Estimate of uncertainties in city carbon emissions from high spatial resolution CO_2 observations

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See also poster by Broquet et al. for complementary results

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Inversion of CO_2 emissions from cities and satellite data

- Existing use of **satellite XCO_2 measurements** (e.g. GOSAT) for **atmospheric inversion of GHG fluxes at global scale**
- Political need for **improving or verifying** the quantification of **emissions from cities**

→ Increasing number of projects for the atmospheric **inversion of city emissions based on in situ CO_2 measurement networks**:

  - difficulties to deal with **local signals**, to get integrated views of city plumes
  - **political issues** for setting-up in situ networks dedicated to verification

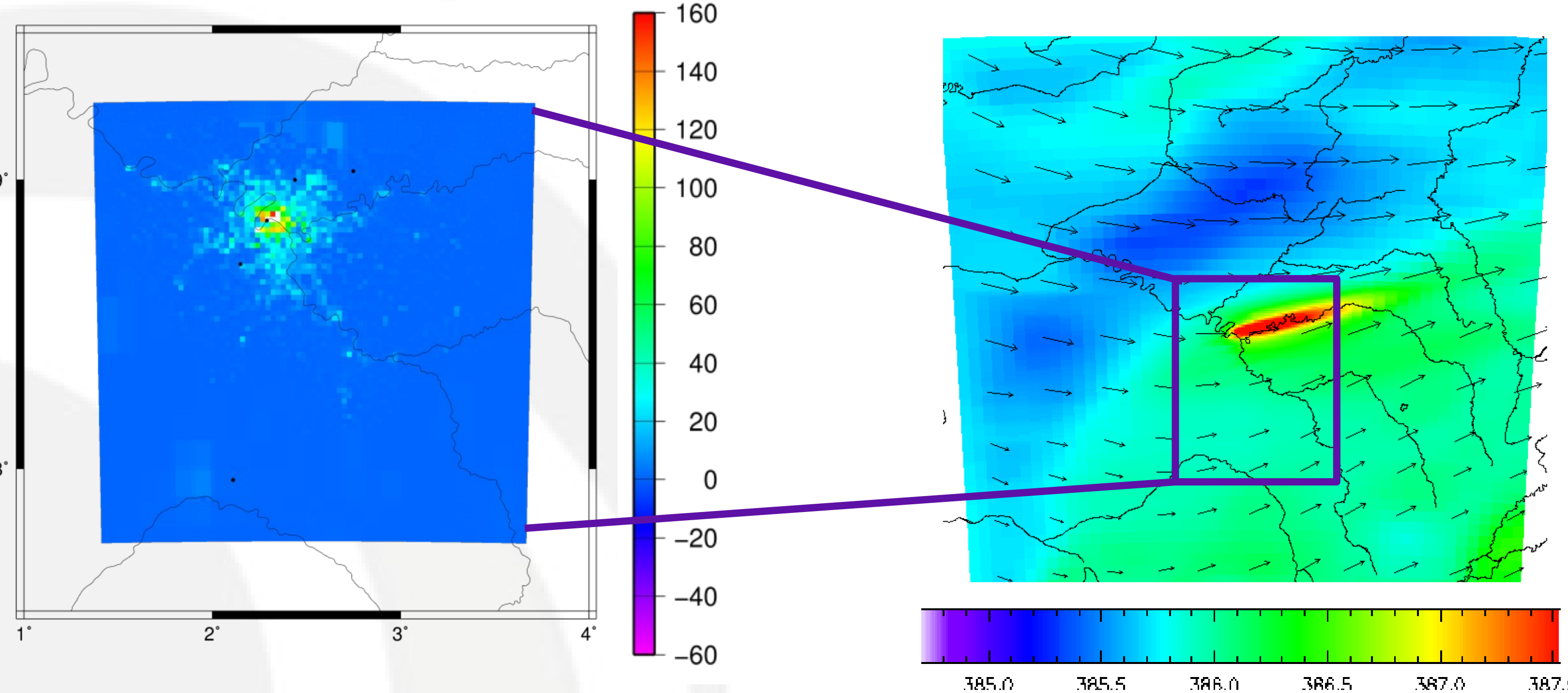
→ Satellite measurement of XCO_2 may solve for these 2 problems. Challenges:

  - **Getting a clear image of the city plume in the XCO_2 fields (need for high resolution obs)**
  - Ability to invert the fluxes using images of the city plume despite **high measurement errors** that can be comparable to the signature of emissions

- Plans for **high resolution imagery of XCO_2: Carbonsat & Sentinel-5**

  → In the framework of the **LOGOFLUX project and of the chaire BRIDGES,** studies on the potential of Carbonsat & Sentinel-5 for quantifying city emissions using the study case of **the Paris area**

Modelling the CO_2 transport in the Paris area seen from space



FF in the Paris area in October ($gC.m^{-2}.s^{-1}$; total per year ~ 15MtC)

Simulation of the transport of XCO2 (ppm; time=11:00) at 2km res. and ECMWF winds at ~700m high

- Paris area = good test case: strong emissions in a relatively narrow area
- Typical width / intensity of the Parisian plume: 20km / +3ppm
- **Time for the signature of fluxes (anthropogenic=FF; natural=NEE) to vanish from the XCO2 image in the domain ~5h**

Inversion of CO_2 urban emissions in the Paris area

	Inversion of hourly FF and NEE during the 5-hour window prior to sat obs (20 different cases for 20 different days)
Default (not fixed) assumptions: parameters perfectly known	**Atmospheric transport** = CHIMERE-ECMWF **2km res.**
	Hourly **spatial distribution** of the FF and NEE at 2km res (use of realistic distribution)
	FF and NEE outside of the 5 hours inversion window
	CO_2 at the domain **boundaries:** prescribed by global inversion using LMDZ
Observation	**Carbonsat: XCO_2** at less than 150km from Paris **(assumes no cloud coverage)** or at locations simulated by IUPB **at 2km res and at 11:00**
	Sentinel-5 (2 config) : XCO_2 over the whole domain (large swath) **at 4km / 10km res and at 11:00 everyday (assumes no cloud coverage)**
Measurement errors	**Default: random/Gaussian with 1.1 ppm (CSat) / 2.1ppm (Sent5 1SWIR) / 1.2 (Sent5 2SWIR) STD, no spatial correlation; or values from IUPB (CSat only)**
Control (inversion) of	**Hourly scaling factors for the FF and NEE = 5x2 parameters**
	Background concentration (uniform in space and time in the domain): $CO_{2,back}$
Uncertainty prior to inversion	**50% uncertainty (normal unbiased distribution) on the factors**
	10ppm uncertainty (normal unbiased distribution) on $CO_{2,back}$

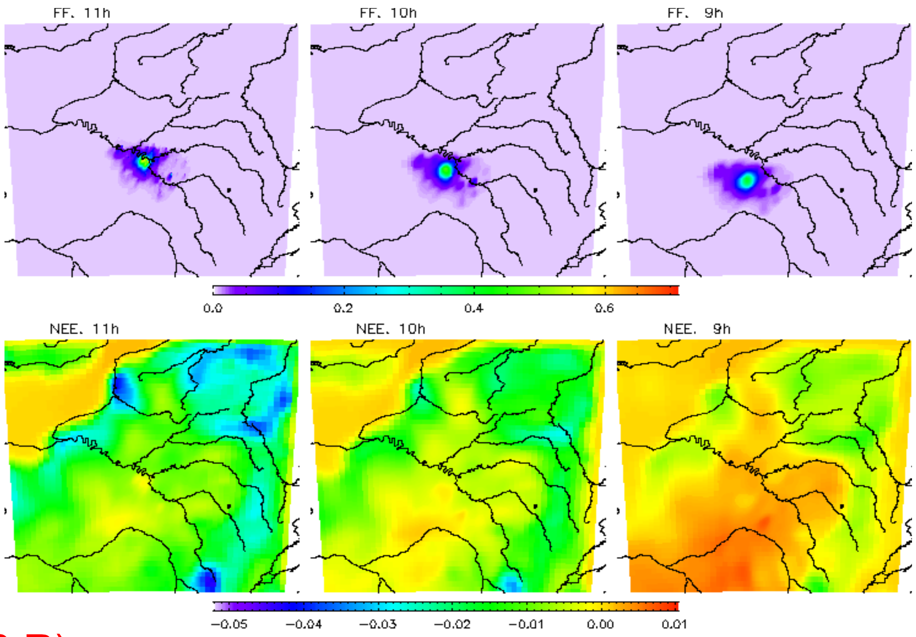
→ **Analysis of the uncertainty reduction and biases due to the assimilation of satellite data**

→ **"Sectorial" inversion analyzed in the poster Broquet et al.**

Mathematical framework of the inversion

- Control variables: **s** (emission scaling factors + background)
- Observation space: **y** = maps of XCO2 seen from carbonsat/Sentinel-5
- Atmospheric transport **M**: $\mathbf{y} = \mathbf{M}\mathbf{s} + \mathbf{y}^{fixed}$
  - ➔ Computed from **"response functions"** to variations in individual control parameters

Response functions
FF=Fossil Fluxes
NEE=Net Ecosystem Exchange

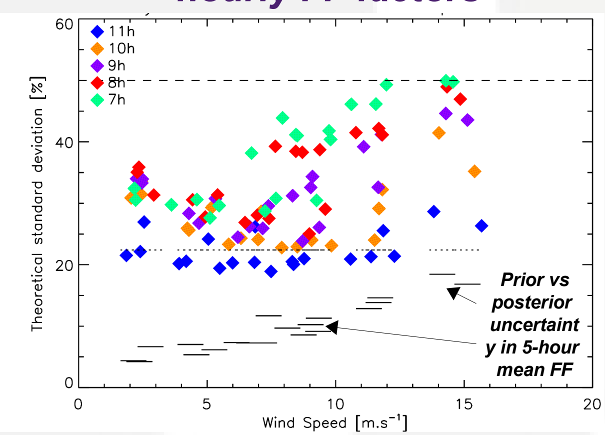


- Prior uncertainty in **s**: $N(0,\mathbf{B})$
- Measurement errors (uncertainty in obs **y**): $N(\mathbf{0},\mathbf{R})$
  - ➔ Bayesian update: posterior uncertainty in **s**: $N(\mathbf{0},\mathbf{A})$ where $\mathbf{A} = (\mathbf{B}^{-1} + \mathbf{M}^T\mathbf{R}^{-1}\mathbf{M})^{-1}$
  - ➔ **Analysis of A vs B ➔ potential of satellite XCO2 to reduce uncertainty in the fluxes**:
    - uncertainties in control parameters = STD (diagonal terms)
    - ability to separate the signature in XCO2 of different control param = correl in **A**

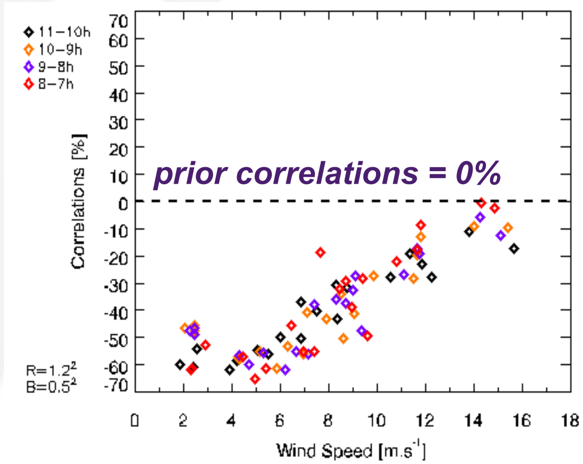
Results with the default configuration

- **Dependence to the wind speed** (wind speed values given at 700m above paris)
- Some potential to solve for temporal profiles in FF
- Rather good separation FF vs NEE & $CO2_{back}$(cf plots of correl in poster Broquet et al.)
- **5-15% posterior uncertainty in 5-hour mean FF** with Csat (vs 22.4% prior uncertainty)
- **Strong dependence to spatial resolution and measurement error** (check 5-day exp in the poster Broquet et al for more adapted comparisons between CSat and Sent5 **accounting for the frequency of overpass)**

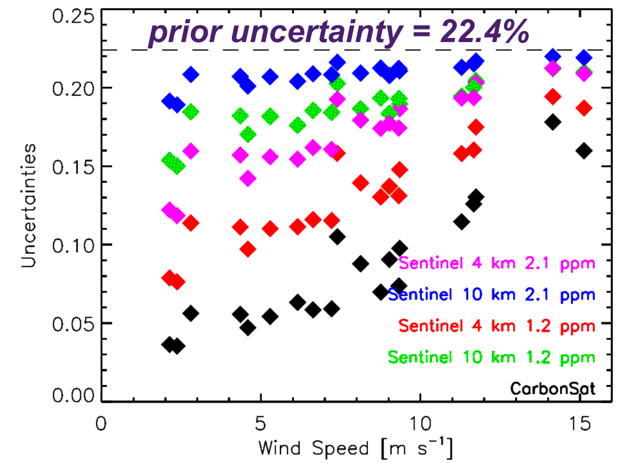
CSat: posterior uncertainty in hourly FF factors



CSat: posterior correlations (x100 = in %) between consecutive hourly FF



Total uncertainties in 5-hour mean FF for 1-day experiments (Sent5 & CSat)



Accounting for perturbing factors: method

- Present account for errors in the CO_2 from outside of the domain (**errors in the BC**) **as a bias** for a given day that are ignored by the inversion system
- Account for **uncertainties in the spatial distribution of the FF**: the inversion system assumes that the city source is uniform over a 20 or 45 km radius, and assimilates concentrations simulated using a more realistic pattern **= a bias** for a given day

  → **Need to estimate the impact of biases in the fluxes**

  $= \mathbf{K}\,(\text{delta\_}\mathbf{y}^{bias})$ where $\mathbf{K}=\mathbf{BM}^T(\mathbf{R}+\mathbf{MBM}^T)^{-1}$

  $\text{delta\_}\mathbf{y}^{bias}$= **variations of XCO2 from the boundaries** based on global LMDZ inv. and/or **diff in FFXCO2 from fluxes distributed on a disk or on realistic maps**

- Account for **realistic distributions of observation (clouds), random and systematic error (based on simulations from IUPB)**: **Monte Carlo ensemble of inversions**
  - → Estimate of the obs vector $\mathbf{y}_i$ and obs error $\mathbf{R}_i$ defined by the maps of random errors from IUPB $\mathbf{R}^{rand}_i$ (combined with $\mathbf{R}^{syst}_i$=0.3 ppm for syst error): estimate of $\mathbf{M}_i$ and $\mathbf{K}_i$
  - → Sample of uncertainty in prior flux: $\mathbf{e\_s}^b_i$ & sample of $N(\mathbf{0},\mathbf{R}^{rand}_i)$: $\mathbf{e\_y}^o_i$
  - → Assumption: maps of syst error $\boldsymbol{\eta}\mathbf{\_y}^o_i$ sample a **non Gaussian** & biased error distrib
  - → Sample of post uncertainty: $\mathbf{e\_s}^a_i = \mathbf{e\_s}^b_i + \mathbf{K}_i\,(\text{delta\_}\mathbf{y}_i^{bias} + \boldsymbol{\eta}\mathbf{\_y}^o_i + \mathbf{e\_y}^o_i - \mathbf{M}_i\mathbf{e\_s}^b_i)$

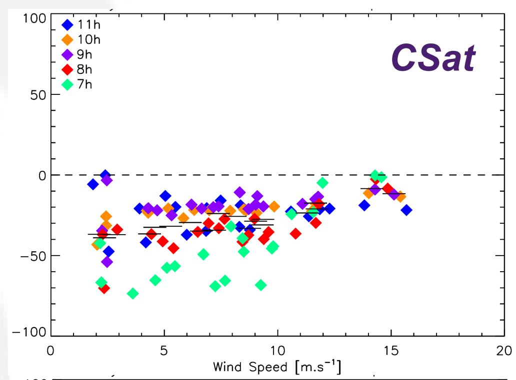
➢ **Statistics (mean, variance = "true" A) on the ensemble of $\{\mathbf{e\_s}^a_i\}$**

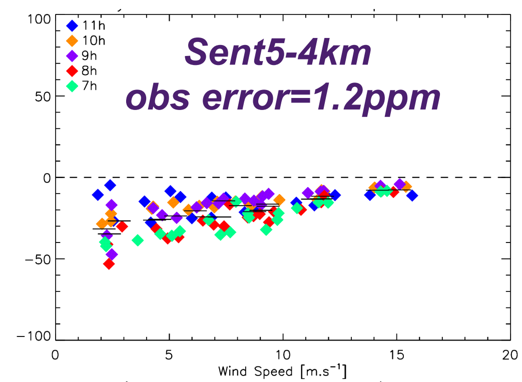
Impact of biases on FF spatial distribution

- Rather **small impact** from errors in the spatial distribution of FF **if the modeled distribution encompasses the actual one** (the actual plume is entirely seen by the response functions to FF in the inversion); **otherwise large potential biases**
- sensitivity to the satellite configuration (more obs → more sensitivity to biases)

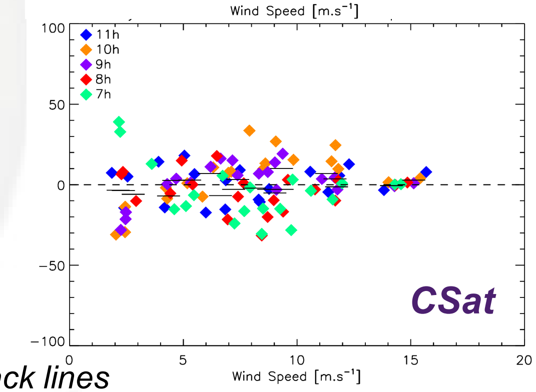
Estimate of biases in inverted FF (in % of the prior FF) when ignoring the true spatial distribution of the FF (distributing the FF homogeneously on a 20km to 45km-radius disk)

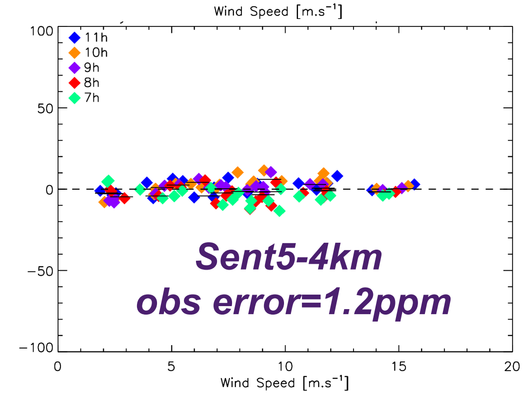
Bias from spatial distrib with too narrow spread: inversion assuming homogeneous emission over 20 km radius





Bias from spatial distrib with too large spread: inversion assuming homogeneous emission over 45 km radius

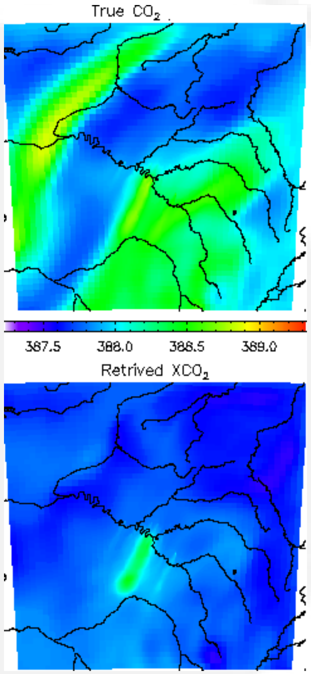




values for 5-hour avg: black lines

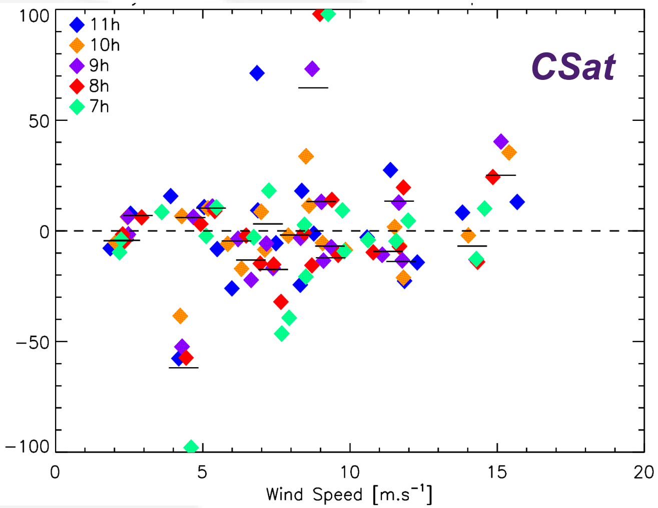
Impact of biases on Boundary Conditions

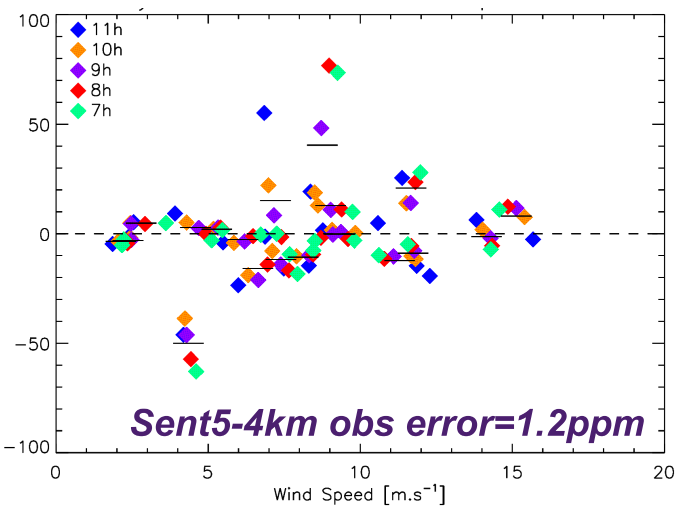
- The CO2 patterns generated by fluxes from outside of the domain have a **large impact** on the inverted fluxes, in particular at hourly scale
  - ➔ lack of pattern recognition with the least square inversion methodology ?
  - ➔ **need for "randomizing" the error on BC** (as other similar sources of errors: use of the Monte Carlo to keep the typical spatial structures of errors from BC; ongoing work)



True XCO2 and XCO2 from inversion using CSat when ignoring the variability from the BC (Oct 14th)

Estimate of biases in inverted FF when ignoring the variability from the BC (values for 5-hour avg: black lines)



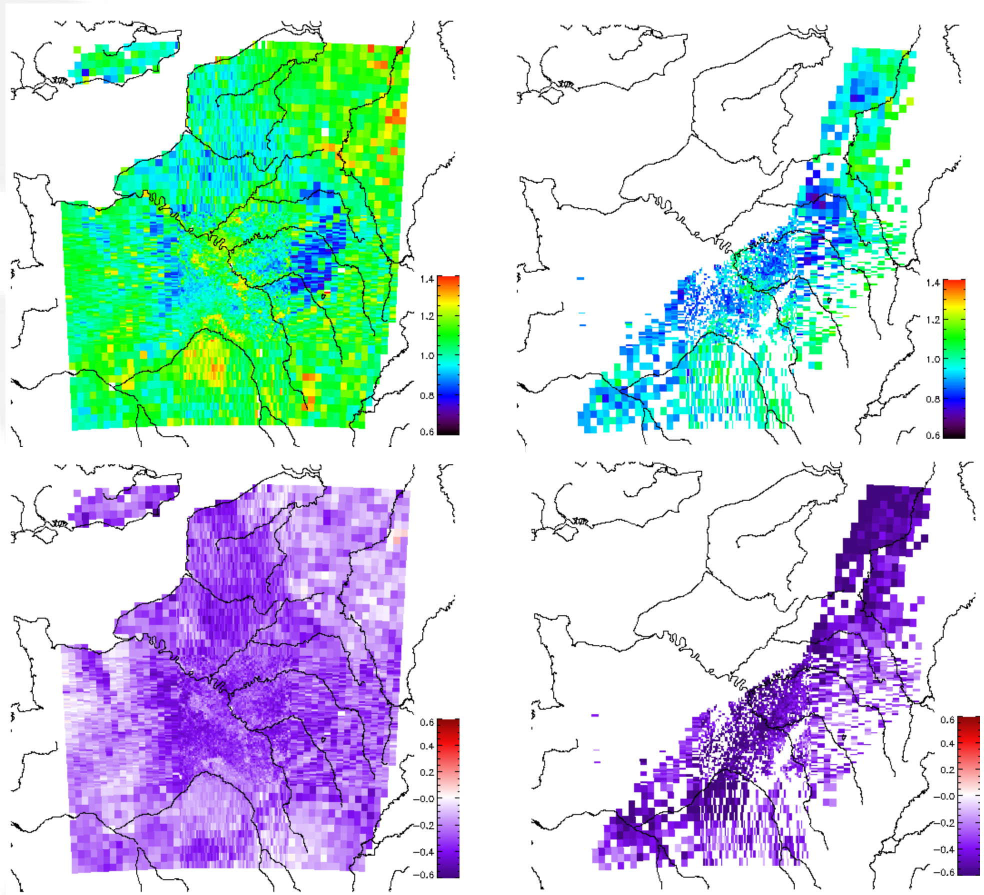


Errors on XCO2 from IUPB (Buchwitz et al.)

Examples of simulations for random and systematic errors: favorable and unfavorable cases

Random error

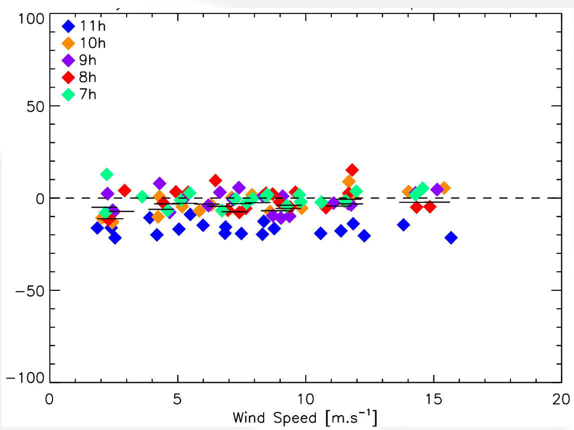
Systematic error

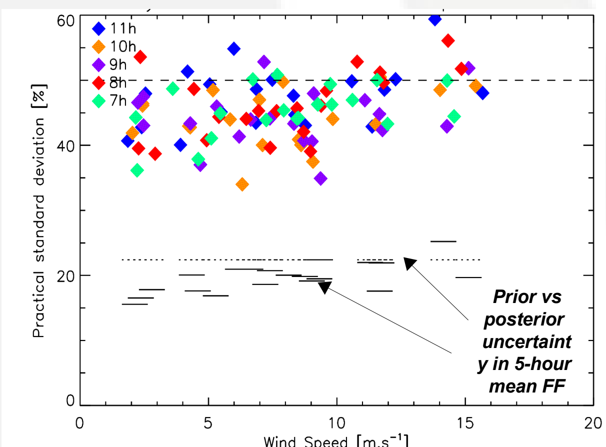


- **Realistic patterns of random and systematic errors**: should not be summarized with the “traditional” Gaussian framework with null or isotropic correlations in space
- A lot of tracks over Paris which do not “see” the Parisian plume due to cloud cover

Account for errors from IUPB (Monte Carlo approach)

Estimate of bias and standard deviation of the Monte Carlo ensemble of posterior FF when including errors from IUPB (CSat)





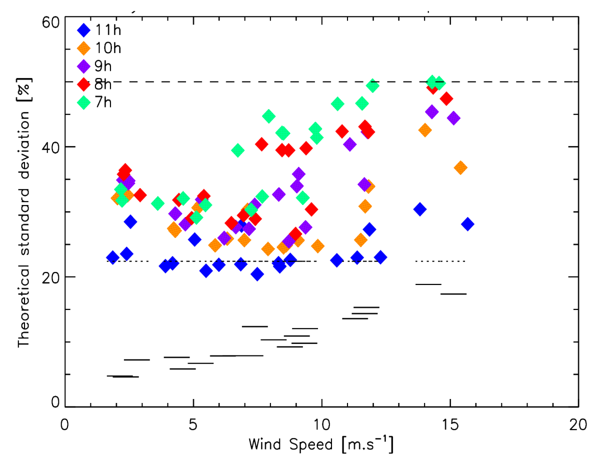
- Use more realistic spatial distribution of observations (clouds), random and systematic errors (from IUP Bremen simulations)

➔ **The error reductions are much smaller than in the more idealized cases**

One reason are biased and non-Gaussian errors not perfectly anticipated by the inversion system; the other is the fact that observations sample is often much smaller than "ideal" due to cloud cover

➔ **maps without obs over Paris (contributing to relax the uncertainty toward the prior one) should have been removed (ongoing work)**

Theoretical estimate of uncertainty (STD) when using a 1.1ppm observation error (CSat)



Perspective and conclusions

- A **critical source of error** not yet investigated: the **atmospheric transport**
- The account of error on XCO2 simulated by IUPB can be refined since **maps without cloud-clear obs of the Parisian plume should not be used** for inversion
- **Theoretical uncertainty reduction** for 5-hour mean fluxes **with the idealistic / default configuration is significant** (20 to 70% depending on the wind), but it **may be insufficient** (theoretical posterior uncertainty for 5-hour mean fluxes often exceeds 15%) given that it concerns 5-hour out of ~6 days (ignoring cloud coverage for CSat) or out of ~24-hours (ignoring cloud coverage for Sent5)

  → **Need to rely on large temporal correlations for uncertainties in prior FF**

- Current results indicate that the satellite observation cannot resolve city-scale fluxes with sufficient accuracy when major perturbing factors are accounted for. This result is based on an analysis with some optimistic and some pessimistic assumptions.
- Lack of pattern recognition with the traditional least square inversion approach: **need to develop stronger inversion systems algorithms to exploit the potential of Sentinel-5 / Carbonsat data ?**