POTENTIAL OF THE REMOTE SENSING OF CO2 BY SENTINEL-5 FOR THE ESTIMATE OF CO2 NATURAL AND ANTHROPOGENIC FLUXES

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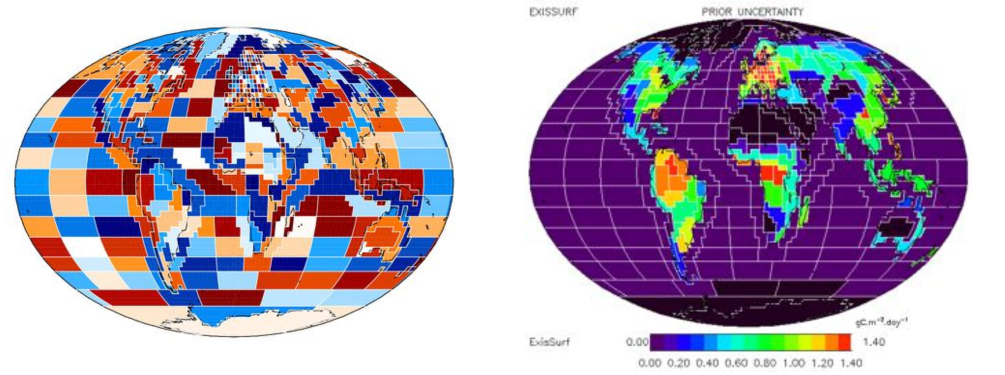
Abstract: The Sentinel-5 instrument on-board the MetOp satellite could measure **vertically integrated CO2 (XCO2) mixing ratios with a near global daily coverage at 5-10 km horizontal resolution.** In this study, Observing System Simulation Experiments using global and local atmospheric inversion systems are conducted to assess the potential of XCO2 data from Sentinel-5 for improving the estimates of CO2 natural fluxes at global scale and CO2 anthropogenic emissions in the Paris area. These systems are based on a modelling of the CO2 atmospheric transport at ~3° and 2 km horizontal resolution respectively. The potential of Sentinel-5 is compared to that of carbonsat at city scale and to that of other satellite / in situ observation networks at global scale. A special care is given to the configuration of realistic biases and random errors in the XCO2 measurements and to the estimate of their impact for the retrieval of CO2 fluxes. At global scale, on-going estimates and previous studies suggest that biases would likely prevent the satellite from significantly improving the knowledge on natural fluxes. At urban scale, the large swath and the high spatial resolution of Sentinel-5 seem to provide some potential for reducing uncertainties in the emissions few hours before the satellite observation.

Context:
- Needs to monitor the **CO2 natural fluxes (Net Ecosystem Exchange -NEE- & ocean flux) at continental scale** and the **CO2 anthropogenic fluxes (Fossil Fluxes - FF) at city scale**
- Flux inversions using existing space borne CO2 data (e.g. GOSAT) hardly improve the knowledge of CO2 fluxes
- Several plans for satellite missions studied at ESA: on-going **LOGOFLUX study on Carbonsat**
- Potential for observing **1 or 2 bands bands of CO2 absorption in the SWIR with Sentinel-5**
- Previous ESA study for assessing the potential of Sentinel-5 XCO2 observations at global scale only, for a configuration using 1 SWIR band only, and without accounting for systematic errors + new improvement of the global inversion system used for this assessment

➔ **Need for resuming the ESA study at global scale and for studying the potential of Sentinel-5 data at city-scale**

I. THE CITY-SCALE AND GLOBAL CONFIGURATIONS

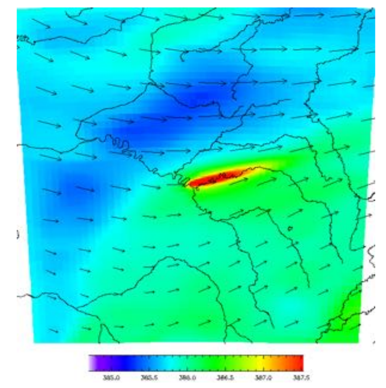
	Inversion of anthrop (FF) and natural (NEE) CO2 fluxes per sector / ecosystem type at city scale	Inversion of hourly FF and NEE at city scale during the 5-hour window prior to sat obs	Inversion of weekly NEE for large regions at global scale
Default (not fixed) assumptions: parameters perfectly known	**Atmospheric transport** = CHIMERE-ECMWF **2km res.** (no error)		**Mean atmospheric transport** = LMDZ with res. **3.25°x2.75°** (unbiased)
	Temporal profiles for each sector of FF / eco-type of NEE at hourly res	Hourly **spatial distribution** of the FF and NEE at 2km res	(Uniform) spatial distribution of NEE within each region defined by the control vector (No) temporal variations in NEE at scales smaller than 1 week
	Fluxes per sectors/ecosystems not controlled	**FF and NEE outside of the 5 hours inversion window**	Other type of fluxes (FF or emissions from fires)
	CO2 at the **boundaries**		CO2 initial conditions (not yet included in the control vector)
Observations	**Sentinel-5 (2 config) : XCO2** over the whole CHIMERE domain (large swath) **at 4km / 10km res and at 11:00 everyday (assumes no cloud coverage)**		**Sentinel-5: avg at LMDZ res of cloud free XCO2 at 10km res and on 2500km width heliosynchronous trajectory at ~9:30 (cloud coverage based on MODIS)**
	Carbonsat : XCO2 at less than 150km from Paris **at 2km res and at 11:00 every 6 days (assumes no cloud coverage)**		**Daily / 6-hour mean concentrations at each ground station / tower of the existing global in situ network** used by Hungershoefer et al. (2010, ACP)
Measurement & transport errors	**Default measurement error: random/Gaussian with 1.1 ppm (CS) / 2.1ppm (S5 1SWIR band) / 1.2 (S5 2SWIR bands) STD (assume no spatial correlation)**		**Meas error for Sentinel-5: based on errors at 10km res** (random error: 1. vs 0.87 for 1 vs 2 SWIR; systematic error: 1.86 vs 0.88 for 1 vs 2 SWIR); decrease of the random error with the square root of the number of cloud free obs per LMDZ grid cell.
			Meas error for in situ data: 0.01ppm
	no transport error		Transport error = ~0.8-2ppm for XCO2, ~1.3-3ppm for CO2 at in situ stations (spatial/temporal dependence)
Control (inversion) of	8 (4x2) scaling factors for the total of sectorial FF & NEE per ecosystem types	10 (5x2) hourly scaling factors for the FF & NEE	48 weekly mean NEE for 379 regions (276 large regions + zoom over Europe)
	Background concentration (uniform in space and time in the domain): $CO2_{back}$		
Uncertainty prior to inversion	**50% uncertainty (normal unbiased distribution) on the factors**		Proportional to respiration as simulated by ORCHIDEE vegetation model for land / constant for ocean + 500km(land)/1000km(ocean) spatial & 1 month temporal correlations
	10ppm uncertainty (normal unbiased distribution) on $CO2_{back}$		



Global scale configuration: spatial resolution of the fluxes to be inverted (379 areas) and prior uncertainty ($gCm^{-2}d^{-1}$) in these fluxes at annual scale

Temporal framework

- City scale: S5 & CS do not see significant patterns from Paris more than ~5 hour before the obs
  - ➔ **20 cases (= 20 days) for 5-hour windows before obs**
  - ➔ Analysis of 5-day avg of 5-hour mean fluxes before obs (sensitivity to the frequency of sat overpass)
- Global scale: **1-year inversion of 1-week mean fluxes**



Simulation of the Parisian XCO2 plume at 2km resolution (time=11:00; with ECMWF winds at ~15km res and 700m high): typically ~20km width and +3ppm compared to "background"

II. MATHEMATICAL FRAMEWORK

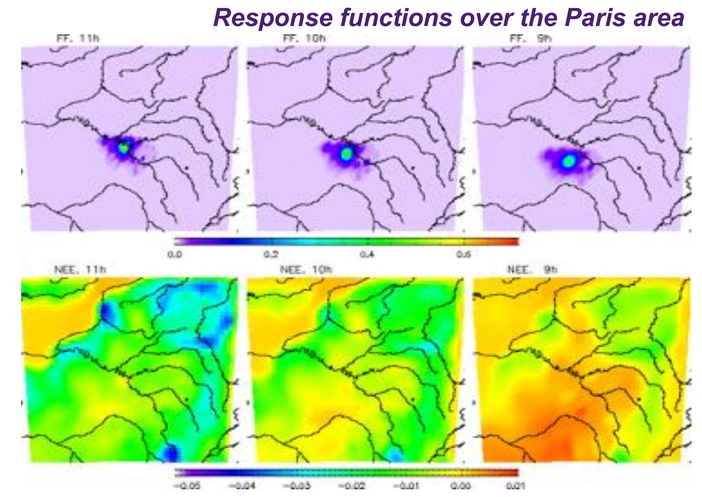
Analytical inversion using the traditional Gaussian assumption

- Control variables: **s** (emission scaling factors + background)
- Observation space: **y** (maps of XCO2 seen from satellite)
- Atmospheric transport **M**: $\mathbf{y}=\mathbf{Ms}+\mathbf{y}^{fixed}$
  - ➔ Computed from **"response functions"** to individual control variables
- Prior uncertainty in **s**: $N(0,\mathbf{B})$
- Measurement+ transport 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** gives the potential of assimilating **y** to estimate the fluxes

Response functions over the Paris area



Account for biases

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

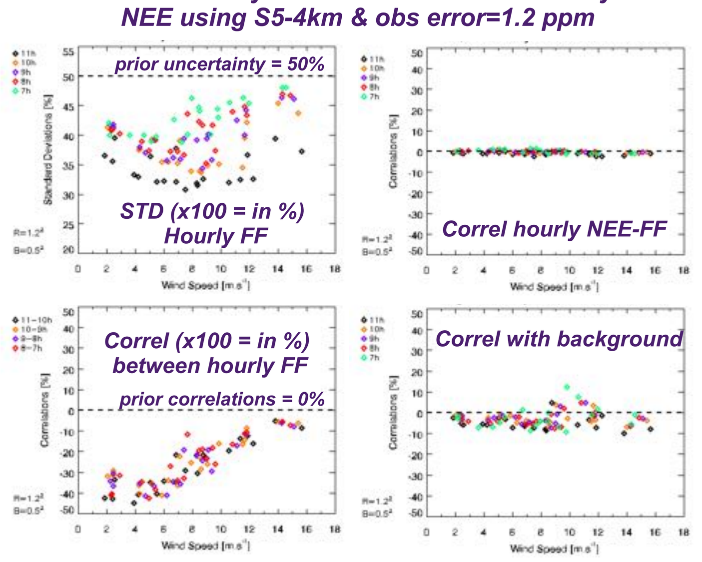
Account for non Gaussian distrib and varying y (cloud cover)

using Monte Carlo approach (cf pres by Bréon et al.): not applied for results shown here

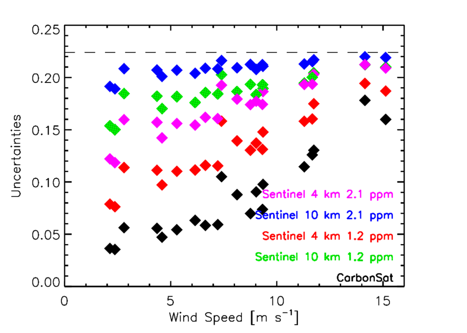
III. RESULTS FOR THE ESTIMATE OF FOSSIL FLUXES IN THE PARIS AREA

Hourly inversion

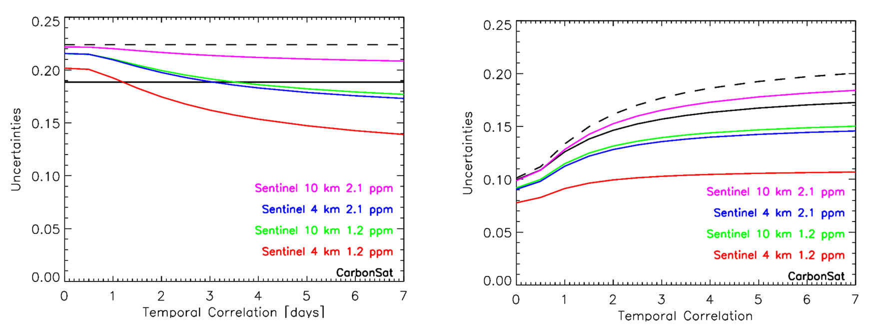
Posterior uncertainty in inverted factors for hourly FF and NEE using S5-4km & obs error=1.2 ppm



Total uncertainties in 5-hour mean FF for 1-day experiments

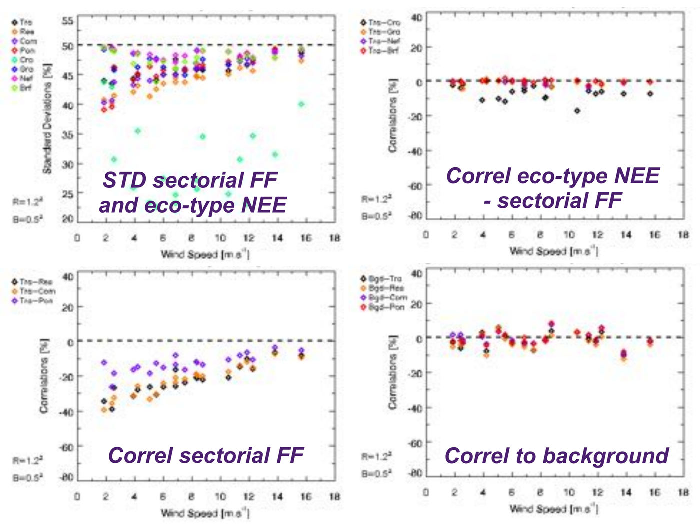


5-day framework: total uncertainties in 5-hour mean FF during the third day (left) and for the 5-day period (right) as a function of the day to day correlation time scale in prior uncertainties at a given time. Overpass of CS on the third day.



- Difficulty to separate hourly FF components depends on wind speed
- **Easy separation of FF and NEE**
- More difficult separation of FF vs $CO2_{back}$ or Boundary Conditions (BC)
  - ➔ **Lack of pattern recognition** with least square approach for inversion ?
- Modeled spatial distribution of FF fine if it encompasses the actual distrib
- Significant but insufficient uncertainty reduction for 5-hour mean FF
- **High sensitivity to satellite measurement error and spatial resolution**
  - ➔ However, 5-day experiments demonstrates that **the most critical parameter could the frequency of overpass**

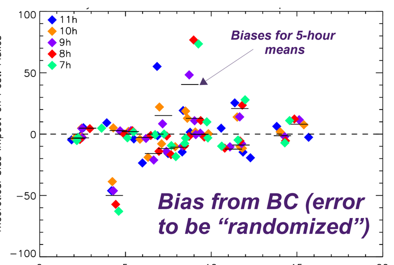
Posterior uncertainty in inverted factors for sectorial FF and NEE per eco-type using S5-4km & obs error=1.2 ppm

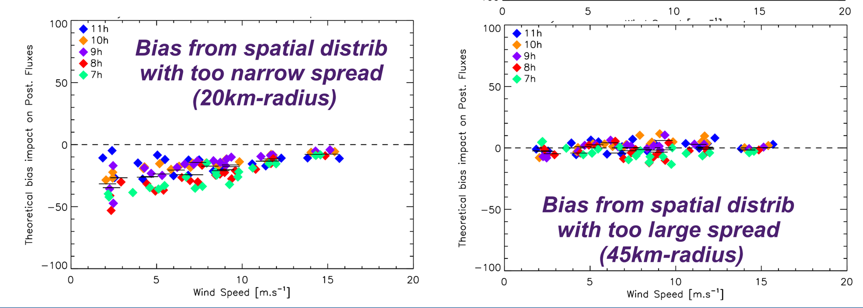


Sectorial inversion

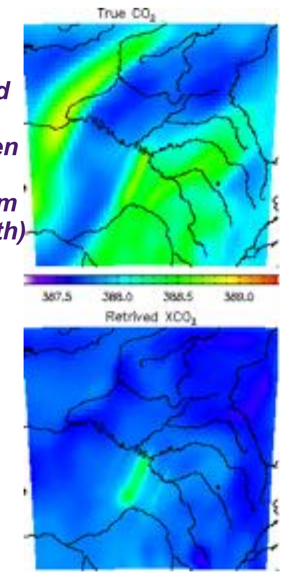
Difficuly to separate the major sectors of FF despite clear separation with NEE

Estimate of biases in inverted FF when ignoring the true spatial distribution of the FF (distributing the FF homogeneously on a 20km to 45km-radius disk) and when ignoring the variability from the BC (exp with S5-4km and obs error=1.2ppm)

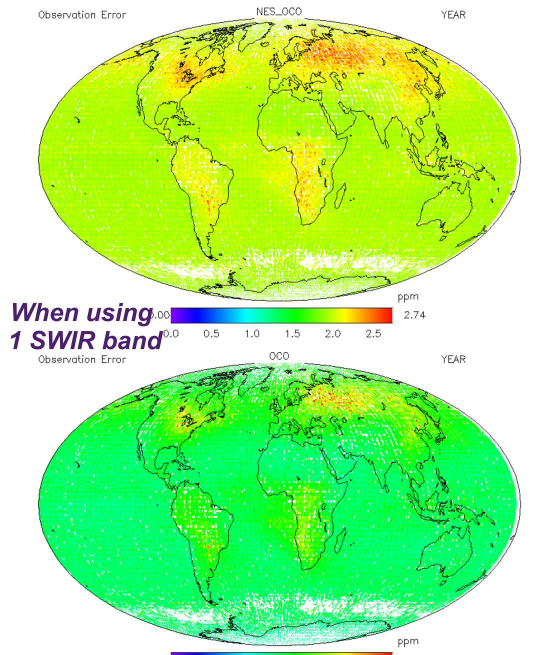




True CO2 and CO2 from inversion when ignoring the variability from the BC (Oct 14th)



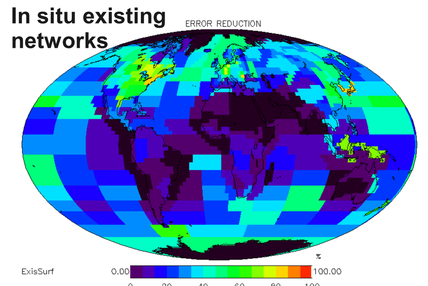
IV. RESULTS FOR THE ESTIMATE OF NATURAL FLUXES AT GLOBAL SCALE

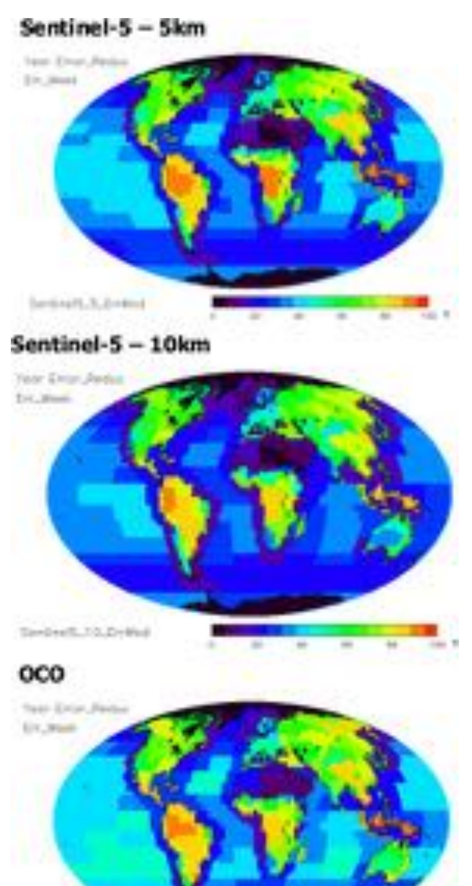


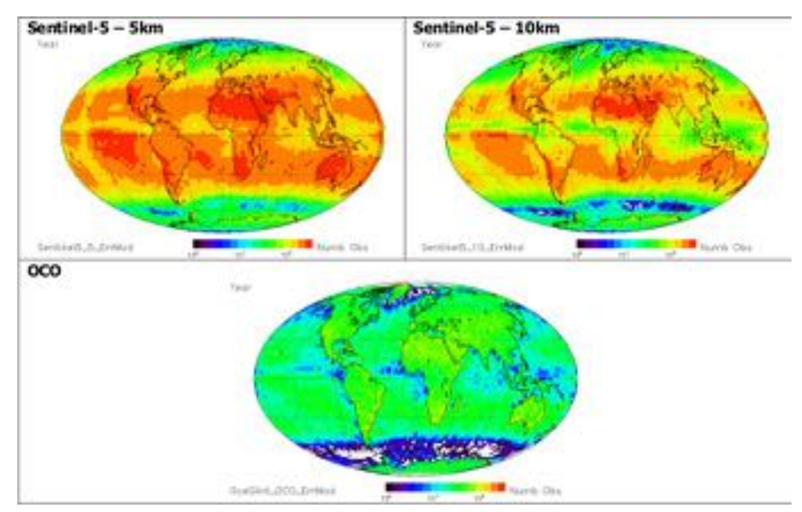
Estimate of the STD of observation errors (transport + measurement errors) for "super_obs" (aggregation of individual XCO2 retrievals at LMDZ resolution) for Sentinel-5 with 10km resolution: annual mean

On-going work:
- ➔ Built on the capabilities developed for the ESA-Sentinel 5 and MicroCARB studies
- ➔ Assessment of the improvement due to **using 2 vs 1 SWIR** CO2 absorption bands
- ➔ Comparison to **ground-based networks and other satellite configurations** (MicroCARB, GOSAT, OCO, Carbonsat-like)
- ➔ **Optimistic results of theoretical uncertainty reduction** due to a present lack of account for complex structures of correlations in the observation error ?
- ➔ Estimate of biases in inverted fluxes due to different sources of biases in the satellite measurement: results for MicroCARB or OCO-like missions reveal biases with a scale similar to prior uncertainties

Estimate of uncertainty reduction (1-post uncert/prior uncert) for weekly mean NEE (annual avg). Results for sat config from ESA Sentinal-5 report: obs error for S5 estimated using 1 SWIR.

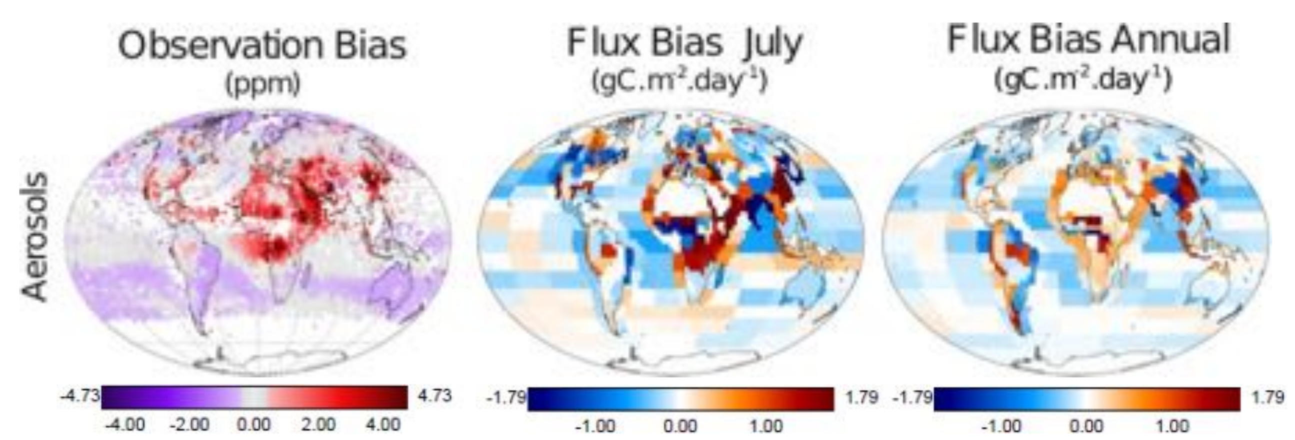






Estimate of the number of cloud-free satellite observation available per grid cell of LMDZ during 1-year (ESA Sentinel-5 report)

Estimate of biases in the inversion of CO2 NEE when assimilating OCO-like satellite observations: example of biases due to aerosol clouds



Conclusion: despite being based on a quite idealistic configuration (transport errors not investigated yet), city-scale inversions based on the traditional mathematical framework and high resolution satellite data indicate uncertainty reduction that are insufficient to properly constrain anthropogenic emissions. Unless having strong time correlations for uncertainty in FF (e.g. assuming that errors are due to emission factors in inventories only), the temporal window "seen" by the satellite would be too short to constrain quantities relevant to policy makers. **Need to develop stronger inversion systems based on pattern recognition algorithms to exploit the potential of S5/CS data ?** At city and global scale, **need to work on the complementarity between satellites and in situ networks ?**

References

- Chimot, J., H. Bösch, H. Bovensmann, M. Buchwitz, F.-M. Bréon C. Camy-Peyret, C. Bacour, M. van Weele, J. de Haan and P. Veefkind (2011): Requirements for CO2 monitoring by Sentinel-5; Final Report; ESA Study Contract no. 103801
- Bovensmann, H., Buchwitz, M., Burrows, J. P., Reuter, M., Krings, T., Gerilowski, K., Schneising, O., Heymann, J., Tretner, A., and Erzinger, J.: A remote sensing technique for global monitoring of power plant CO2 emissions from space and related applications, Atmos. Meas. Tech., 3, 781-811, doi:10.5194/amt-3-781-2010, 2010.
- Hungershoefer, K., Breon, F.-M., Peylin, P., Chevallier, F., Rayner, P., Klonecki, A., Houweling, S., and Marshall, J.: Evaluation of various observing systems for the global monitoring of CO2 surface fluxes, Atmos. Chem. Phys., 10, 10503-10520, doi:10.5194/acp-10-10503-2010, 2010.