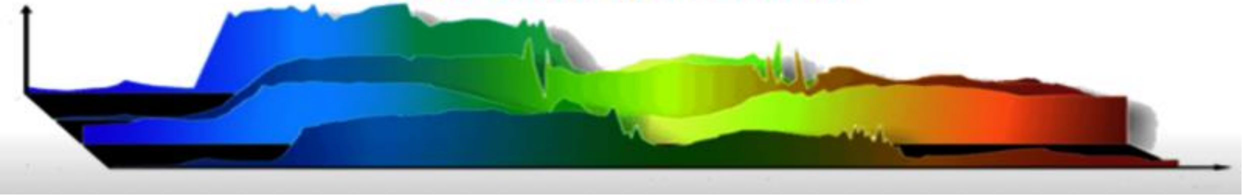
8ème colloque scientifique du groupe SFPT-GH

Paris - 5 & 6 juillet 2023



Inversion of satellite and airborne hyperspectral images with a Gaussian plume model for the restitution of methane emission fluxes

Nicolas NESME[1*], Pascal PRUNET[1], Olivier LEZEAUX[1], Claude CAMY-PEYRET[2], Pierre-Yves FOUCHER[3]

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Introduction

- Robust and validated methods[a,b,c] allow to derive the plume map of the integrated methane column concentration (L1 to L2) from hyperspectral PRISMA and EnMap satellites at high spatial resolution.
- From a CH_4 plume map, it is possible to estimate (L2 to L4) a flow rate (using information on the wind) with different methods.
- Varon et al. 2018 review 4 of them :
  - Integrated Mass Enhancement (IME) and Cross-Sectional Flux (CSF) "*are better adapted to the problem*",
  - "*Point source inappropriate because of wind variability and horizontal turbulent diffusion on the scales of relevance*",
  - "*Gaussian plume inversions are unsuccessful because the instantaneous plumes are too small to follow Gaussian behaviour*" for methane plume.

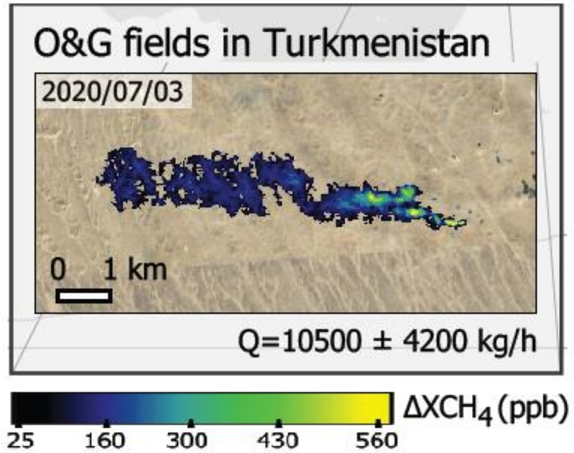
Can a Gaussian plume model estimate methane fluxes from hyperspectral images at high spatial resolution ?

I. Data and methodology

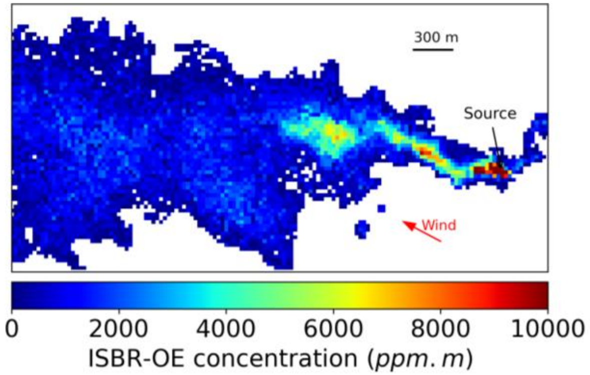
II. Application to satellite data (PRISMA)

III. Application to airborne data (HySpex)

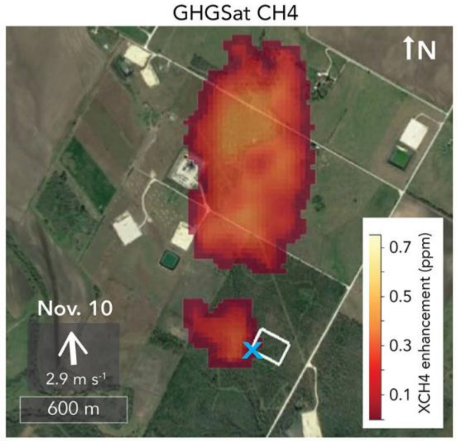
IV. Conclusion



***a)** Plume map from Guanter et al. 2021 using Matched Filters method (CTMF) – PRISMA data on Turkmenistan*



***b)** Plume map from Nesme et al. 2021 using Optimal Estimation derived method (ISBR-OE) – PRISMA data on Turkmenistan*



***c)** Plume map from Cusworth et al. 2021 using Optimal Estimation derived method – GHGSat data on Texas*

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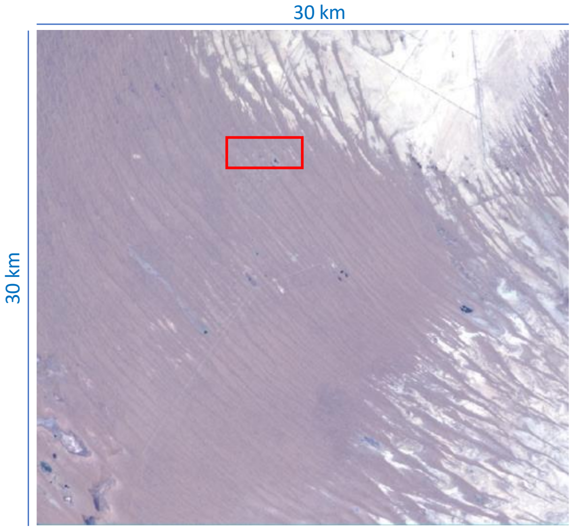
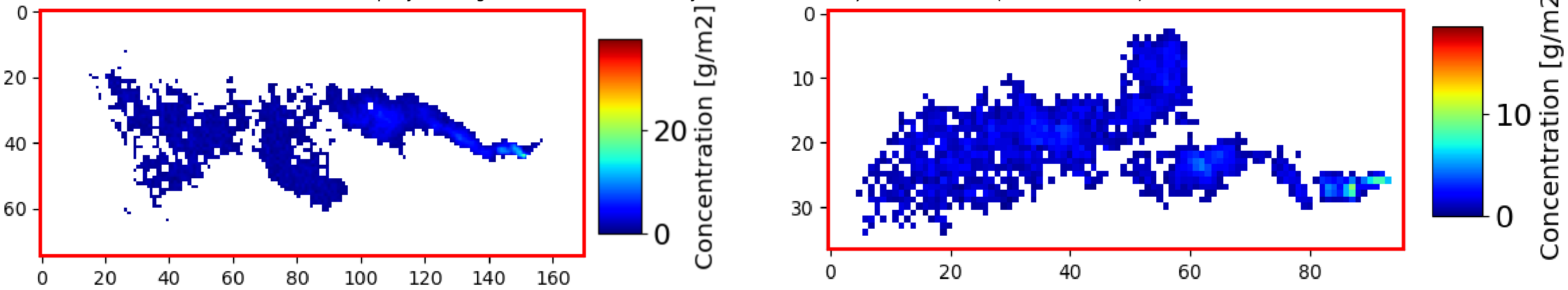
I. Data and methodology

- PRISMA satellite images (spatial resolution 30 m / spectral resolution 10 nm / SWIR) :



Hyperspectral image from PRISMA (R,G,B: 641, 546, 471 nm) above Korpezhe oil and gas site, in *Turkmenistan*

Plume maps of the integrated mass enhancement of methane obtained by ISBR-OE method (Nesme et al. 2021)



21/07/2020

03/07/2020

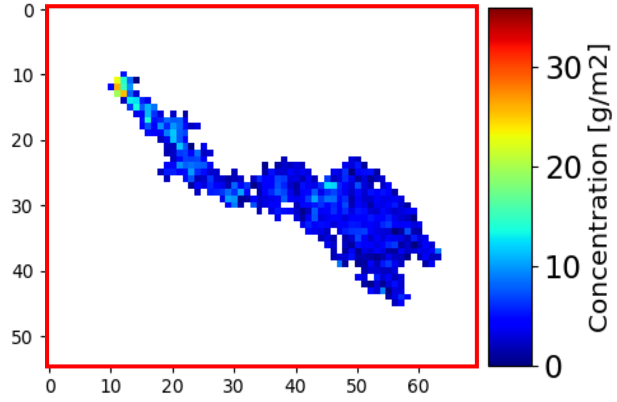
- Real plume exhibiting a typical spatial structure

- Real plume exhibiting a highly turbulent shape
- Availability of an independent flow rate estimation *(Ganter et al. 2021)*

- HySpex airborne image (spatial resolution 1.4 m / spectral resolution 6 nm):

Hyperspectral image from HySpex (at 957 nm) above industrial site, in France

- Very high spatial resolution
- Correlative *in situ* flow rate and wind data measurements



Plume map of the integrated mass enhancement of methane obtained by ISBR-OE method (N. Nesme thesis)

I. Data and methodology

- Gaussian plume formulation (punctual source):

$$X_{GAUSS}(x,y) = \frac{F}{U}\frac{e^{-\frac{1}{2}\left[\frac{y}{\sigma_y(x)}\right]^2}}{\sqrt{2\pi}\sigma_y(x)}$$

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

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} cos(\varphi_U) & \sin(\varphi_U) \\ -sin(\varphi_U) & cos(\varphi_U) \end{bmatrix}\begin{bmatrix} X - P_x \\ Y - P_y \end{bmatrix}$$

$$X_{GAUSS}(x,y) = f(P_x, P_y, F, \varphi_U, b, U, \sigma_0, x_0)$$

- Inversion formulation based on Optimal Estimation:

Forward model linearisation:

$$\boldsymbol{y} = \boldsymbol{f}(\boldsymbol{x},\boldsymbol{b}) + \boldsymbol{\varepsilon_y} = \boldsymbol{f}(\boldsymbol{x_a},\boldsymbol{b_a}) + \boldsymbol{K}(\boldsymbol{x_t} - \boldsymbol{x_a}) + \boldsymbol{K_b}(\boldsymbol{b_t} - \boldsymbol{b_a}) + \boldsymbol{\varepsilon_y}$$

Cost function minimisation:

$$\chi^2 = [\boldsymbol{y} - \boldsymbol{f}(\boldsymbol{x},\boldsymbol{b})]^T \boldsymbol{S_y}^{-1}[\boldsymbol{y} - \boldsymbol{f}(\boldsymbol{x},\boldsymbol{b})] + [\boldsymbol{x} - \boldsymbol{x_a}]^T \boldsymbol{S_x}^{-1}[\boldsymbol{x} - \boldsymbol{x_a}]$$

A posteriori uncertainty budget:

$$\widehat{\boldsymbol{\varepsilon_x}} = (\boldsymbol{I} - \boldsymbol{A})\boldsymbol{\varepsilon_x} + \boldsymbol{G}\boldsymbol{K_b}\boldsymbol{\varepsilon_b} + \boldsymbol{G}\boldsymbol{\varepsilon_y}$$

- List of parameters that can be inverted and/or with propagation of errors:

P_x, P_y	Position of the source	Fixed
F	Flux	Inverted
φ_U	Wind direction	Inverted
b	Spread coefficient	Fixed
U	Wind speed	Fixed *(if F is inverted, U has to be fix)*
σ_0, x_0	Site-specific characterisation	Fixed

I. Data and methodology

- Steps of the inversion:

1) Start with an observed plume map

2) Simulation of gaussian plume as *a priori*

   a priori (based N. Nesme thesis results):

   F = 15 tonCH_4/hr -- φ_U = 198° -- U = 3.3 m/s

3) Inversion with Gaussian-OGEO

(OGEO = Outil Générique d'Etimation Optimale)

   Results:

   F = 8.03 ± 0.34 tonCH_4/hr -- φ_U = 196.8 ± 0.29° -- $\chi^2 = 0.44$

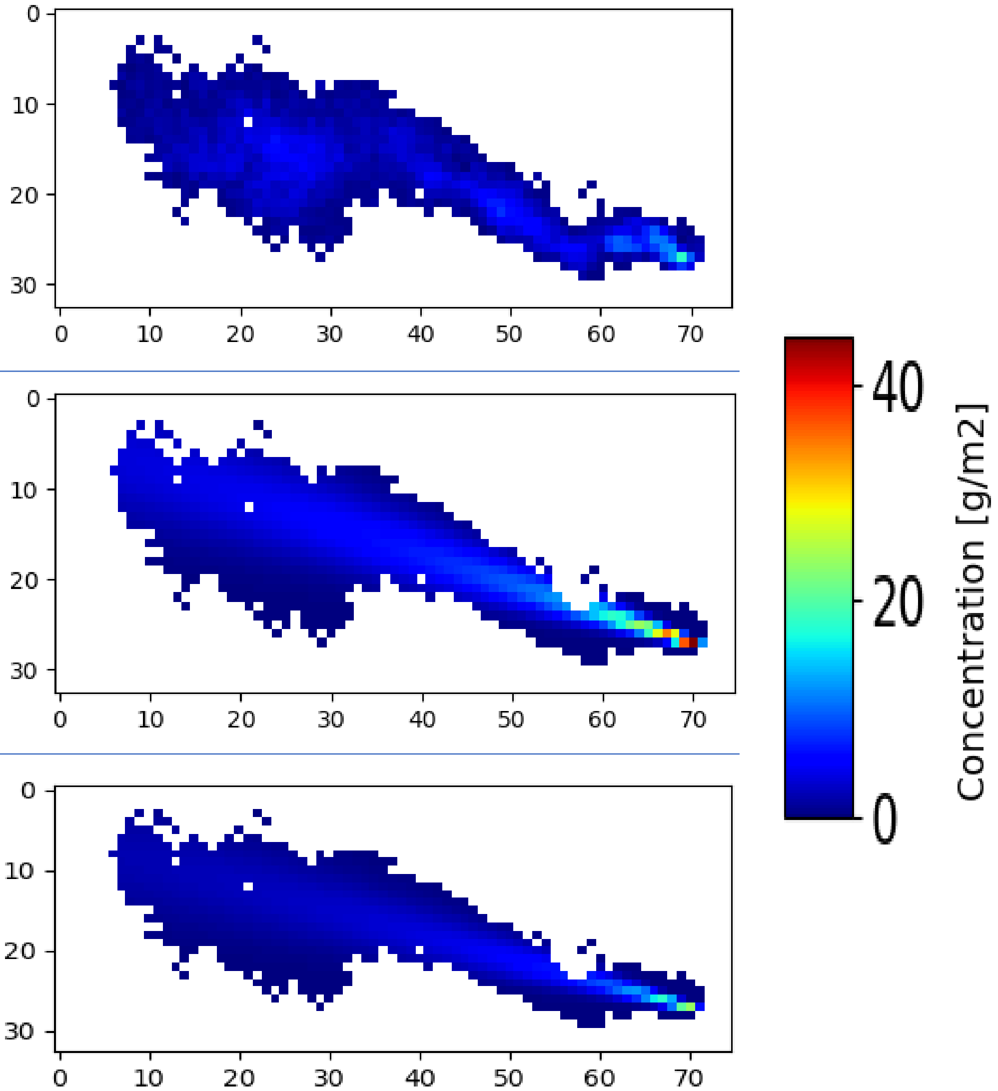
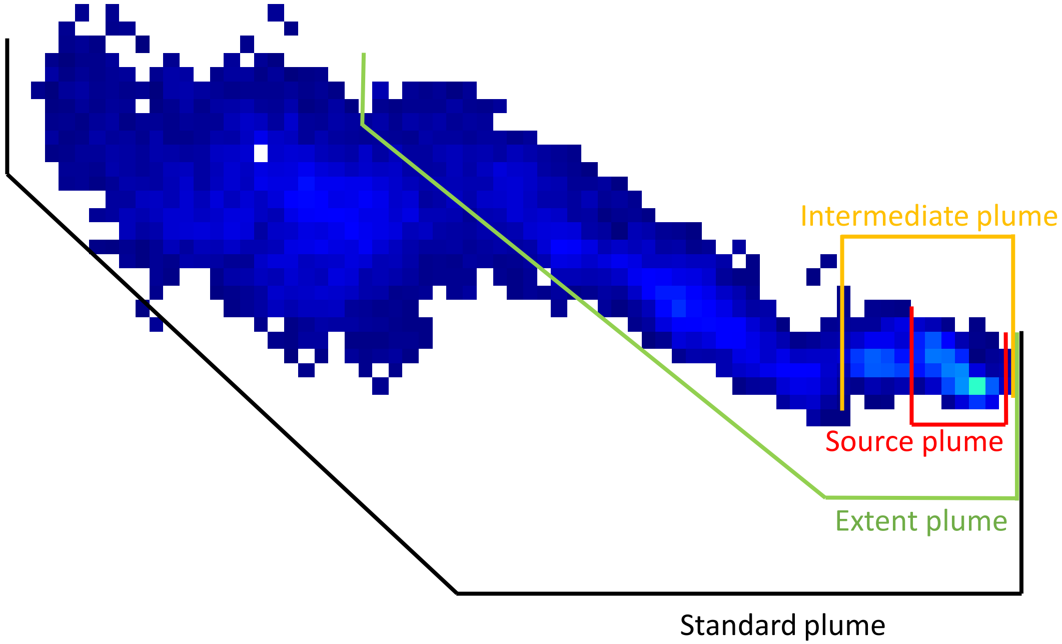


Illustration of the algorithm steps results for a PRISMA satellite case (21/07/2020)

II. Application to satellite data (PRISMA)

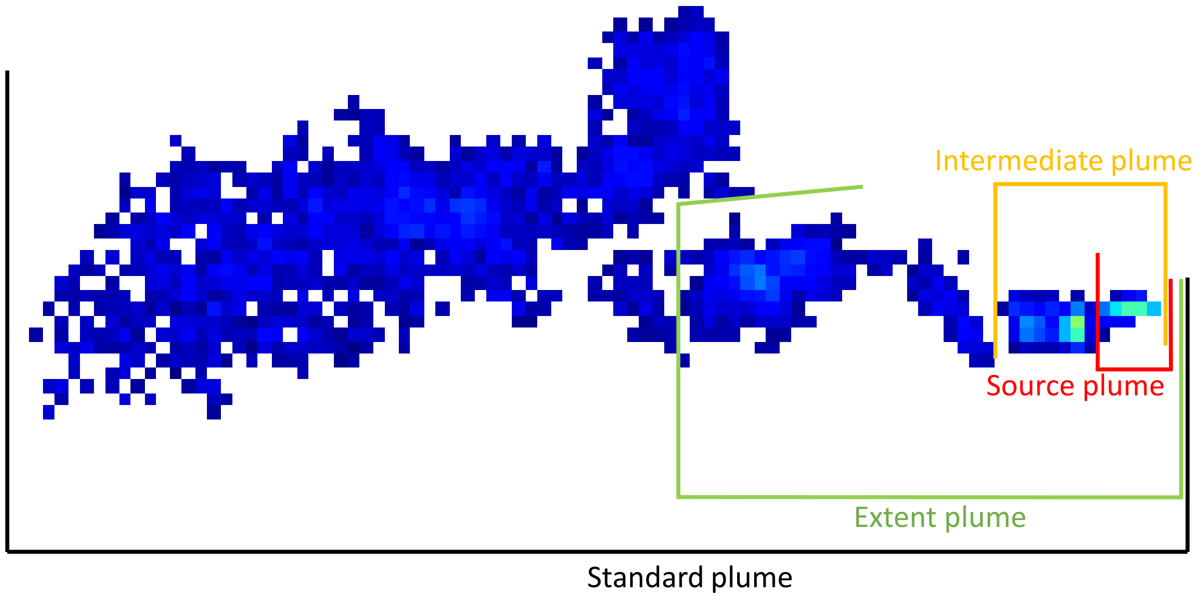
- To analyse the impact of the plume mask on the performances of Gaussian-OGEO method and Cross-Sectional Flux method, we define following plume masks:



21/07/2020

Definition of plume masks for the 03/07/2020 image

2 km



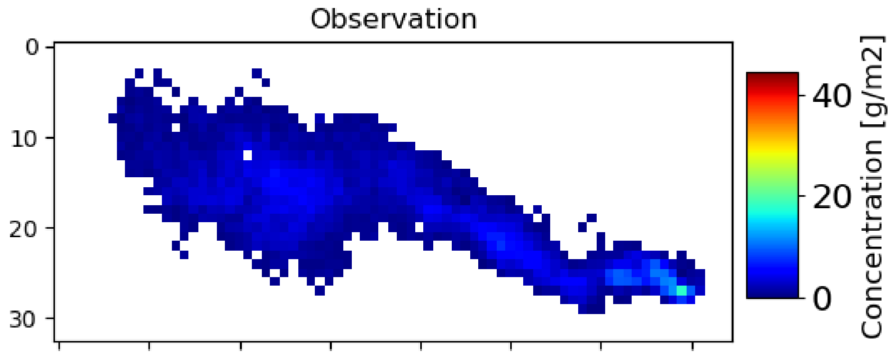
03/07/2020

Definition of plume masks for the 03/07/2020 image

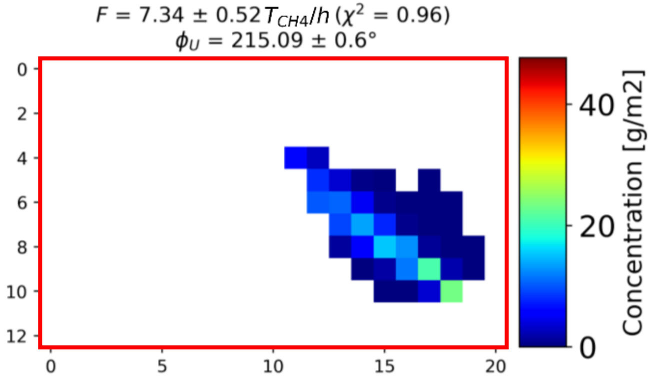
2.7 km

II. Application to satellite data (PRISMA)

- **Gaussian-OGEO results** for the different plume masks for **21/07/2020**: adjusted plume gaussian simulation and retrieved parameters

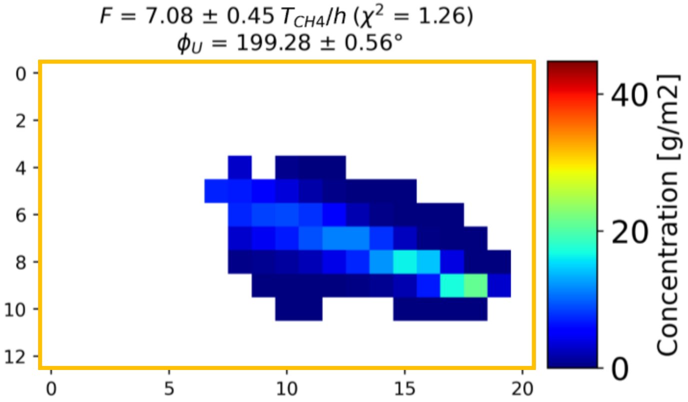


Plume of methane map of 21/07/2020


$F = 7.34 \pm 0.52 T_{CH4}/h$ ($\chi^2 = 0.96$)
$\phi_U = 215.09 \pm 0.6°$

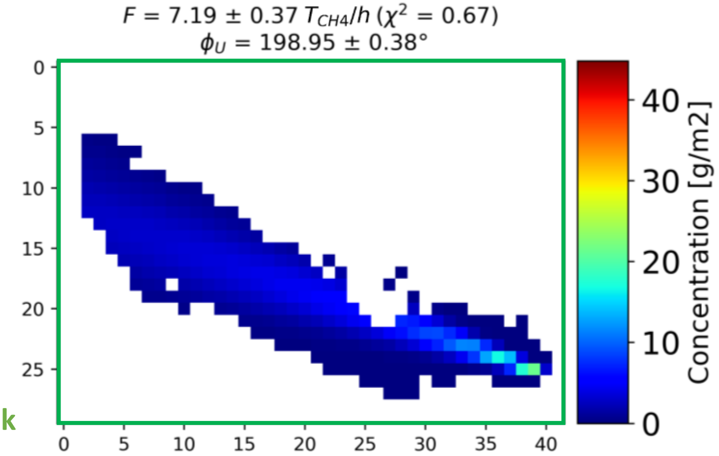
Source plume mask

Gaussian plume resulting of the inversion by Gaussian-OGEO


$F = 7.08 \pm 0.45 T_{CH4}/h$ ($\chi^2 = 1.26$)
$\phi_U = 199.28 \pm 0.56°$

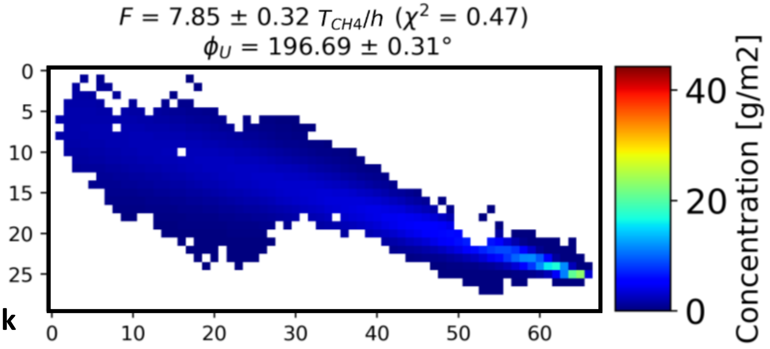
Intermediate plume mask

Gaussian plume resulting of the inversion by Gaussian-OGEO


$F = 7.19 \pm 0.37 T_{CH4}/h$ ($\chi^2 = 0.67$)
$\phi_U = 198.95 \pm 0.38°$

Extended plume mask

Gaussian plume resulting of the inversion by Gaussian-OGEO

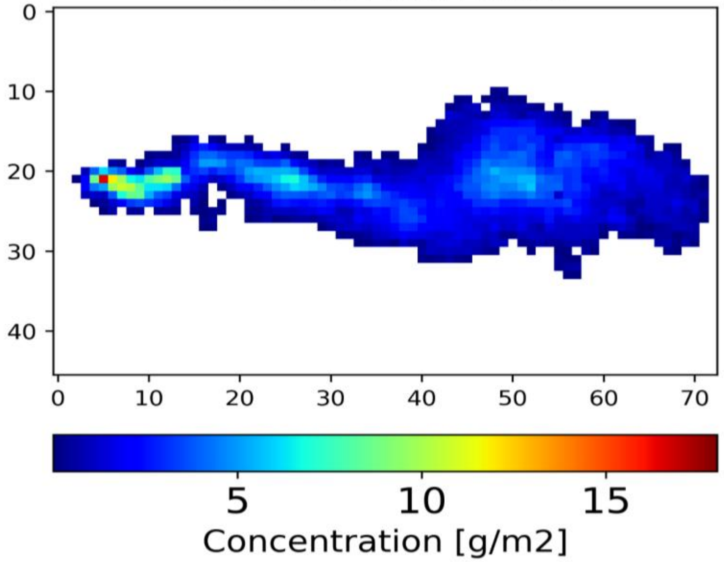

$F = 7.85 \pm 0.32 T_{CH4}/h$ ($\chi^2 = 0.47$)
$\phi_U = 196.69 \pm 0.31°$

Standard plume mask

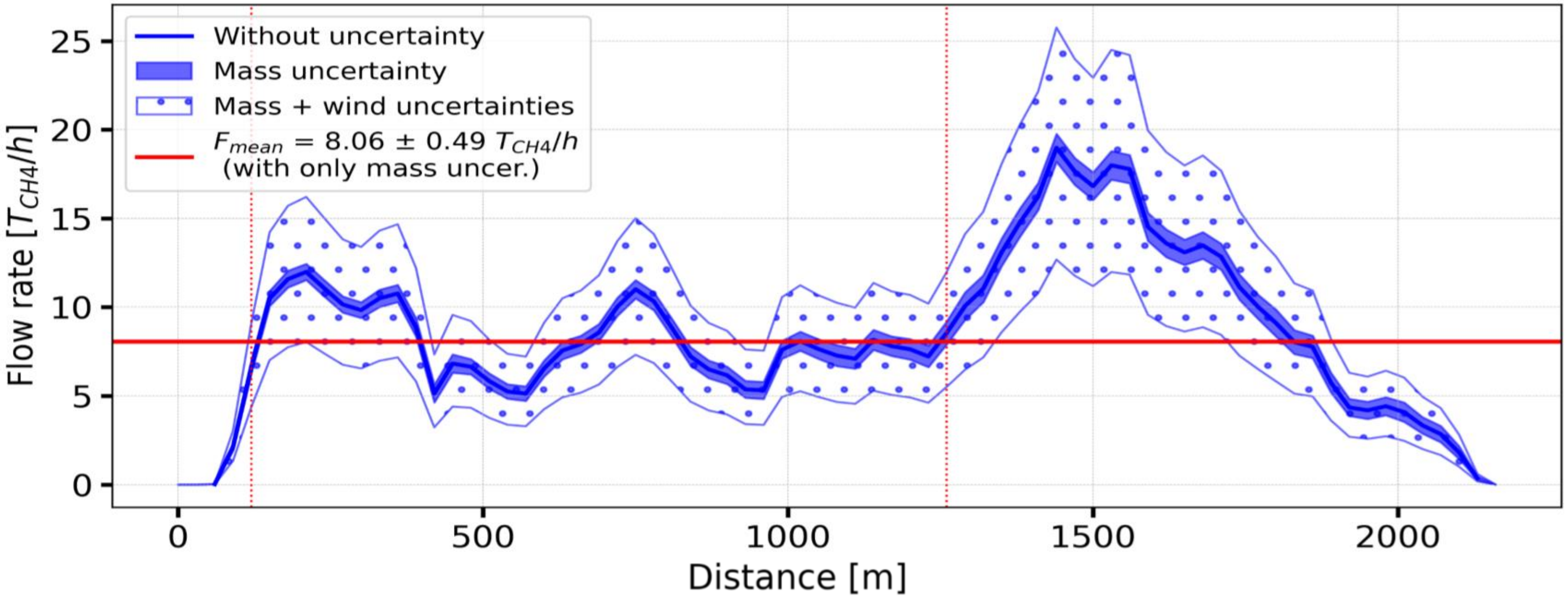
Gaussian plume resulting of the inversion by Gaussian-OGEO

II. Application to satellite data (PRISMA)

- **Cross-Sectional Flux (CSF) results** for the different plume masks from **21/07/2020**:
  - Define the global direction of plume propagation, which depends on the mask used
  - Cut the plume in slices perpendicular to this direction, sum the mass and multiply by the wind speed
  - Determine a constant plate section of the flow rate for each slice and estimate the mean flow rate.



Plume of methane map of 21/07/2020 after rotation

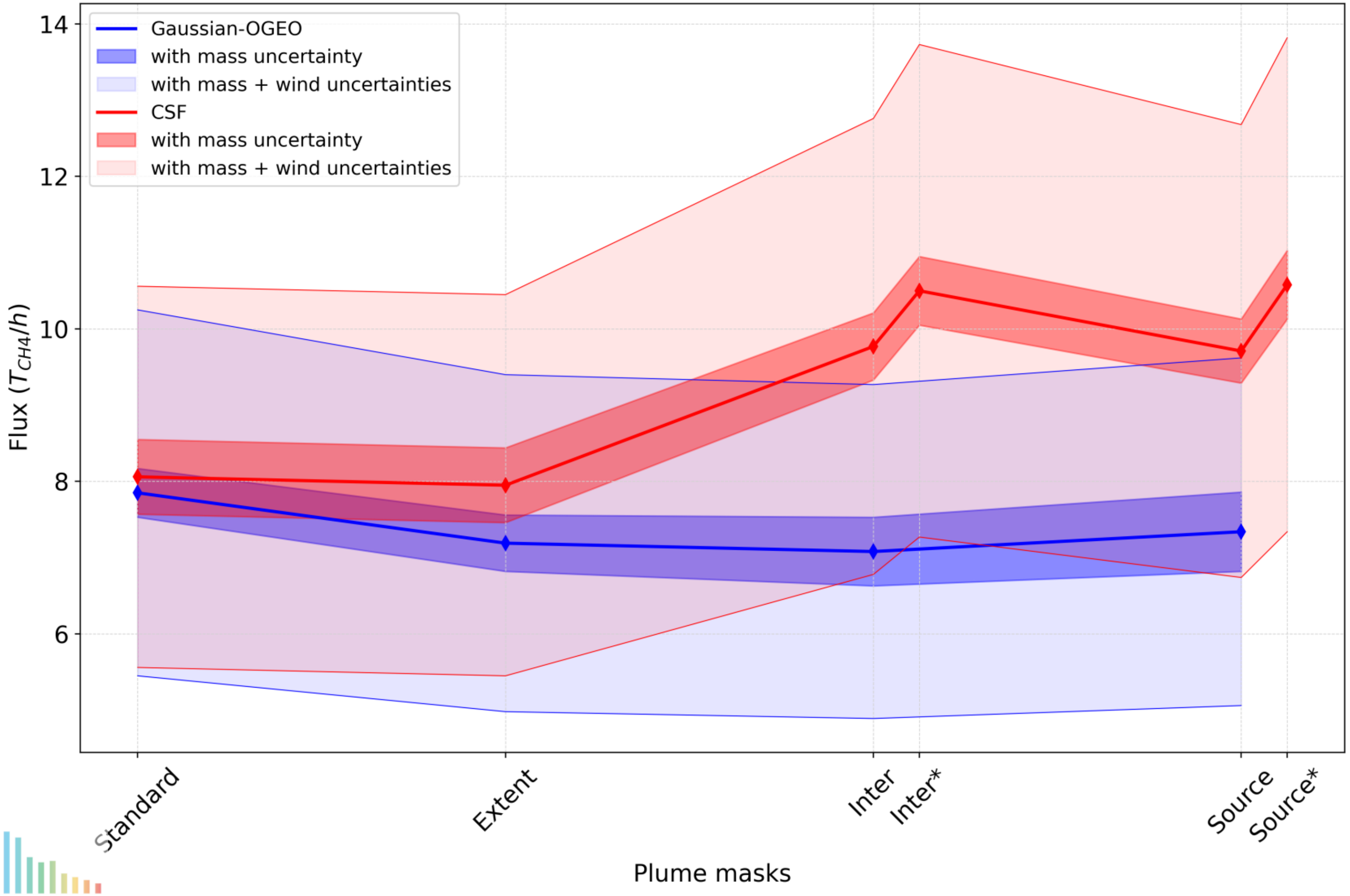


Flow rate for each slice of the plume as a function of the distance

- Large sensibility of CSF method to :
  - Detected pixel of the plume (lose mass in slices due to non-detected methane concentration
  - Global direction used if there are variations in the wind direction
  - Distance used to average the flow rate (in dashed red line)

II. Application to satellite data (PRISMA)

- Synthesis of results for the **21/07/2020** plume with U = 3.3 ± 1 m/s from ECMWF reanalysis:



Flow rate as a function of the mask used (and the distance to average the flow rate in the CSF method)

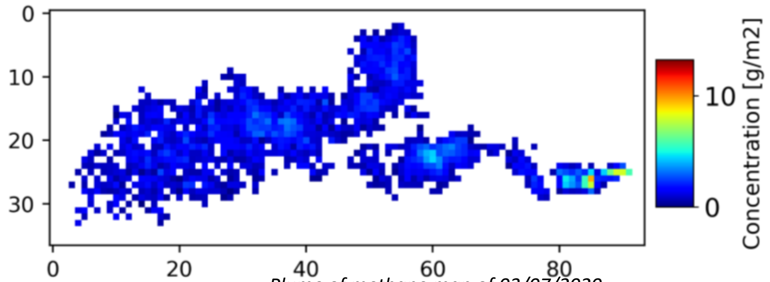
✓ The retrieved flow rate with Gaussian-OGEO method is basically independent from the plume mask

○ The retrieved flow rate is more variable with CSF method

○ In addition to the plume mask, CSF method requires a choice of the distance over which to calculate (using the same mask) the mean flow rate F_{mean}. The Inter* result is computed with two additional slices of the plume as compared to Inter.

II. Application to satellite data (PRISMA)

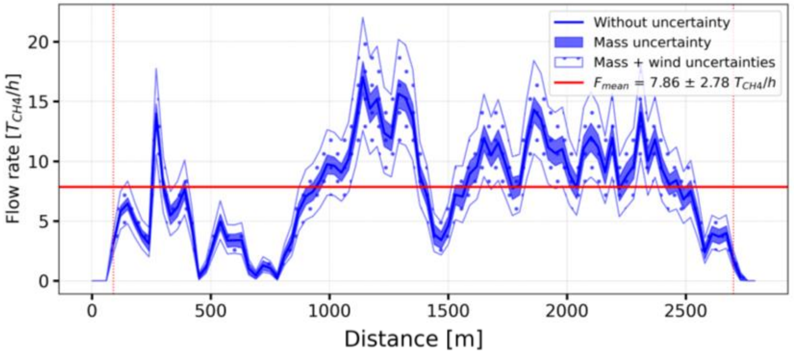
- Synthesis of results for the **03/07/2020** plume with U = 5.0 ± 1 m/s from ECMWF reanalysis:



Plume of methane map of 03/07/2020

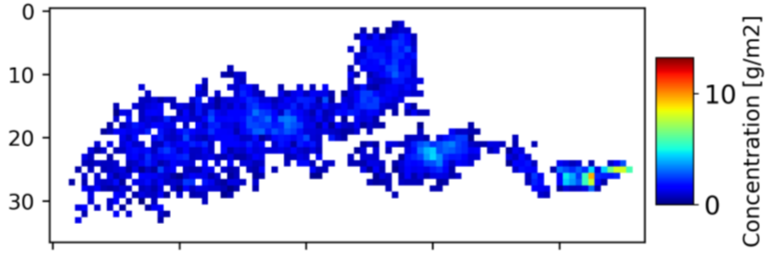
Highly turbulent shape

CSF applied in non-nominal conditions (not possible to define a distance with “constant” flow rate)



II. Application to satellite data (PRISMA)

- Synthesis of results for the **03/07/2020** plume with U = 5.0 ± 1 m/s from ECMWF reanalysis:

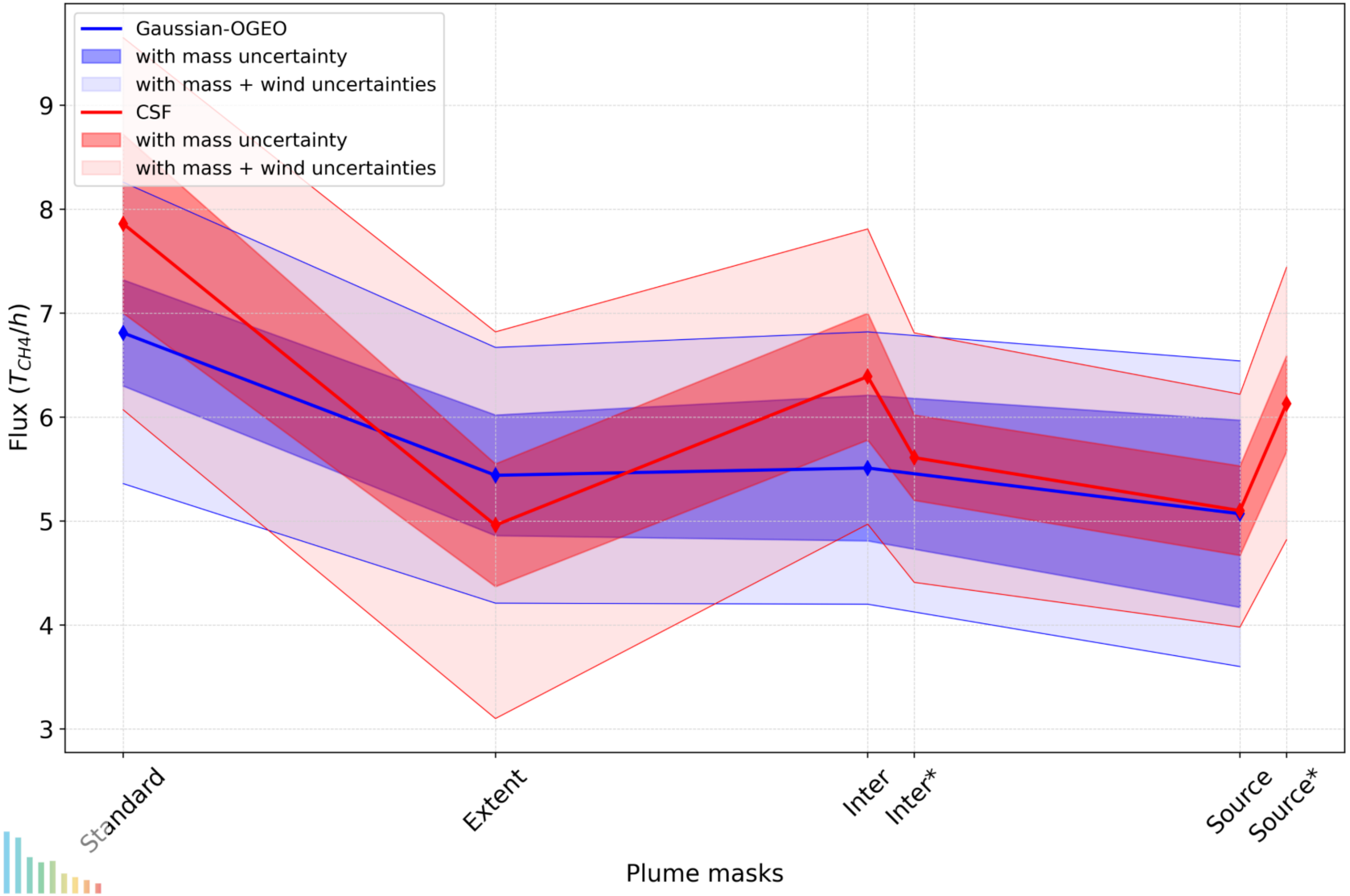


Plume of methane map of 03/07/2020

Highly turbulent shape

CSF applied in non-nominal conditions

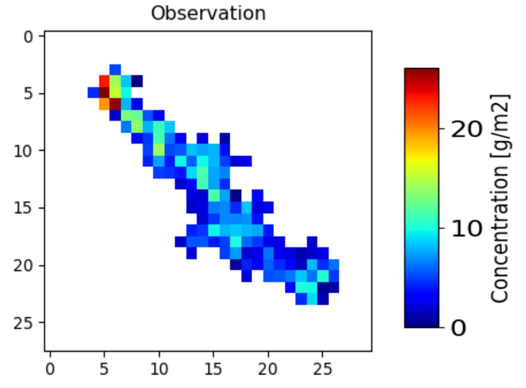
- ✓ Retrieved flow rate with Gaussian-OGEO method more stable
- ✓ Gaunter et al. 2021 : F = 10.5 ± 4.2 tonCH_4/hr with IME method : coherent results (on the errors bars) + not the same wind speed value (improve retrieval differences)



Flow rate as a function of the mask used (and the distance to average the flow rate in the CSF method)

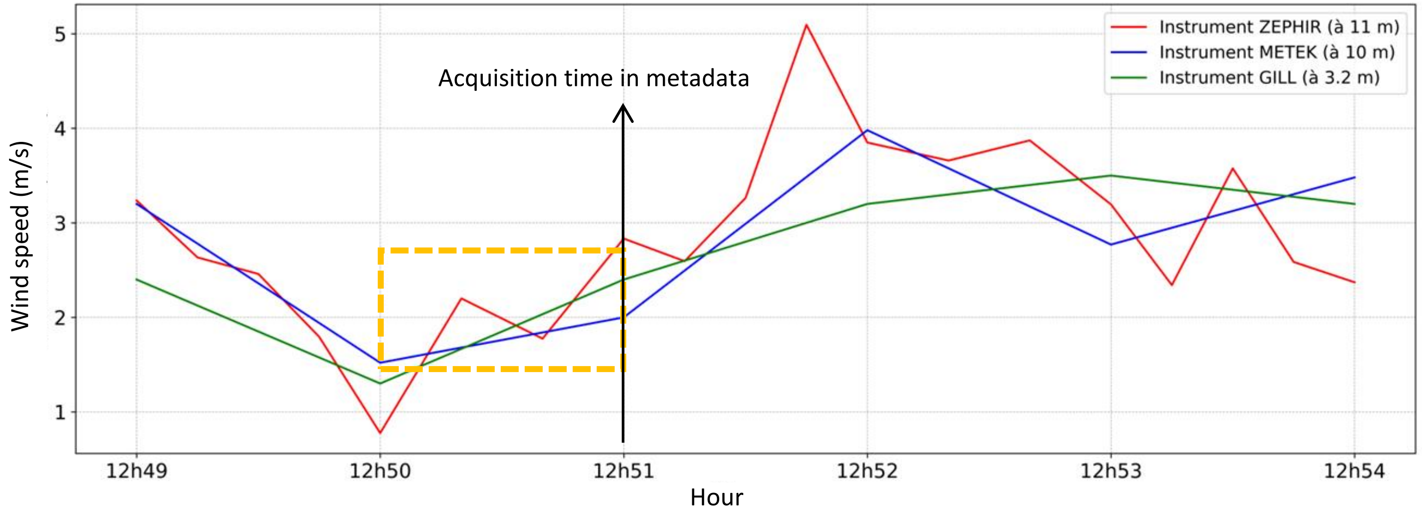
III. Application to airborne data (HySpex)

- Available airborne and ground measurements gives us access to *in situ* flow rate and three wind speed from anemometers close to the source



Plume of methane map for the HySpex image

  - Flow rate at 12h51 : 75 gCH_4/s
  - Wind speed measurements :



Temporal evolution of the wind speed measured by three anemometers

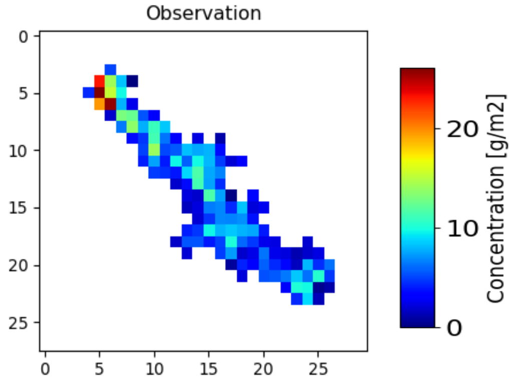
$U \sim$ 1.5 m/s at 12h50

$U \sim$ 2 m/s at 12h50min30s

$U \sim$ 2.5 m/s at 12h51

III. Application to airborne data (HySpex)

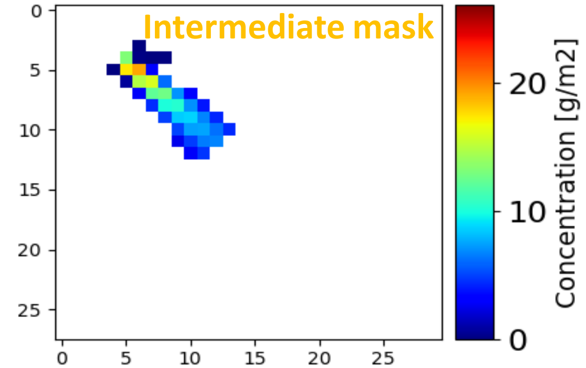
- With Gaussian-OGEO, we can fix the flow rate (F = 75 g/s) and invert the effective wind speed U_{eff}



Plume of methane map for the HySpex image

$U_{eff\ Gaussian\text{-}OGEO}$ = 2.01 ± 0.18 m/s

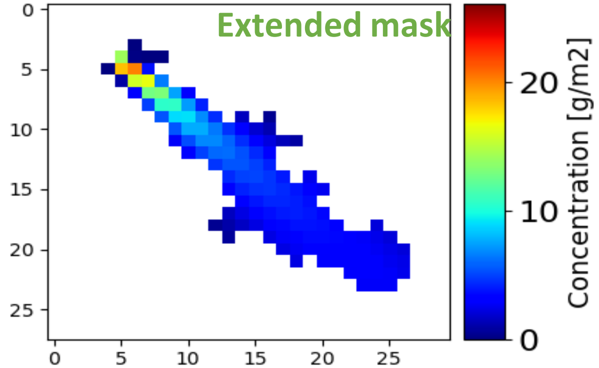
φ_U = 43,3 ± 1,6° χ^2= 1,62



Gaussian plume resulting of the inversion by Gaussian-OGEO

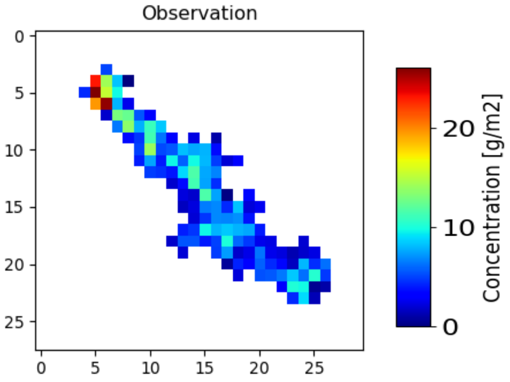
$U_{eff\ Gaussian\text{-}OGEO}$ = 1.89 ± 0.12 m/s

φ_U = 43,4 ± 1,1° χ^2= 1,27



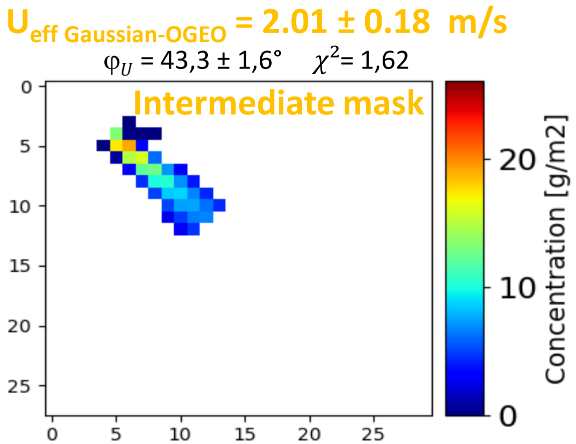
Gaussian plume resulting of the inversion by Gaussian-OGEO

III. Application to airborne data (HySpex)



Plume of methane map for the HySpex image

- With Gaussian-OGEO, we can fix the flow rate (F = 75 g/s) and invert the effective wind speed U_{eff}



$U_{eff\ Gaussian\text{-}OGEO}$ = 2.01 ± 0.18 m/s
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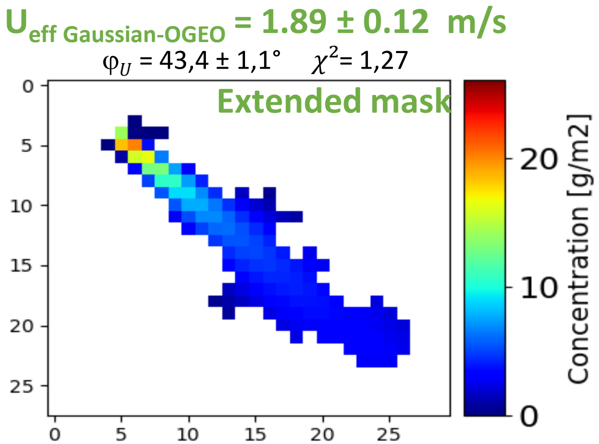
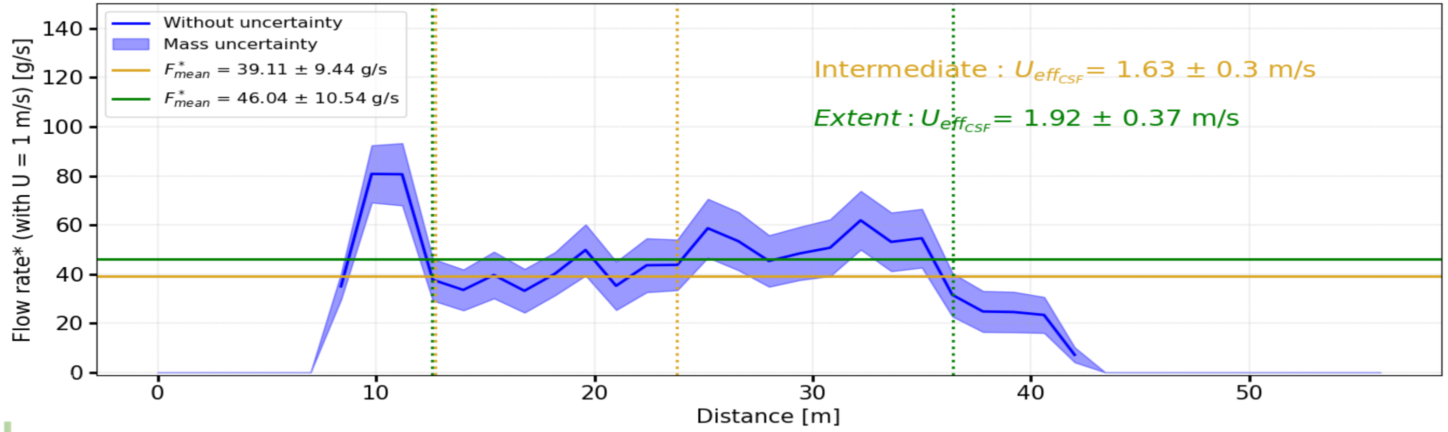
Gaussian plume resulting of the inversion by Gaussian-OGEO



$U_{eff\ Gaussian\text{-}OGEO}$ = 1.89 ± 0.12 m/s
φ_U = 43,4 ± 1,1° χ^2= 1,27

Gaussian plume resulting of the inversion by Gaussian-OGEO

- With CSF, we derive a flow rate retrieved for U_{eff} = 1 m/s in order to estimate the effective wind required to obtain a flow rate F = 75 g/s



Flow rate(calculated with 1 m/s) for each slice of the plume as a function of the distance

- ✓ **Small sensitivity to the two masks with Gaussian-OGEO**
- ○ Results more sensitive to the mask/ mean distance with CSF
- ✓ Lower uncertainties with Gaussian-OGEO than with CSF
- ✓ **All results are in good with the measured value of the wind speed few moment before the acquisition time**

IV. Conclusion

- We implemented and tested **a Gaussian plume model and OEM inversion method** to retrieve flow rate (or wind speed) from real imagery data at high (PRISMA, 30 m) and very high (HySpex, 1.4 m) spatial resolutions.
- We demonstrated on 3 different case studies that Gaussian-OGEO provides reliable results compared with independent estimation or correlative measurements.
- Gaussian-OGEO results are consistent with results from CSF method, but :
  - ✓ With higher stability according to the plume mask used,
  - ✓ Avoiding arbitrary choices (such as the distance used to compute the mean flow rate in CSF method),
  - ✓ Avoiding uncertainty/bias due to possible undetected mass of the plume (present in CSF method),
  - ✓ With a better control of the uncertainty sources, error propagation, information content : Optimal Estimation formalism allows to selected parameters to be retrieved or fixed, to propagate errors of the fixed parameters, and provide extensive diagnostics on information content and retrieval quality (χ^2 tests, …).

- The definition, knowledge and uncertainty on the effective wind speed is still a critical point to flow rate inversion

Work in progress: test an optimisation of the source position (not presented here) with a significant impact on the retrieved flow rate.

Future work: apply to other data sets with controlled flow and correlative measurements to continue evaluation and consolidation of the Gaussian-OGEO approach

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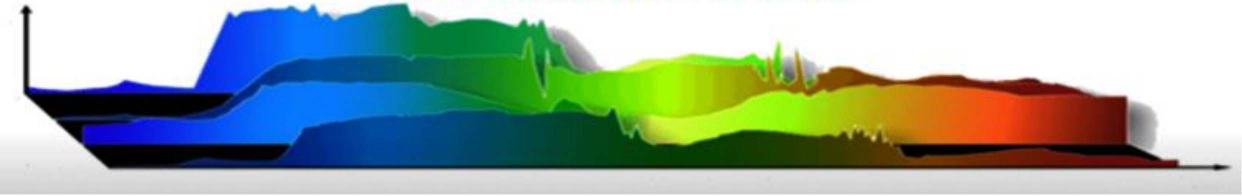
Paris - 5 & 6 juillet 2023



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