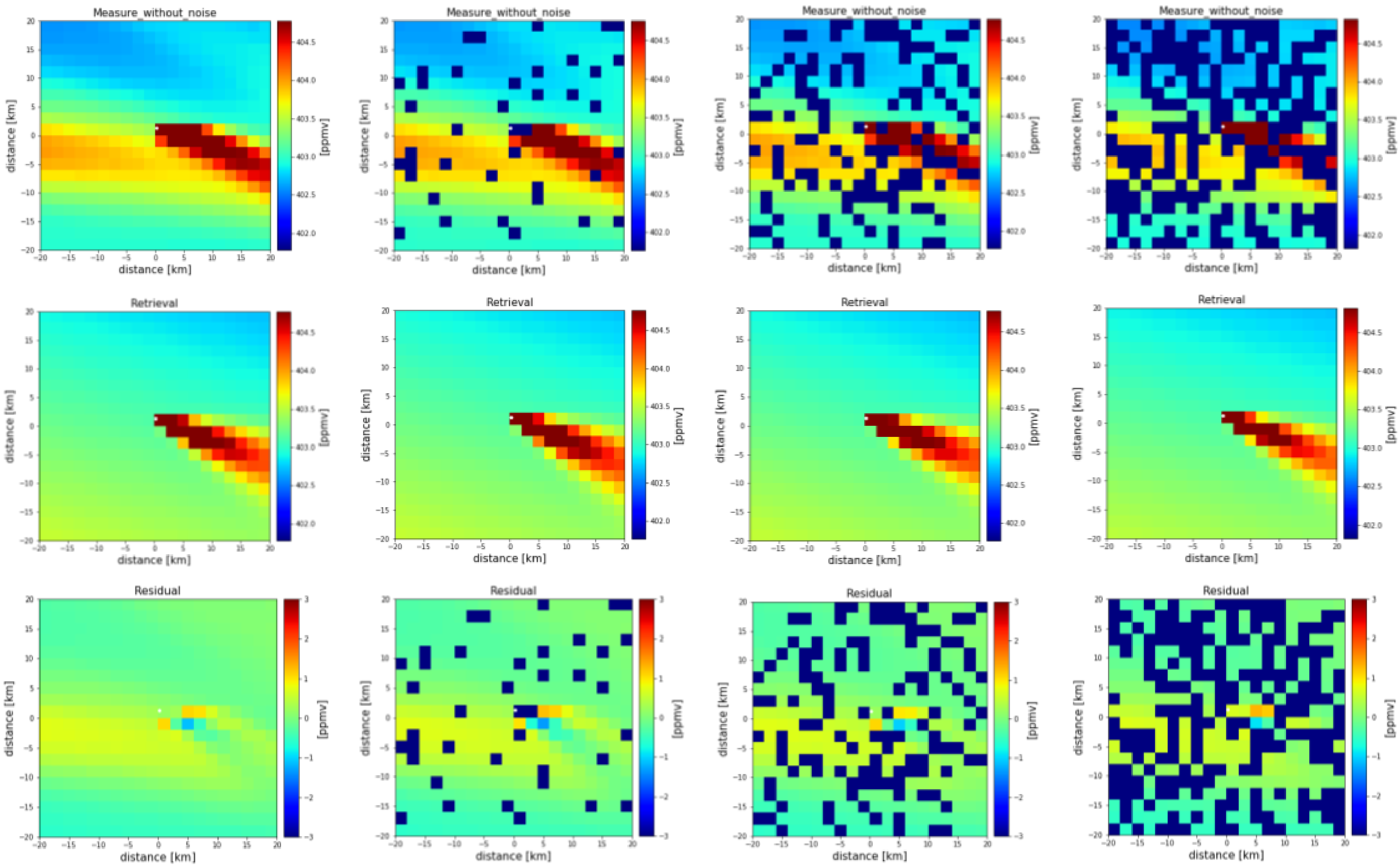
LSCE

Impact of clouds

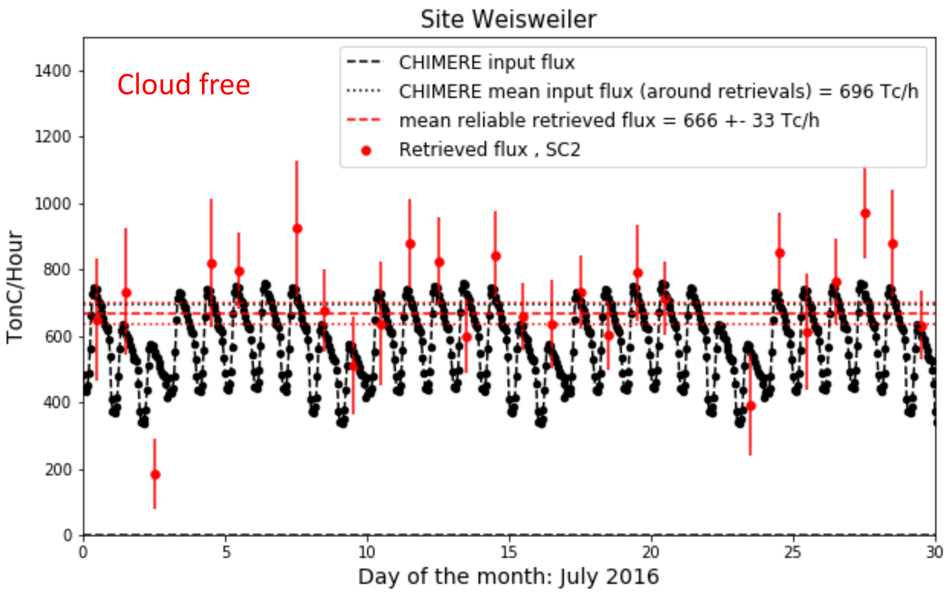
SPASCIA LSCE

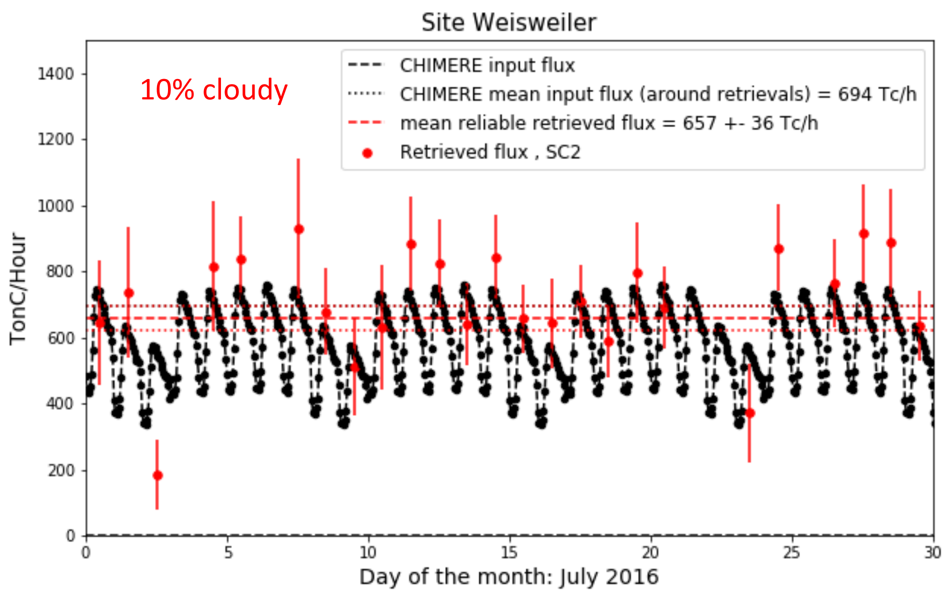
Test on power plant : site Weisweiler, day 6

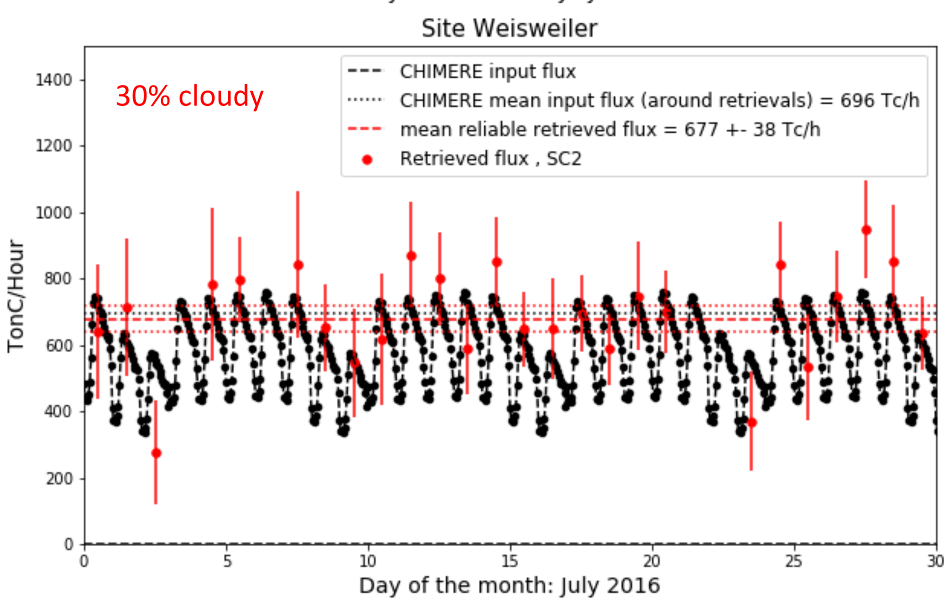
Cloud free | **10% cloudy** | **30% cloudy** | **50% cloudy**

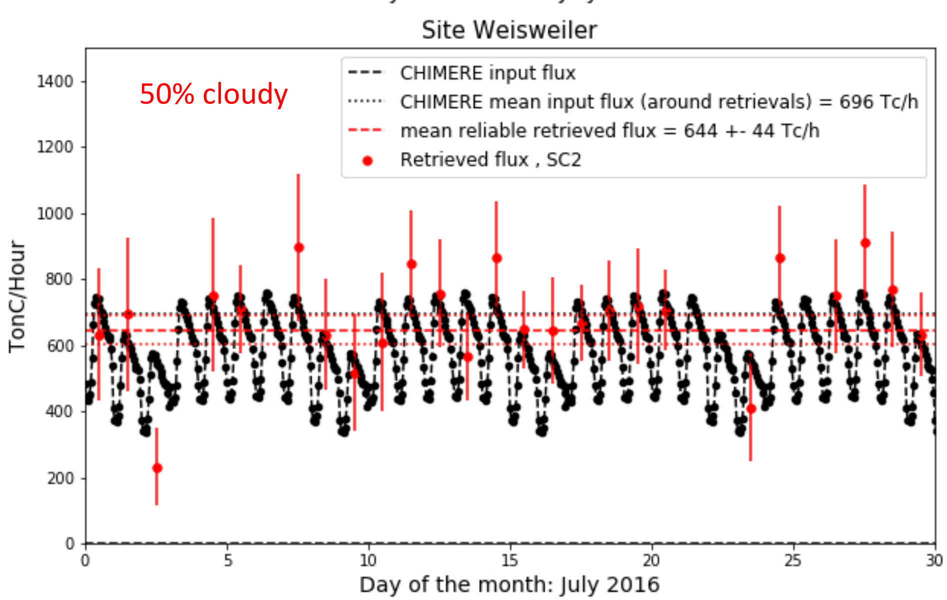


Test on power plant : site Weisweiler



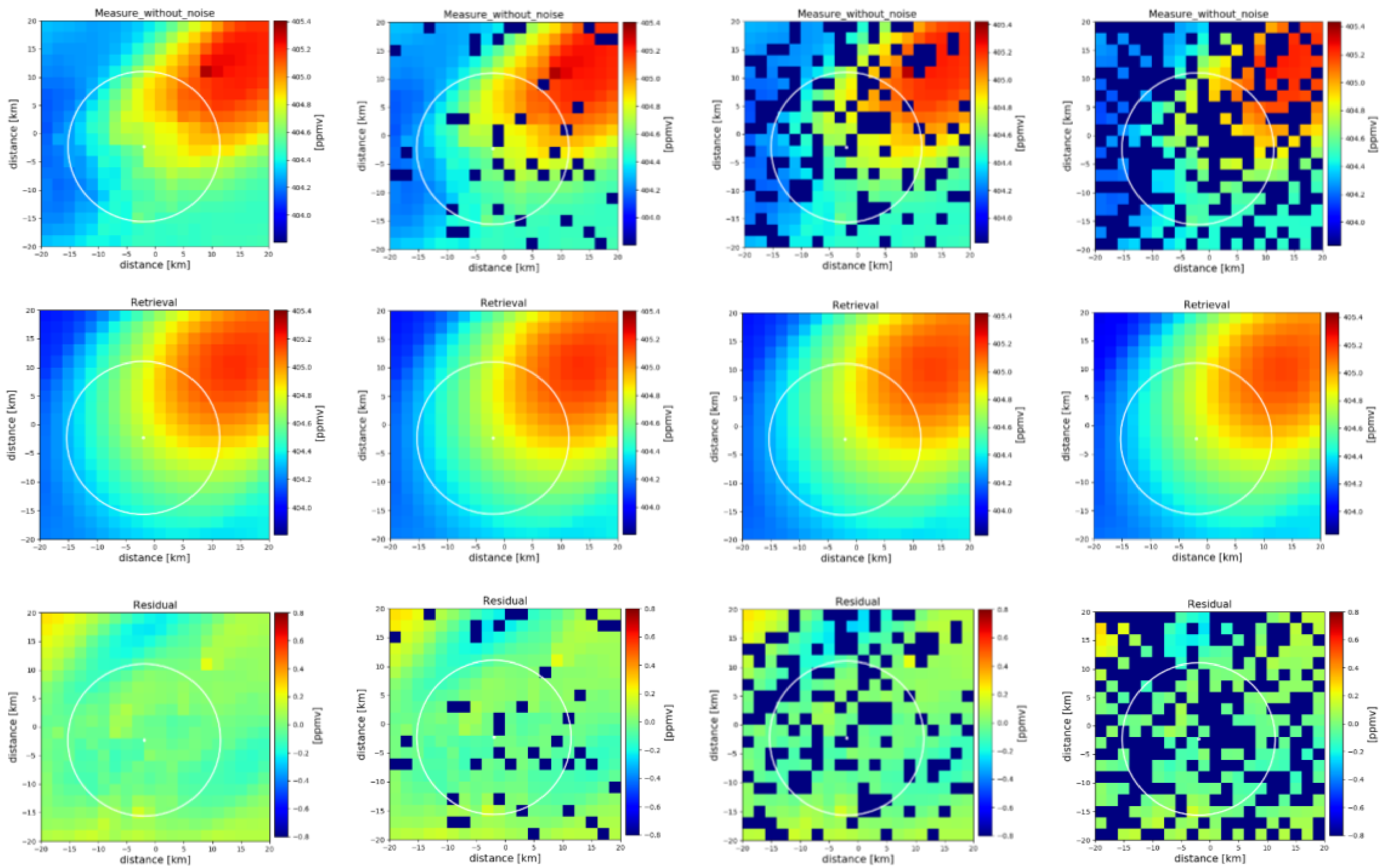




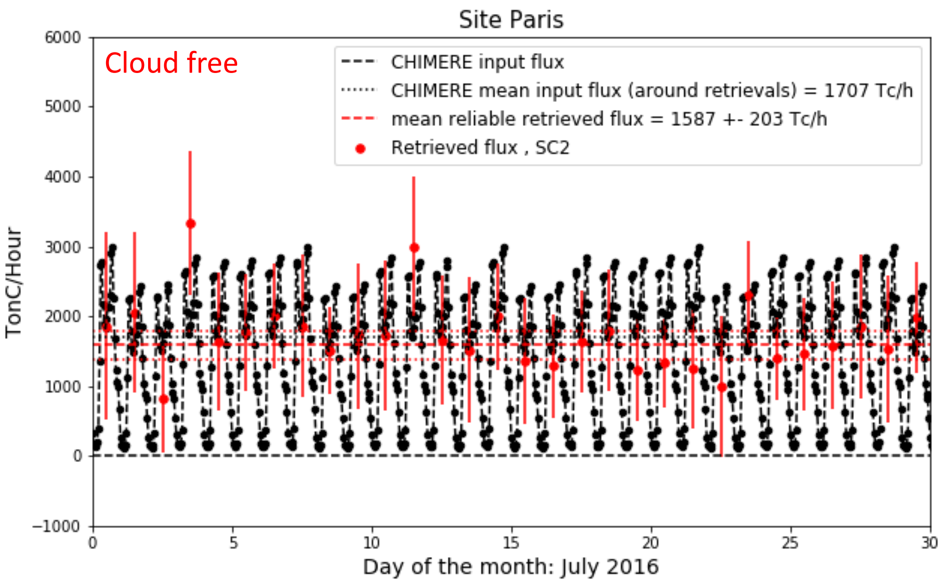


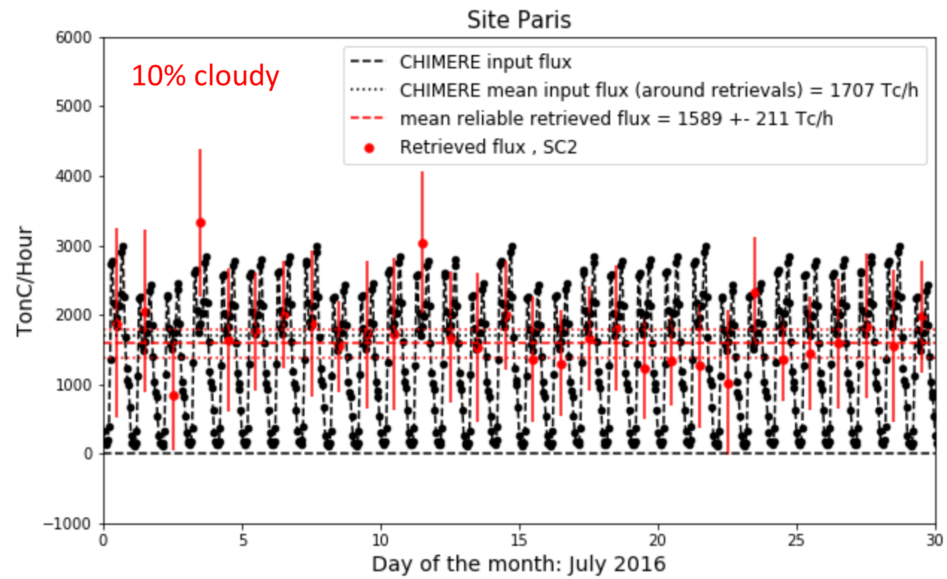
Test on city: site Paris, day 9

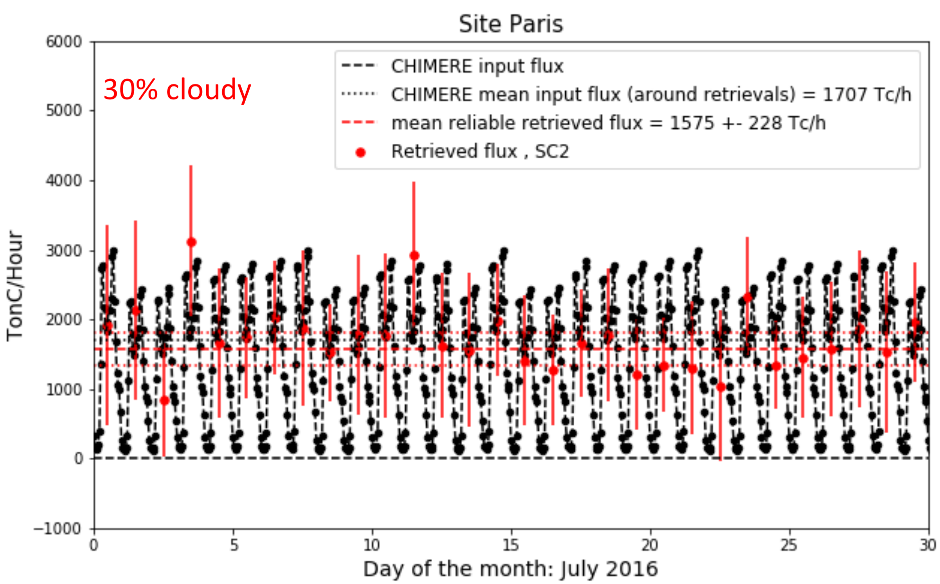
Cloud free | **10% cloudy** | **30% cloudy** | **50% cloudy**

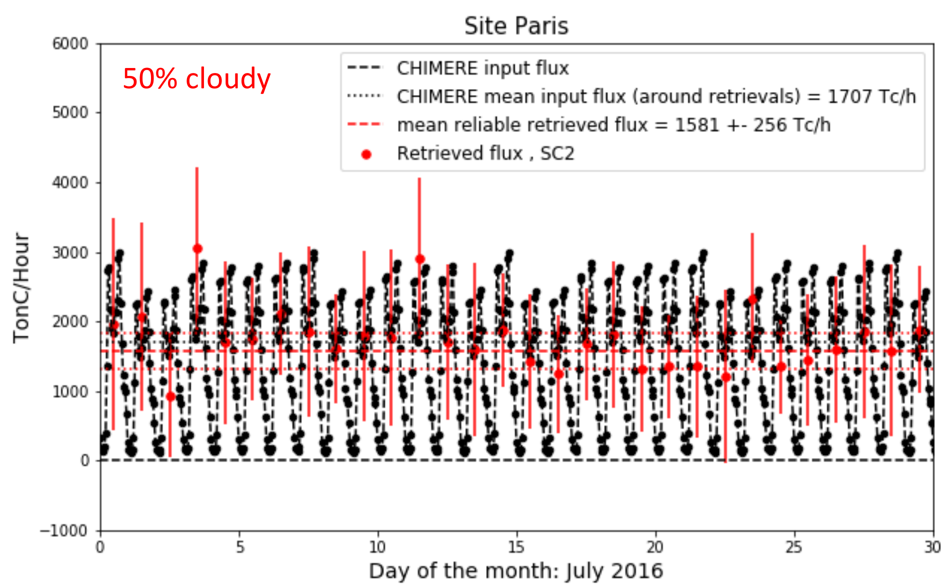


Test on city: site Paris









SYNTHESIS AND FURTHER WORK

- **Preliminary test with cloud fraction randomly applied on the images suggests that flux retrieval could be robust to the impact of clouds up to 30 % cloud fraction**

- **Next steps:**
  - Method and processing improvement (see previous slides)
  - Applying on different scenarios of cities
  - Test on real data : OCO-3, Sentinel 5P
  - More realistic cloud distrubances of the XCO_2 images

Thank you for your attention

Pascal.prunet@spascia.fr
Claude.camy-peyret@upmc.fr
Olivier.Lezeaux@Spascia.fr

Related presentations, Session 7, Wednesday June 5 :

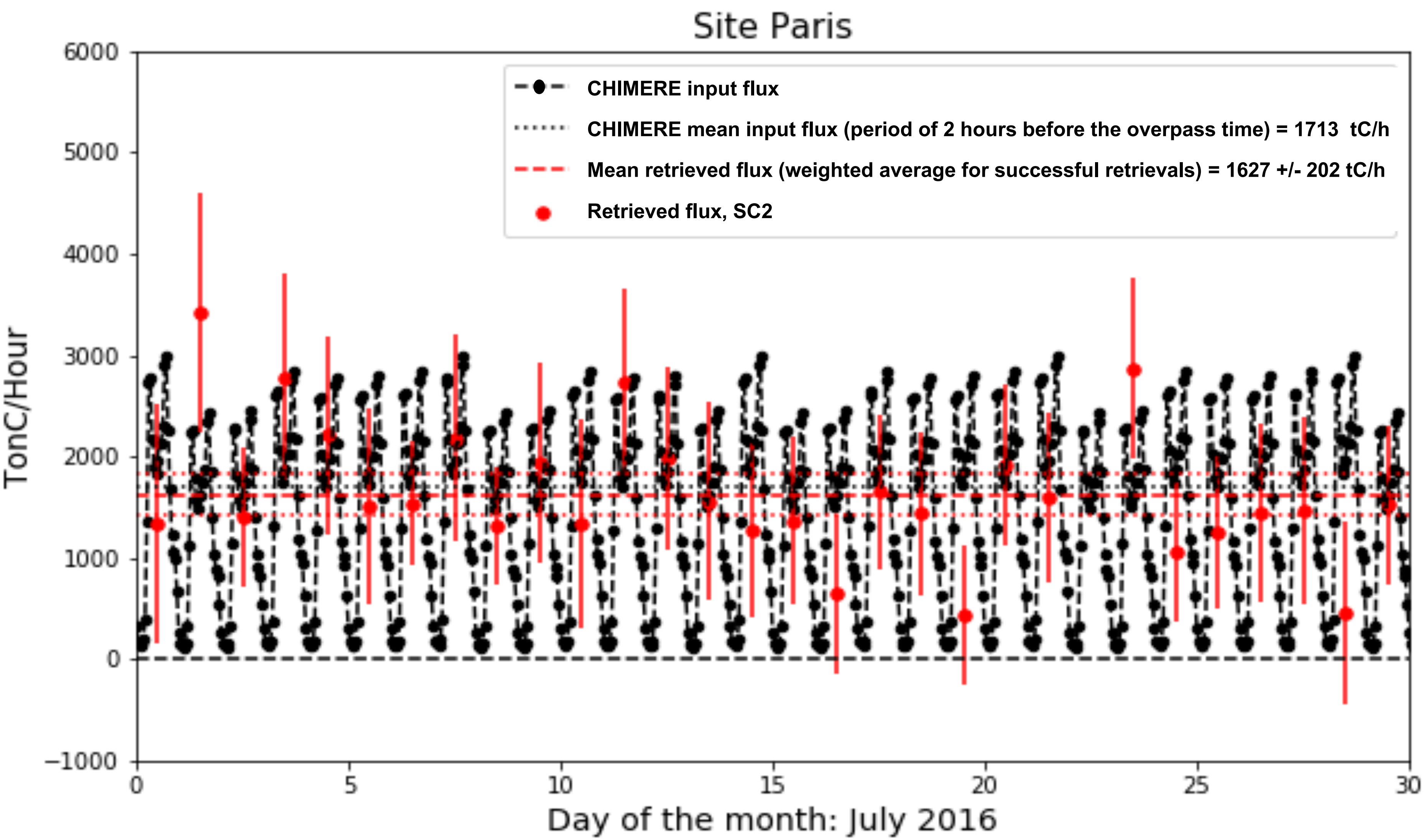
GeoCarb, B. Moore
MicroCarb project, F. Buisson
MicroCarb L1&L2 products, D. Jouglet

Session 1
OCO-3, A. Eldering

Additional slides

Point source emission retrieval: test for Paris, from days 1 to 7 (1/2) : MicroCarb configurations

MicroCarb



Point source emission retrieval: test for Paris, from days 1 to 7 (2/2) : Geo-like configurations

Geo-like