

RECONSTRUCTING A EUROPEAN CAESIUM 137 EPISODE THROUGH INVERSE MODELLING SEPTEMBER 2024



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LMDA/STAAR/PSE-ENV

APRIL 2026



REFERENCE : LEMONDE.FR (2020)

01

CONTEXT

CONTEXT

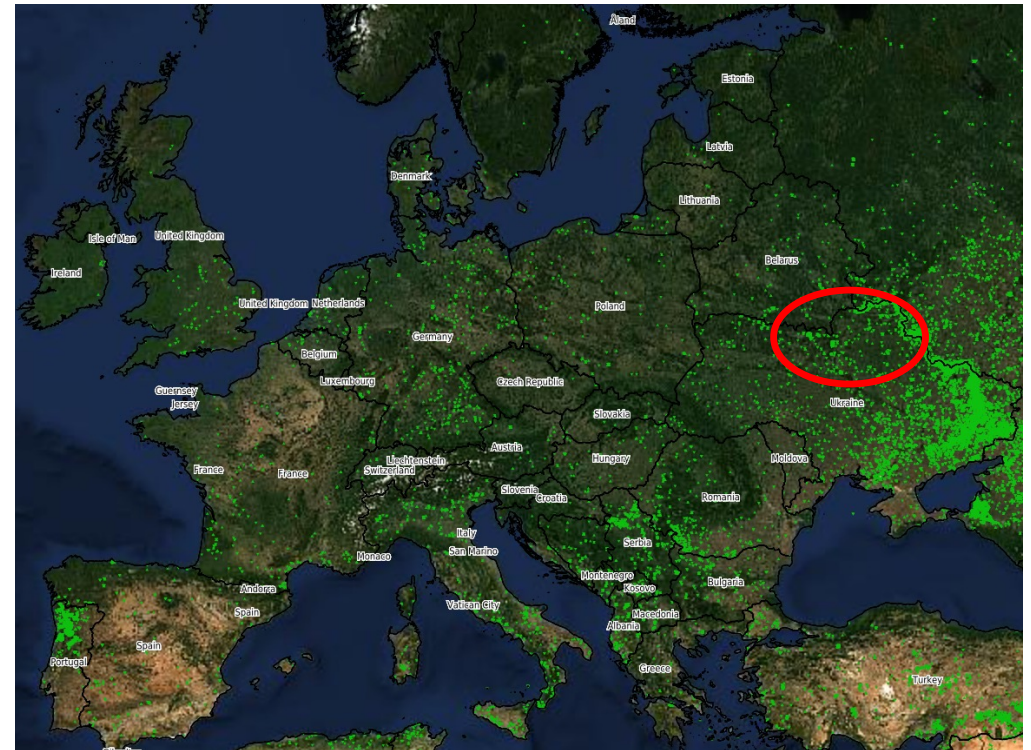
- Between 13/08/24 et le 30/09/24, Measurements of ^{137}Cs in the air exceeding normal levels have been reported by various organisations across Europe. These values were recorded whilst fires were burning in the Chernobyl exclusion zone.

Important dates :

- In late August, the first fires developed approximately 50 to 65 km west of the plant.
- On 3 September, several fires were visible on monitoring satellites imagery in the immediate vicinity of the power plant. Due to an anticyclonic situation, the fire plumes moved toward Ukraine, then Poland, Scandinavia, and a large part of northern Europe.
- From 12 September, the return of rain over northern Ukraine significantly reduced the fires.

OBJECTIVES

Locate and quantify ^{137}Cs releases during the 2024 Chernobyl fires



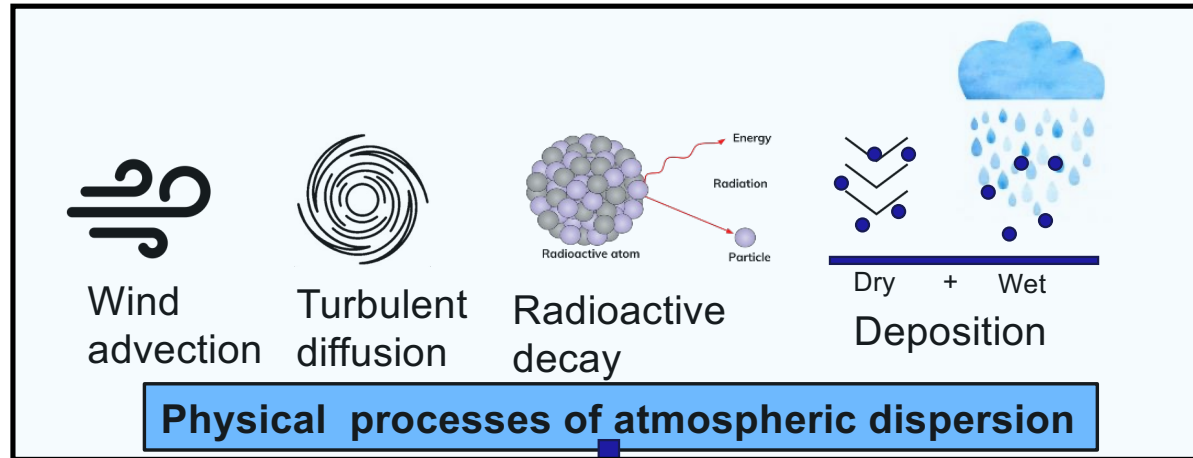
Satellite image of burned surfaces detected by MODIS between 13 August and 1 October 2024

<https://forest-fire.emergency.copernicus.eu>

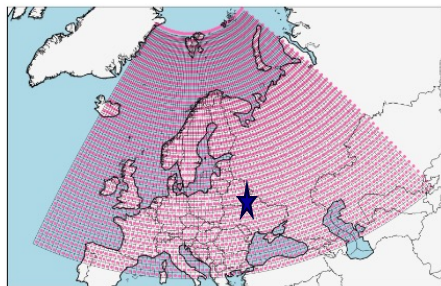
02

METHODOLOGY

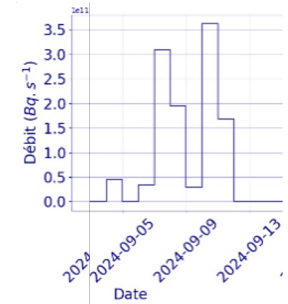
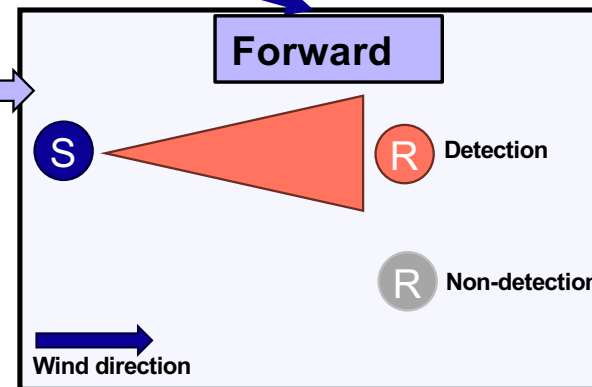
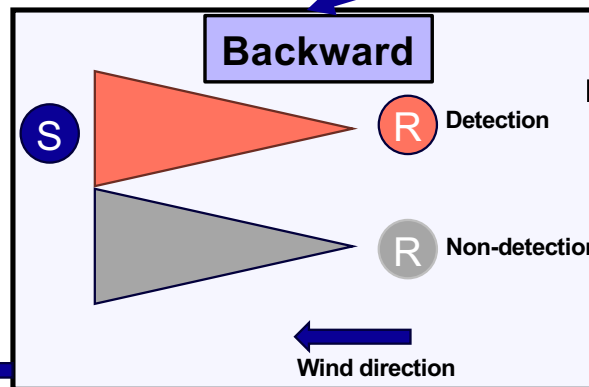
Inverse problem application



Source reconstruction

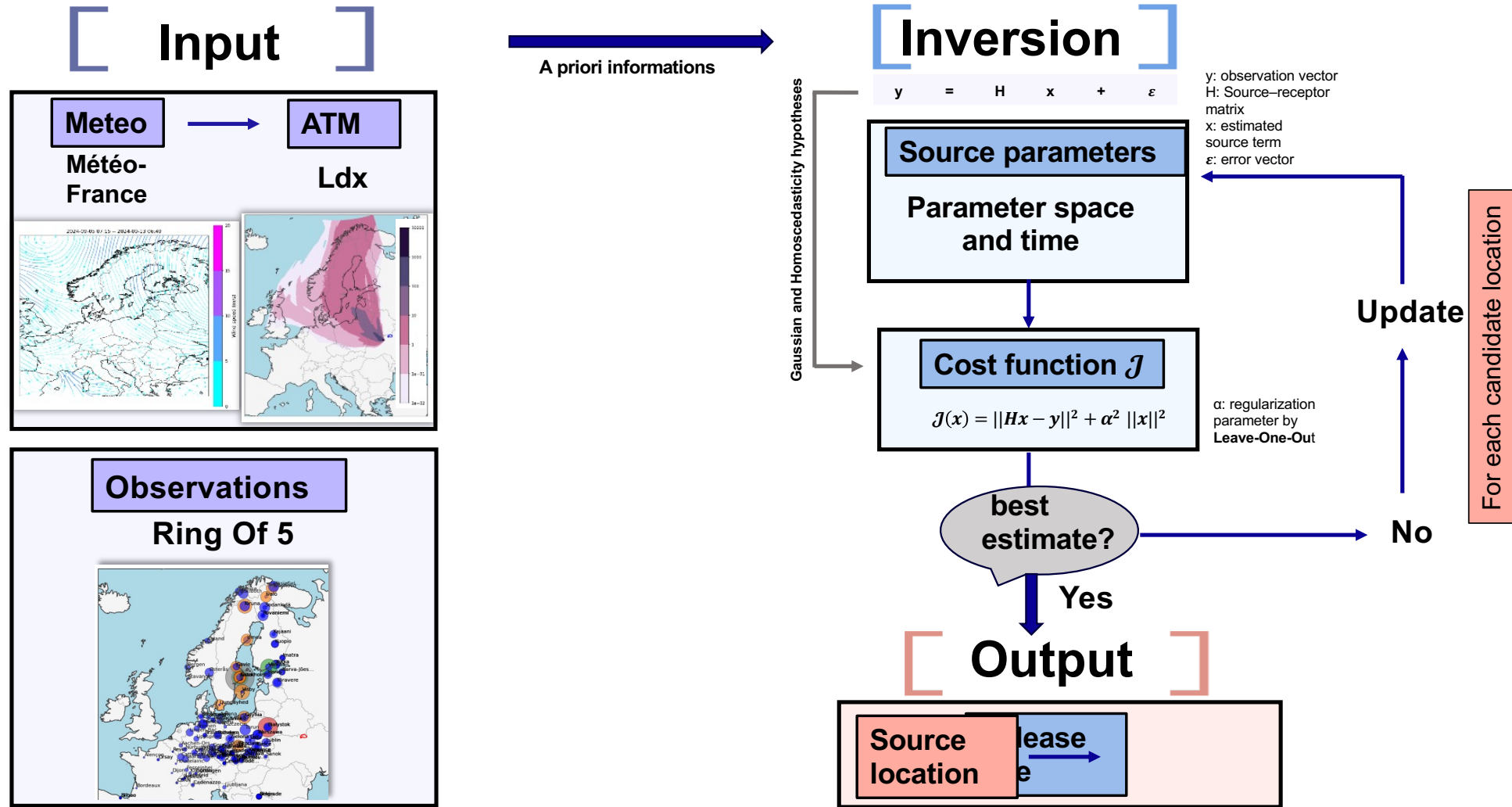


Source term location



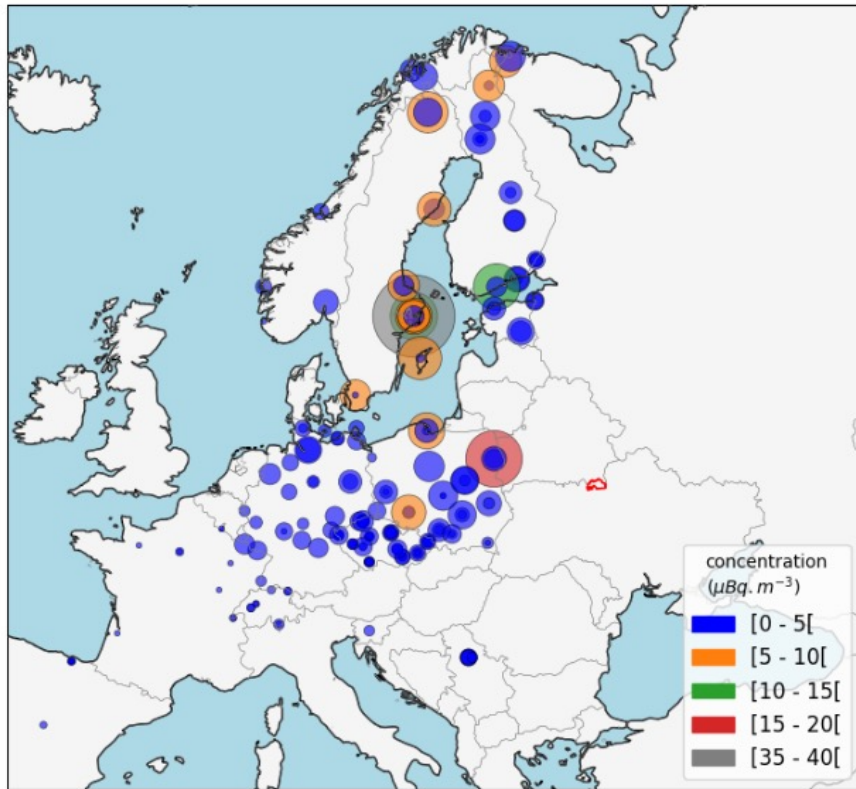
Source term quantification

Inverse problem application



Observation processing

Database description



Map of raw observations

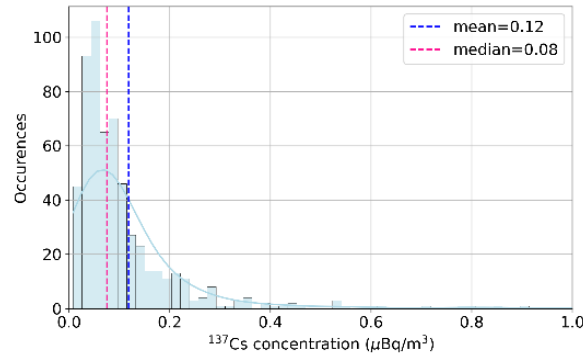
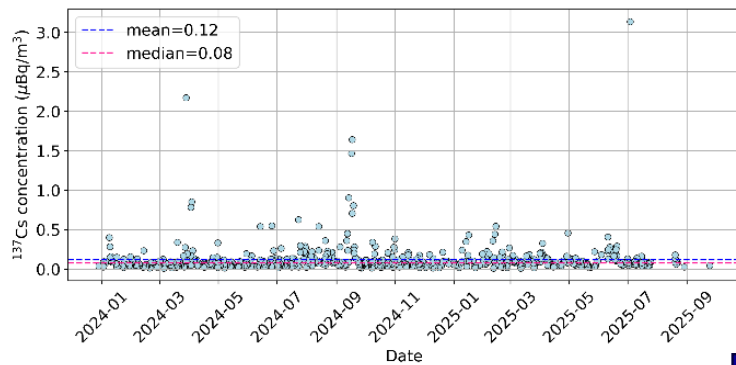
- 195 observations of ^{137}Cs air concentration
- The ^{137}Cs background level is not uniform across stations
- Background statistics are not always provided
- Decision thresholds are never provided



- A specific decision threshold is required for each station
- Only observations greater than the decision threshold are caused by an unusual ^{137}Cs emission

Observation processing

France : Between 2024 and 2025
OPERA TGD Network
Number of observations = 583



➤ The distribution follows a Gamma law

Gamma distribution

$$f(x, \alpha, \beta) = \frac{\beta^\alpha x^{\alpha-1} e^{-\beta x}}{\Gamma(\alpha)}$$

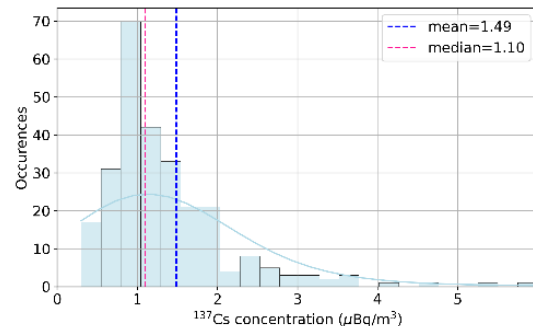
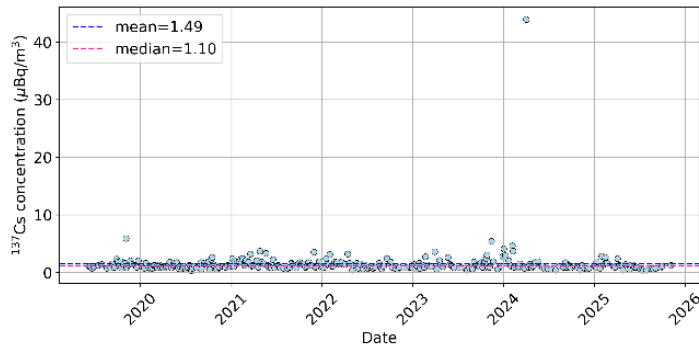
α : the shape parameter
 β : the scale parameter
 $\Gamma(\alpha)$: the gamma function
 $x \in [0, \infty)$

Mean = $\alpha \beta$
Variance = $\alpha \beta^2$

(DANIEL S. WILKS, 2019)

➤ The distribution is better described by the median than the mean

Finland : Between 2020 and 2026
Imatra Network
Number of observations = 268



Median Absolute Deviation (MAD)

$$\text{MAD} = \text{median}|x_i - \bar{x}|$$

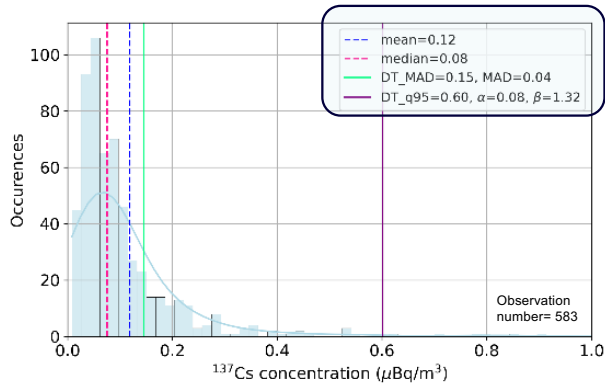
x_i : each point in the dataset

$\bar{x}$: median of the dataset = background

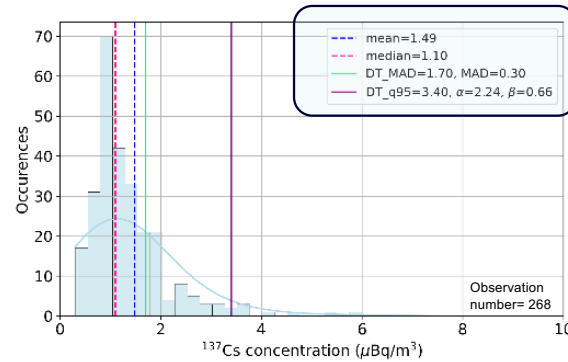
Scatter plot (left) and histogram (right) of air concentrations for all French stations and the Imatra station in Finland.

Observation processing

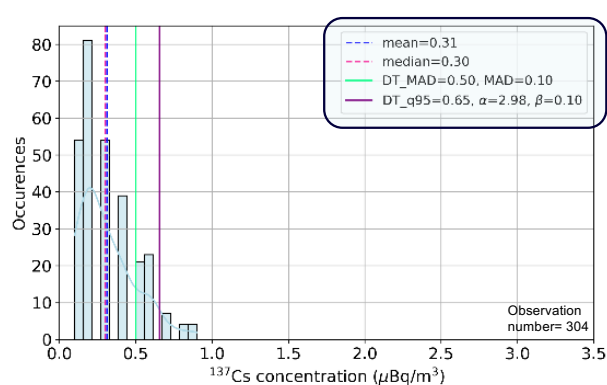
OPERA TGD Network - France



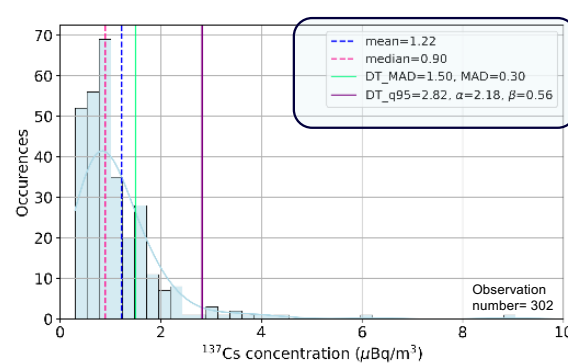
Imatra Network - Finland



Kaajani Network - Finland



Kotka Network - Finland



Histogram of air concentrations for all monitoring stations in France and for the Imatra, Kajaani, and Kotka stations in Finland

Limitations

- The estimated parameters differ from one station to another
- Ideally, these parameters should be characterized individually for each station, when statistics allow, to ensure an accurate background-level subtraction.

Addressing the limitations

1. Assume a constant MAD = 0.1 $\mu\text{Bq}/\text{m}^3$ for all European stations.
2. Decision threshold (DT) for each station

$$DT = \text{Background} + k \cdot MAD$$

Background level (BL) subtraction

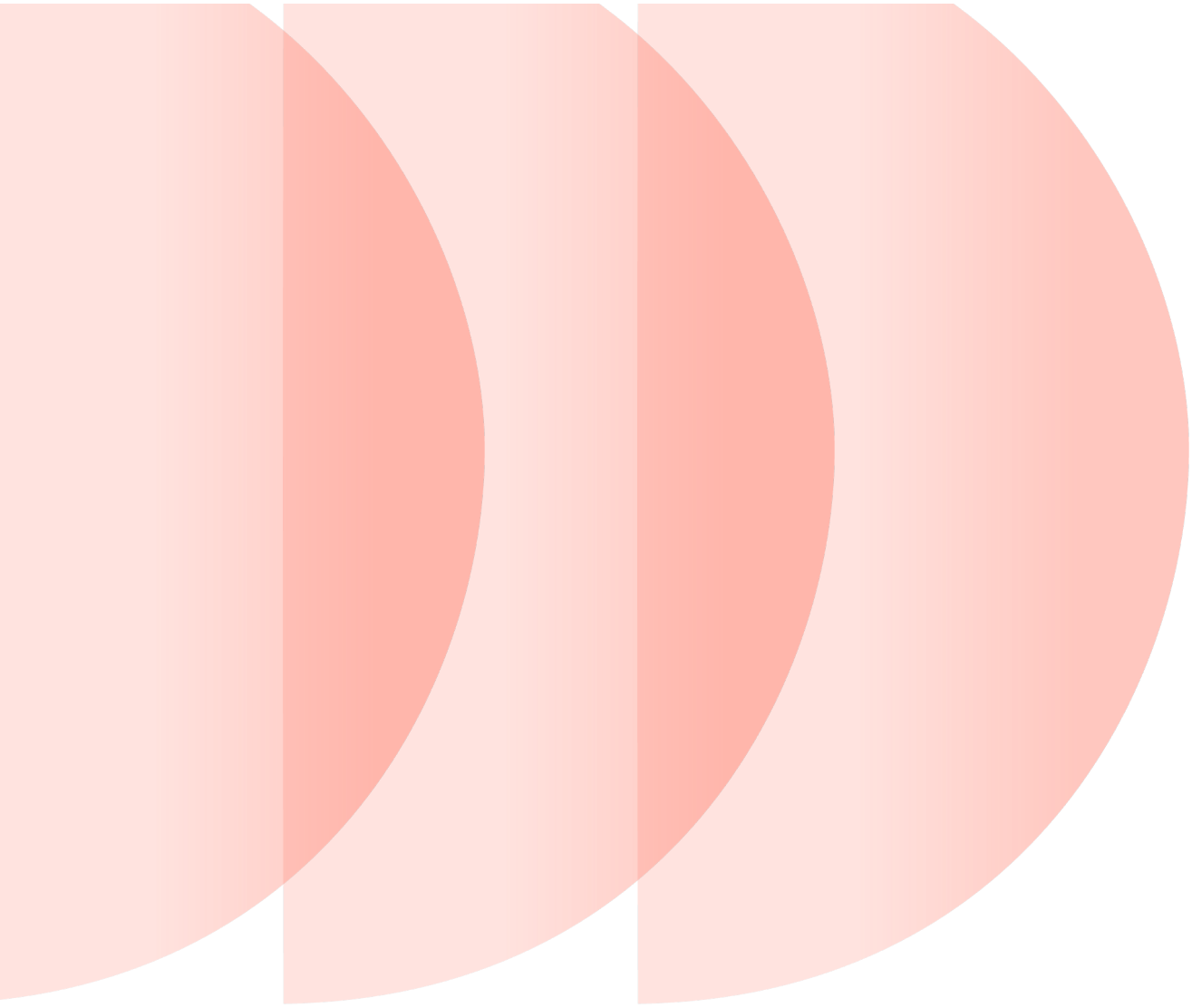
Concentration > DT

YES

NO

Concentration
=
Concentration - BL

Concentration = 0

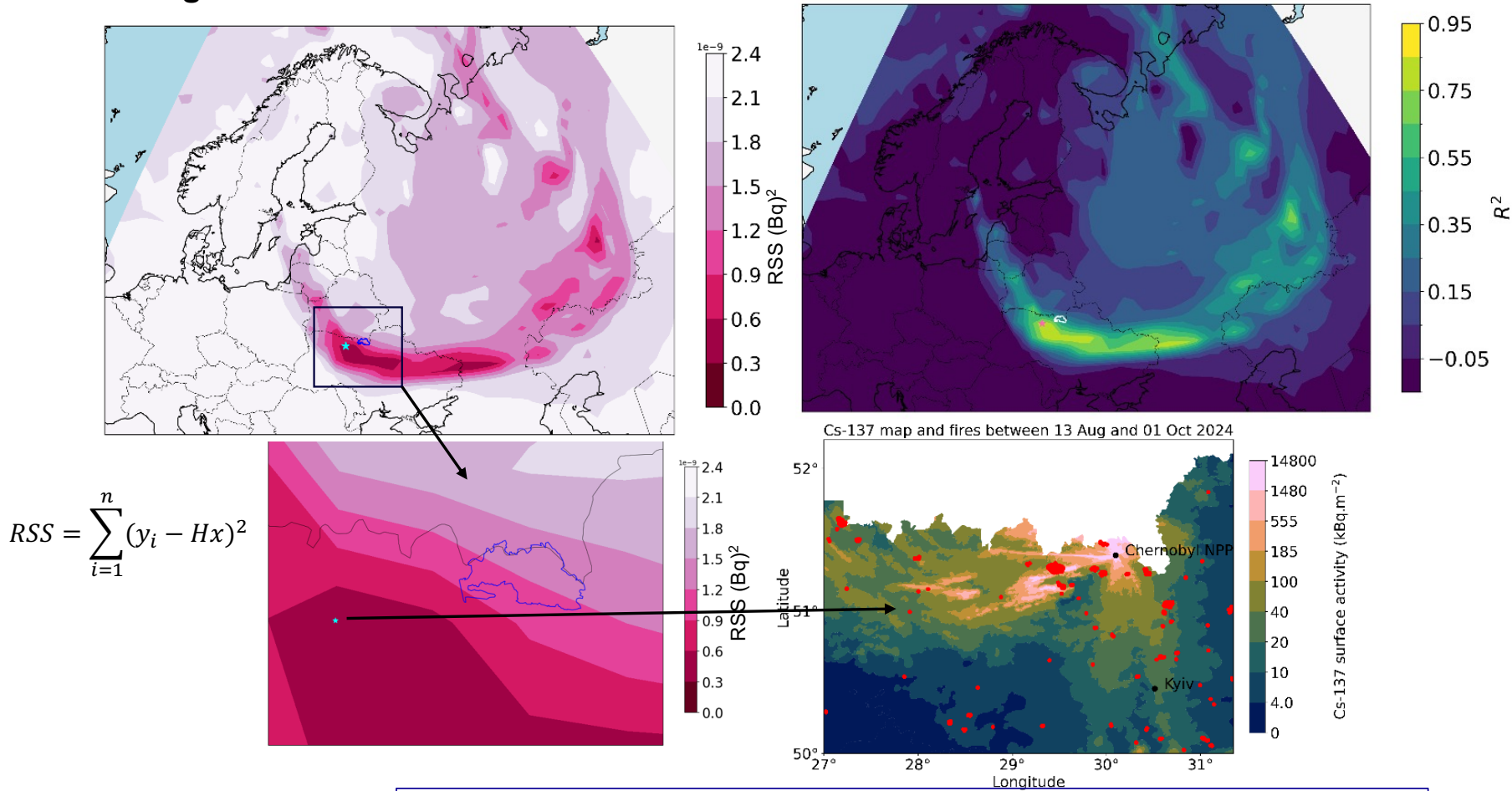


03

RESULTS & DISCUSSIONS

Source term location

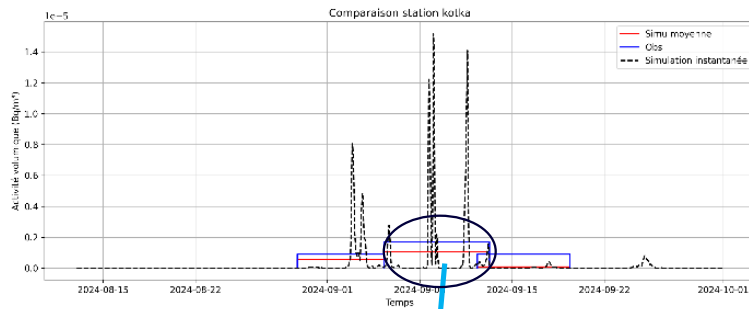
Meteorological data : Glob 0.25°



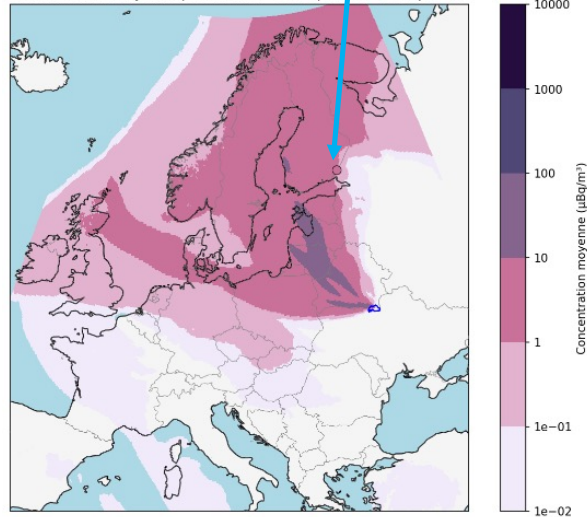
Coordinates of source term: Latitude = 51.0 ; Longitude=28.0

Background subtraction sensitivity

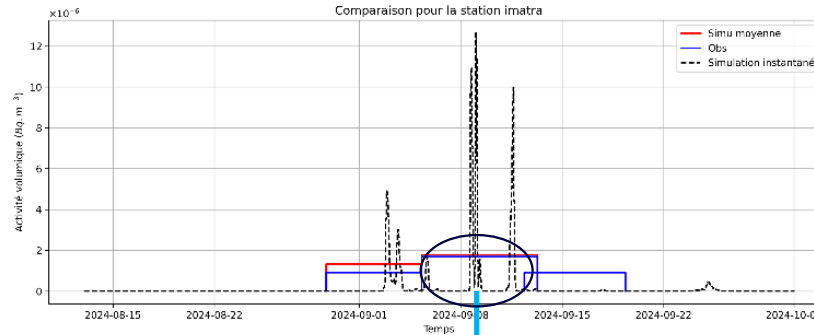
No Background subtraction



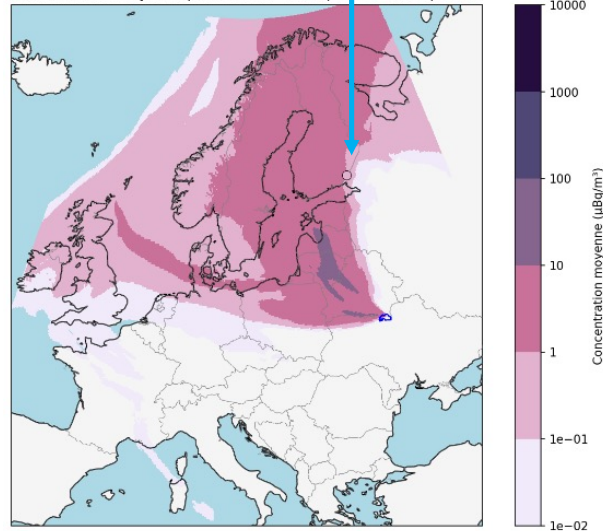
concentration moyenne pour Imatra - 05 Sep 2024 - 13 Sep 2024



Background subtraction



concentration moyenne pour Imatra - 05 Sep 2024 - 13 Sep 2024



BL subtraction leads to an improved model-measurement comparison, for example for points located at the edge of the plume.

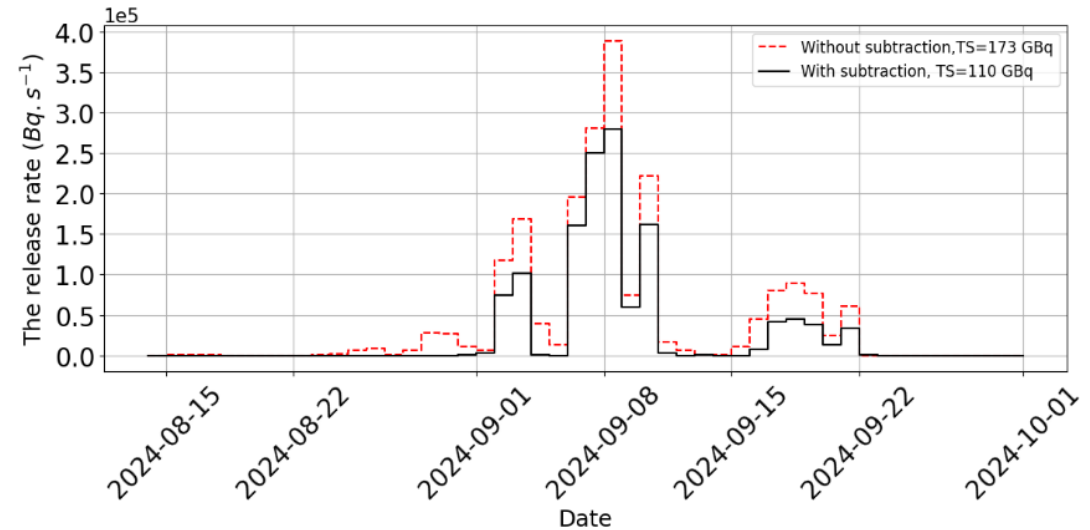
Background subtraction sensitivity

Dispersion conditions :

- Lat=51.38 lon=30.09
- Plume height : between 1900m and 2500 m
- Meteorological data : ARPEGE Europe 0.1°
- Period : 13/08/2024
01/10/2024

Observation description (MAD) :

- 110 observations < DT
- 85 observations > DT



Temporal evolution of the source-term emission rate

Statistical indicators

The source term is sensitive to background subtraction: relative difference = 63 %

Source term estimation is better with the background subtraction.

background subtraction

Yes

No

	Score		Score		Score		Score
Fac2 %	77	Success (%)	90	Fac2 %	73	Success (%)	83
Fac5 %	95	Failure (%)	10	Fac5 %	89	Failure (%)	17

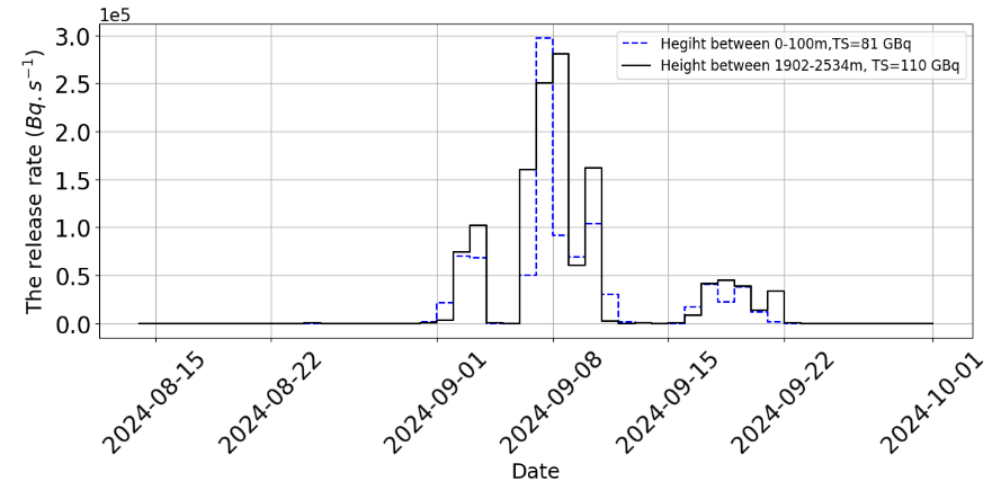
$$Success = \frac{True\ Positive + True\ Negative}{all\ events}$$

$$Failure = \frac{False\ Positive + False\ Negative}{all\ events}$$

Emission height sensitivity

Dispersion conditions :

- Lat=51.38 lon=30.09
- Observations : background level subtraction
- Meteorological data : ARPEGE Europe 0.1°
- Period : 13/08/2024
01/10/2024



Temporal evolution of the source-term emission rate

Statistical indicators

Height

Yes

No

The source term is sensitive to the emission height: relative difference = 29 %

Source term estimation is better with the observed plume height .

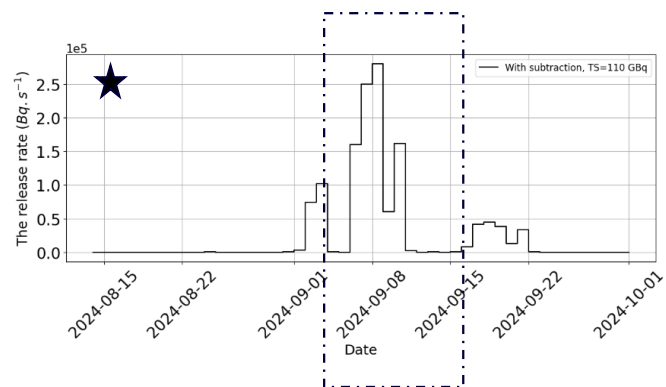
	Score		Score
Fac2 %	77	Success (%)	90
Fac5 %	95	Failure (%)	10

	Score		Score
Fac2 %	70	Success (%)	86
Fac5 %	98	Failure (%)	14

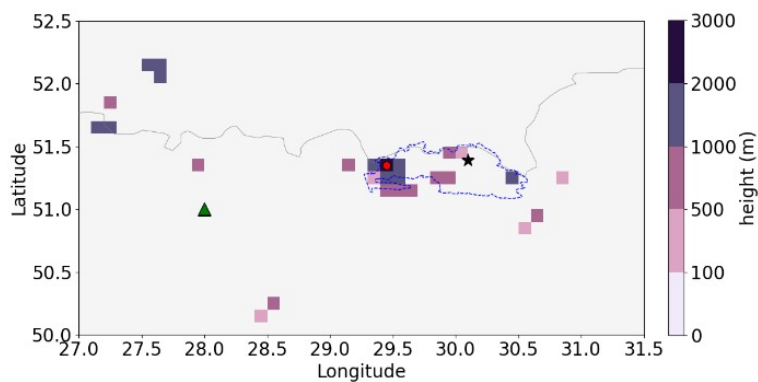
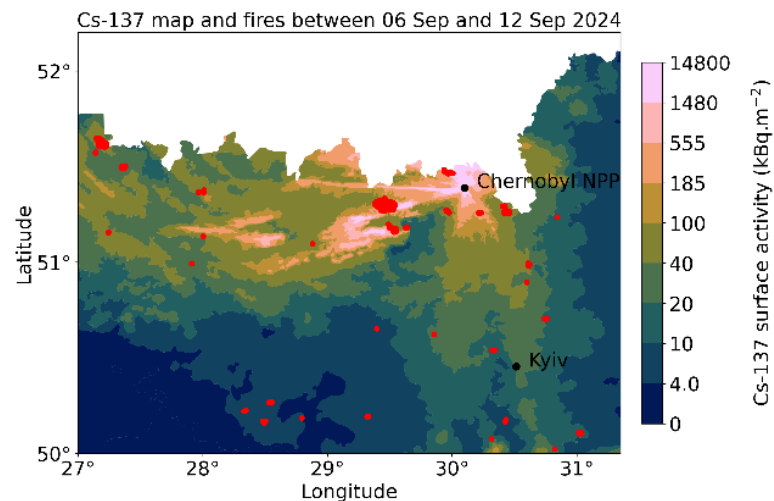
$$Success = \frac{True\ Positive + True\ Negative}{all\ events}$$

$$Failure = \frac{False\ Positive + False\ Negative}{all\ events}$$

Emission location sensitivity



Temporal evolution of the source-term emission rate at nuclear power plant



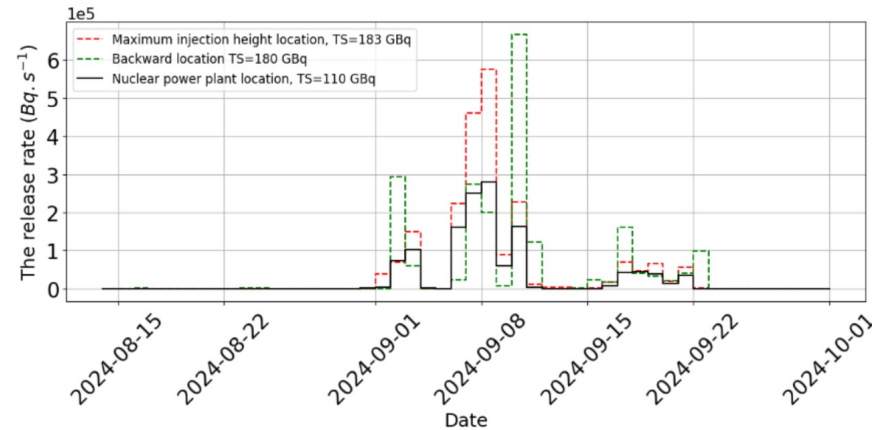
Maximum injection height plume between 6 September and 12 September 2024, in northern Ukraine - satellite observations

Data from the Copernicus emergency forest fire information system

Location sensitivity

Dispersion conditions :

Plume height : between 1900 m and 2500 m
 Observations : subtraction background level
 meteorological data : ARPEGE Europe 0.1°
 Inversion period : 13/08/2024 - 01/10/2024



Temporal evolution of the source-term emission rate

Location

Nuclear power plant

	Score		Score
Fac2 %	77	Success (%)	90
Fac5 %	95	Failure (%)	10

Backward

	Score		Score
Fac2 %	77	Success (%)	85
Fac5 %	98	Failure (%)	15

Largest fire spot

	Score		Score
Fac2 (%)	77	Success (%)	88
Fac5 (%)	96	Failure (%)	12

The best-estimate
 source term is
 110 GBq.

$$Success = \frac{True\ Positive + True\ Negative}{all\ events}$$

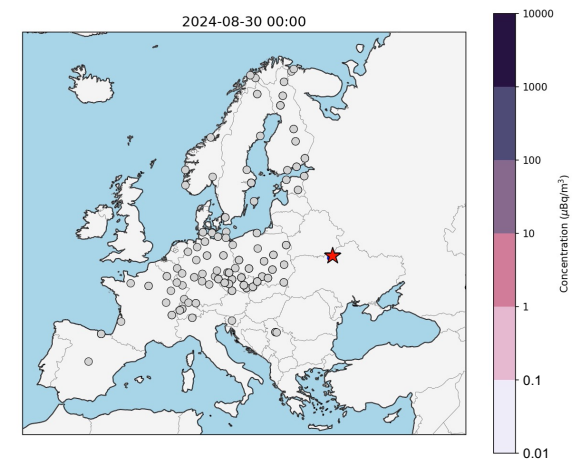
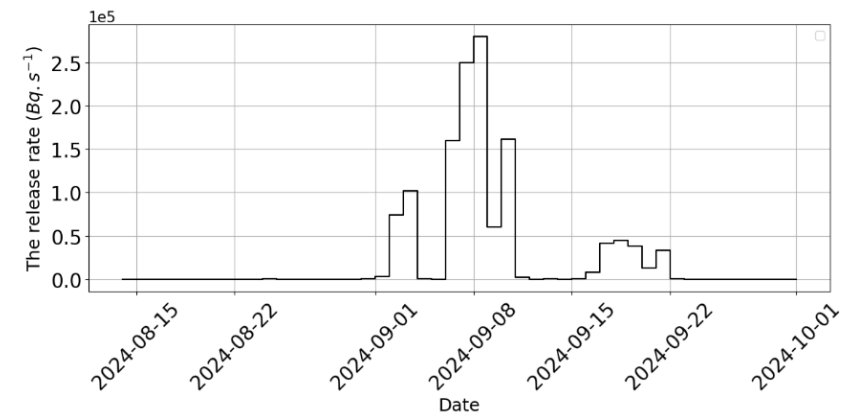
$$Failure = \frac{False\ Positive + False\ Negative}{all\ events}$$

04

CONCLUSIONS & PERSPECTIVES

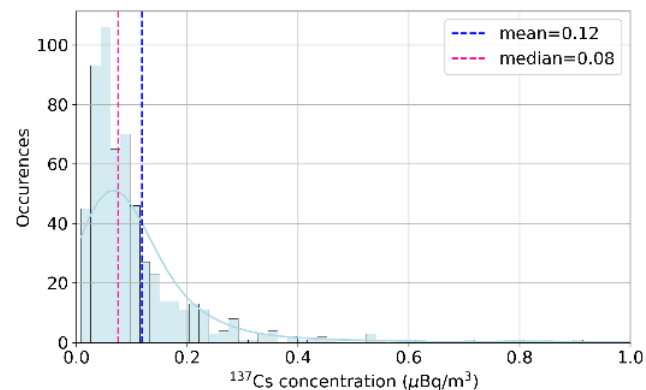
CONCLUSIONS

- ❑ The ^{137}Cs detected in Europe in September 2024 resulted from the wildfires in Chernobyl (Chornobyl) area.
- ❑ The estimated ^{137}Cs release from the 2024 Chernobyl wildfires converges to about 100 GBq. x10 smaller than the April 2020 event, during which 700-1200 GBq of ^{137}Cs were released into the atmosphere (Masson et al. 2021).
- ❑ Background level and decision threshold should be representative.
- ❑ Without an adequate background subtraction, the resulting relative error can exceed 50%.
- ❑ Without an adequate plume height, the resulting relative error can exceed 20%.
- ❑ The fire hotspots give comparable statistical indicators and a source term of the same order of magnitude.
- ❑ Combining satellite observations with the inverse dispersion provides improved statistical indicators.



PERSPECTIVES

- ❑ Application of alternative cost-function calculation approaches.
- ❑ Improved estimation of the ^{137}Cs background statistics for each station in Europe, and consequently of the decision threshold.
- ❑ Extending the source-term localization method to incorporate several simultaneous sources.
- ❑ More realistic representation of the error-covariance matrix and the source-term covariance matrix.



Histogram of volumetric activities for all French stations

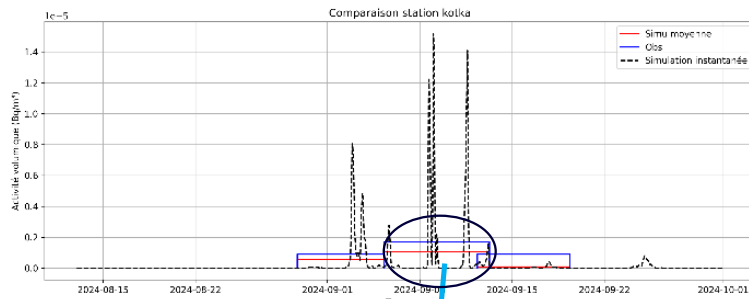
Thank you
Questions?

Contact : hanane.bounouas@asn.fr

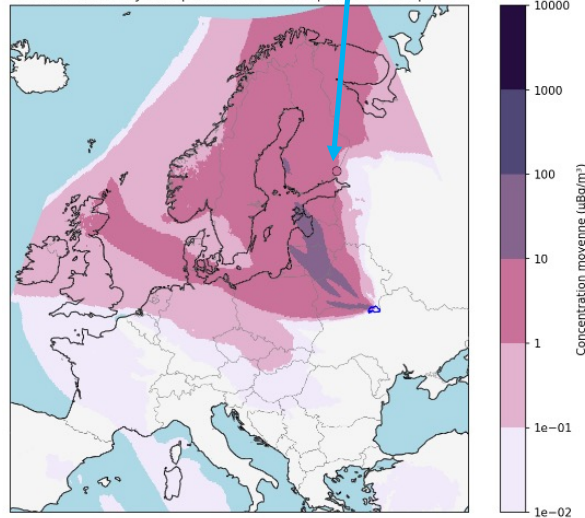
APPENDIX

Background subtraction sensitivity

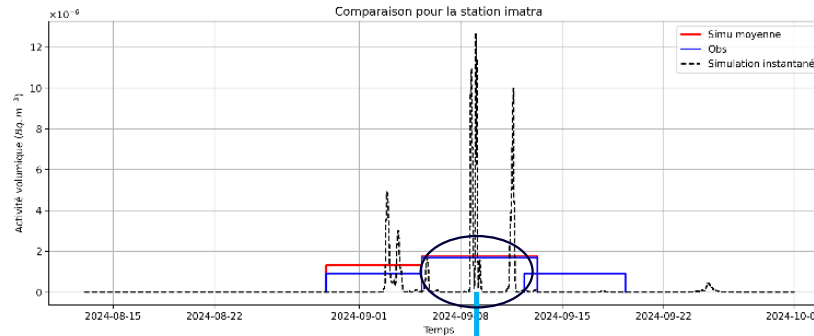
No Background subtraction



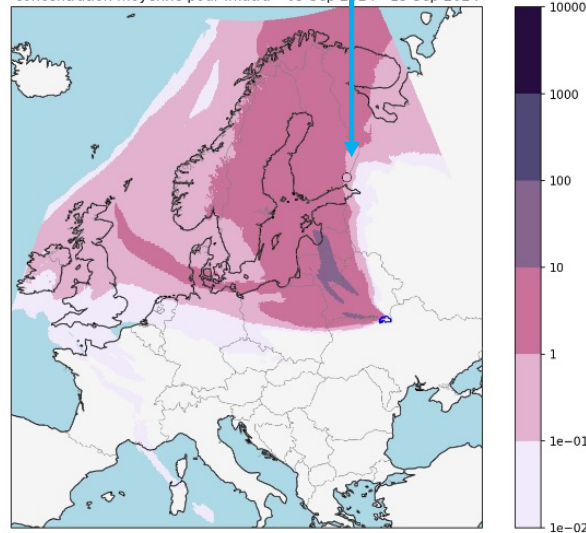
concentration moyenne pour Imatra - 05 Sep 2024 - 13 Sep 2024



Background subtraction



concentration moyenne pour Imatra - 05 Sep 2024 - 13 Sep 2024

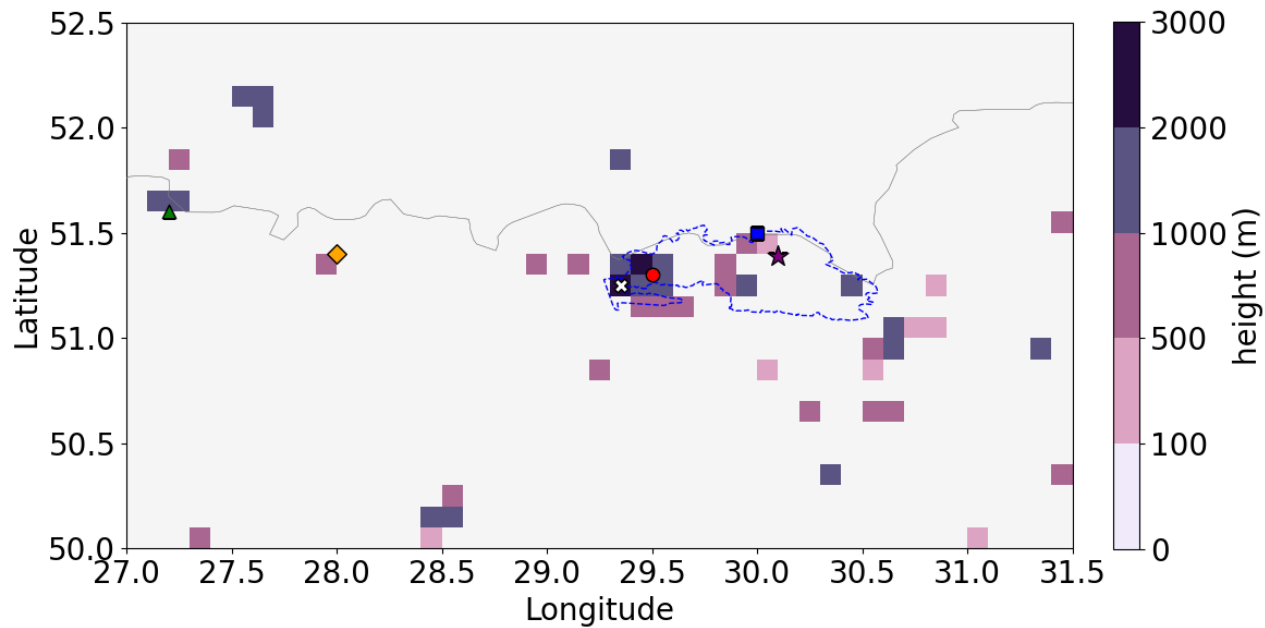


Statistical indicators

	Score		Score
Fac2 %	77	Success (%)	90
Fac5 %	95	Failure (%)	10

- For the **10 % failure cases**
 - all observed values are on the order of the BL.
 - Simulated values are sensitive and/or close to the background-noise level."
- BL subtraction leads to an improved model-measurement comparison, for example for points located at the edge of the plume.

Satellite-observed characteristics of forest fires



Maximum injection height between August 13 and October 1, 2024,
in northern Ukraine

Data from the Copernicus emergency forest fire information system

Plume height

Maximum injection height
2127.30m
Altitude of plume bottom
2533.61m
Altitude of plume bottom
1903.88m
Latitude=51.35,
Longitude=29.45
date=2024/09/09

Localization

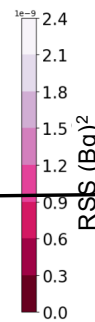
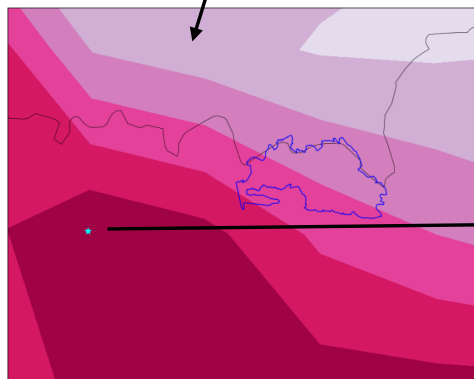
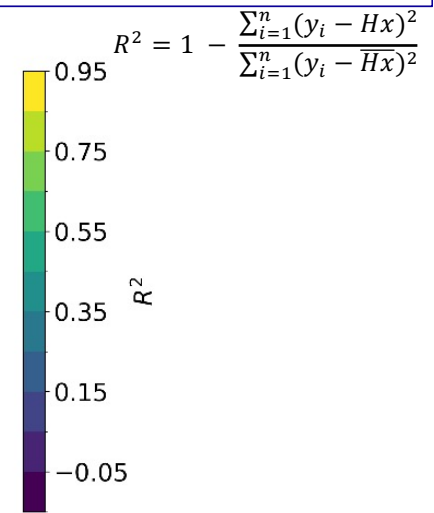
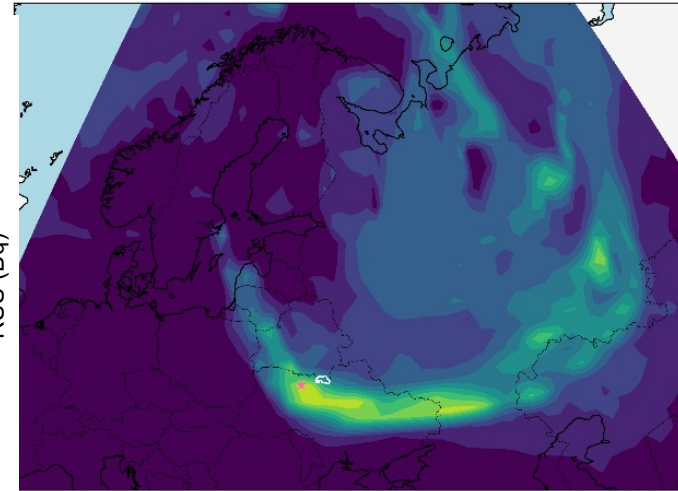
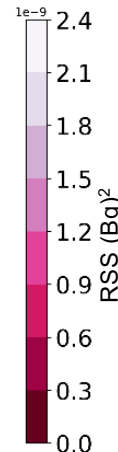
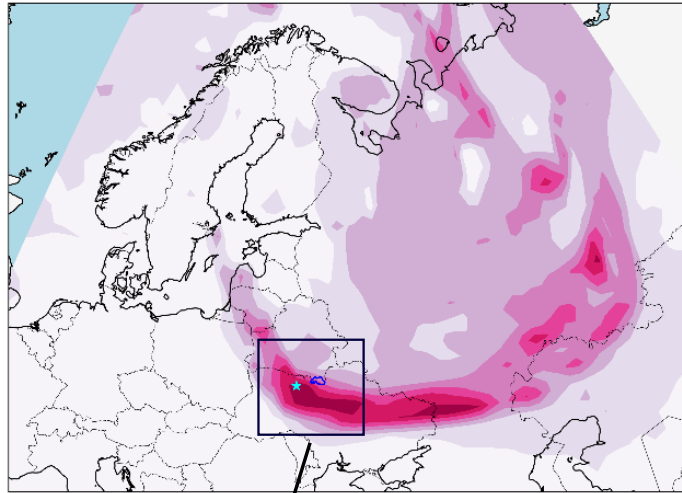
Several fire hotspots:

- Lat=51.3 Lon=29.5
- Lat=51.5 Lon=30.0
- ▲ Lat=51.6 Lon=27.2
- ◆ Lat=51.4 Lon=28.0
- ★ Nuclear plant
- ⊗ Comparison with
backward localization
results

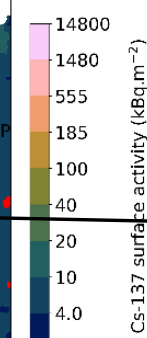
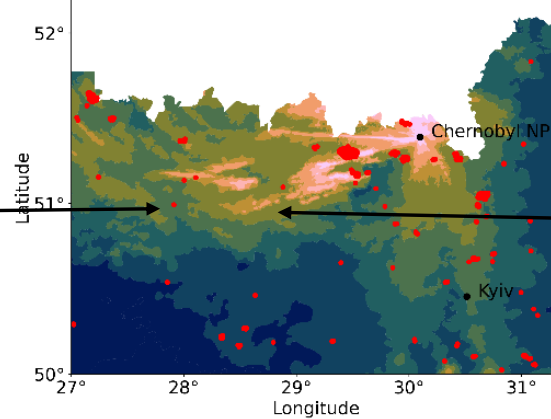
Source term location

$$RSS = \sum_{i=1}^n (y_i - Hx)^2$$

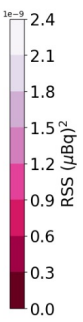
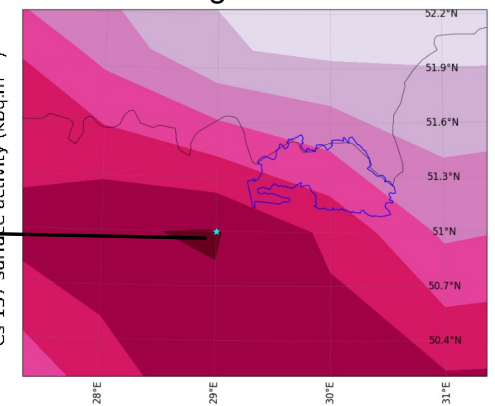
Meteorological data : Glob 0.25°



Cs-137 map and fires between 13 Aug and 01 Oct 2024



Meteorological data : Glob 0.1°



Coordinates of source term:
Latitude = 51.0 ; Longitude=28.0

Coordinates of source term:
Latitude = 51.0 ; Longitude=29.0

Source term quantification

Backward Location

Dispersion conditions :

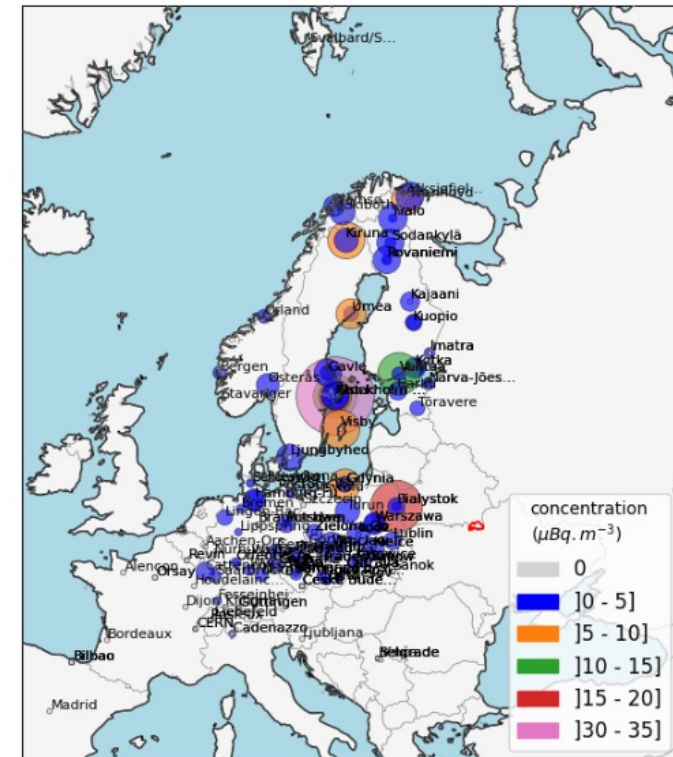
Lat=51.389167 lon=30.099444

Plume height : between 1902m and 2534 m
meteorological data : Arpège Europe 1°

Inversion period : 13/08/2024
01/10/2024

Observation description :

- 110 observations < TD
- 85 observations > TD
- The maximum activity below the TD is 1.5, $\mu\text{Bq}/\text{m}^3$ at the Belgrade station, with background levels is 1.5 $\mu\text{Bq}/\text{m}^3$.
→ TD excludes values at the background level



Inverse problem

y	$=$	H	x	$+$	ε
Observation vector		Source–receptor matrix	source term		Error vector - Observations - Model

Objective: Construct posterior distributions of the variables of interest from the observations.

Principle: A Bayesian inverse problem can be expressed according to Bayes' theorem:

$$p(x|y) = \frac{p(y|x)p(x)}{p(y)}$$

$x \in \mathbb{R}^{N_{var}}$
 $y \in \mathbb{R}^{N_{obs}}$

$$\max p(x|y) = \min J(x)$$

$$J(x) = \underbrace{\|y - Hx\|_{R^{-1}}^2}_{\text{residuals}} + \underbrace{\|x - x_b\|_{B^{-1}}^2}_{\text{Tikhonov Regularization}}$$

Gaussian assumptions

J : Cost function

R : Measurement errors related to the instruments used and observation errors

B : Error associated with the prior term = discrepancy between the prior estimate and the true state

x_b : The prior term is introduced when the system is underdetermined ($N_{var} > N_{obs}$)

The cost function J measures the differences between:

- The observations and the model,
- A prior term x_b and an unknown source term to be estimated.

Error modelling

The error covariance matrices R and B are not well known.



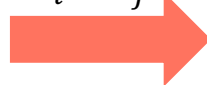
Homoscedasticity assumption: matrices with constant diagonal elements

- No spatio-temporal correlation between measurements (possibly false)
- No temporal correlation in the release emissions x (false)

$$R = \begin{pmatrix} r_1 & 0 & 0 & 0 \\ 0 & r_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & r_d \end{pmatrix}$$

$$B = \begin{pmatrix} b_1 & 0 & 0 & 0 \\ 0 & b_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & b_d \end{pmatrix}$$

$$r_i = r_j$$



$$b_i = b_j$$

$$J(x) = ||Hx - y||^2 + \alpha^2 ||x - x_b||^2$$

$$\text{Avec } \alpha^2 = \frac{r^2}{b^2}$$

In the specific case where $x_b=0$

$$J(x) = ||Hx - y||^2 + \alpha^2 ||x||^2$$

J : cost function

R : measurement errors related to the instruments used and observation errors

B : Error associated with the prior term = discrepancy between the prior estimate and the true state

x_b : The prior term is introduced when the system is underdetermined ($N_{\text{var}} > N_{\text{obs}}$)

y : Observation vector

H : Source-receptor matrix

x : Source term

Determination of the regularization parameter α

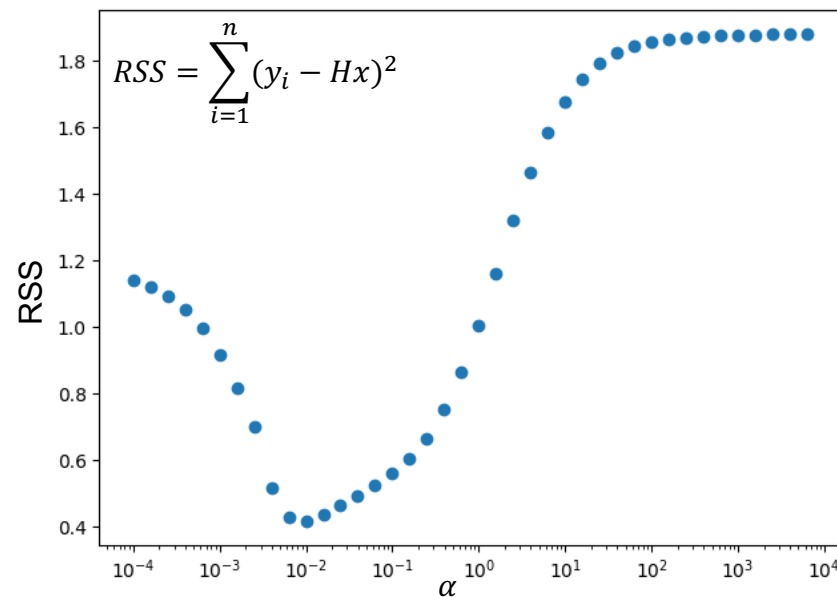
$$\mathcal{J}(x) = ||Hx - y||^2 + \alpha^2 ||x||^2$$

$\mathcal{J}$: cost function
 H : Source–receptor matrix
 y : Observation vector
 x : source term

Significant influence in the case of a small number of observations:

- $\alpha \rightarrow \infty$: The regularization term dominates the cost function and forces the solution toward zero, at the expense of the fit to the observations.
- $\alpha \rightarrow 0$: the solution attempts to fit the observations as closely as possible, which may lead to high sensitivity to outliers and numerical instabilities.

Several automatic approaches are possible for determining α , including **cross-validation**.



Advantages :

- Non-parametric approach
- Low sensitivity to statistical assumptions on errors

...

Disadvantages:

- High computational cost

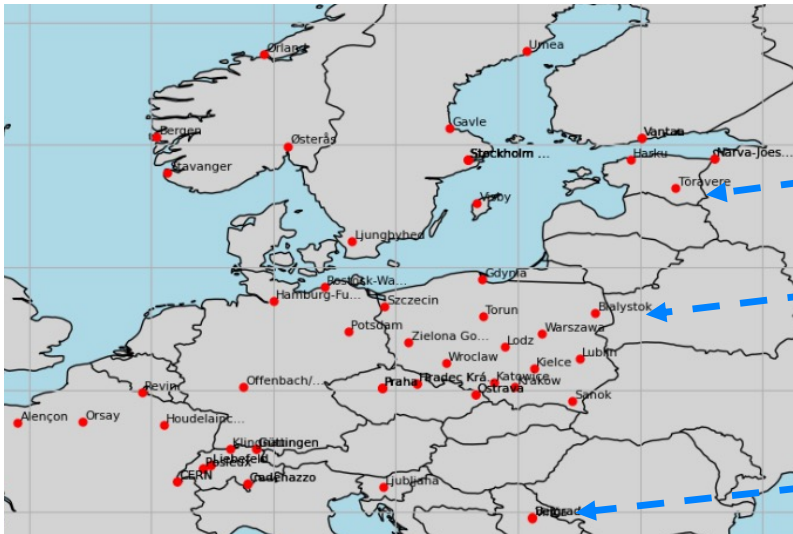
...

The source–receptor matrix H : example of a case study with a known source

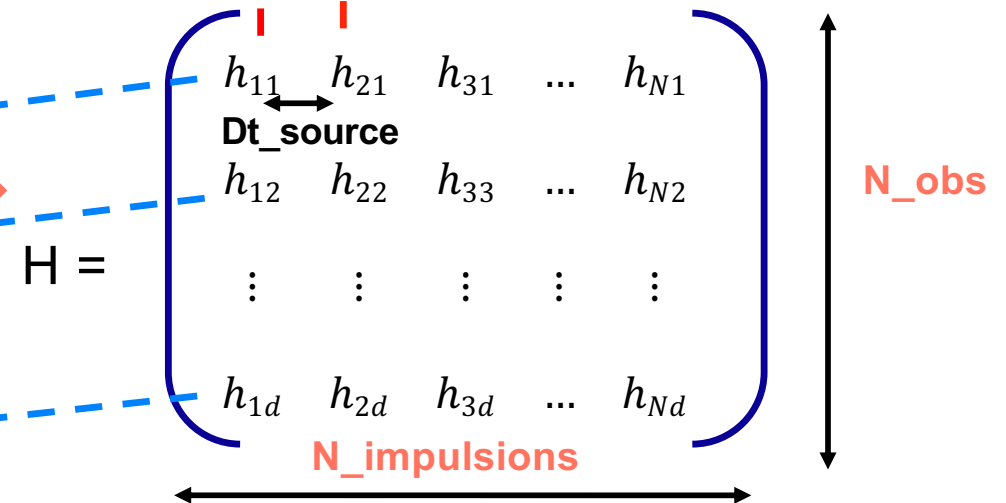
Impulse simulations using the LdX dispersion model



Extraction of concentrations at the stations



Construction of the source–receptor matrix H



Observation vector y

Measurement file

Air concentrations of ^{137}Cs

- Coordinates of the measurement points (latitude/longitude)
- Sampling period (variable, from one day to one week)
- Average air concentration over the sampling period
- Uncertainty on the measured concentration (not systematic)

Country	Title or loc	Lat	Long	Coll. Start	Coll. End	Isotope	Activity	Uncert	Background	Comment	Time zone	Activity unit	Background unit	Uncert unit
Sweden	Stockholm : SI	59,4	17,95	06/09/2024 08:25:35	07/09/2024 08:24:10	Cs-137	1	1	1	Normal level / \ overlaps other observations	UTC	uBq/m3	uBq/m3	%
Sweden	Stockholm : SI	59,4	17,95	07/09/2024 08:25:31	08/09/2024 08:24:10	Cs-137	12	1	1		UTC	uBq/m3	uBq/m3	%
Sweden	Stockholm : SI	59,4	17,95	08/09/2024 08:25:31	09/09/2024 08:24:07	Cs-137	36	1	1		UTC	uBq/m3	uBq/m3	%
Sweden	Stockholm : SI	59,4	17,95	09/09/2024 08:25:29	10/09/2024 08:24:04	Cs-137	7	1	1		UTC	uBq/m3	uBq/m3	%
Sweden	Stockholm : SI	59,4	17,95	10/09/2024 08:25:26	11/09/2024 08:24:09	Cs-137	1	1	1	Normal level	UTC	uBq/m3	uBq/m3	%
Sweden	Stockholm	59,4	17,95	30/08/2024 00:00:00	07/09/2024 00:00:00	Cs-137	5,47	5,40	1	/ \ overlaps other observations	UTC	uBq/m3	uBq/m3	%
Sweden	Kiruna	67,84	20,42	02/09/2024 06:25:00	09/09/2024 09:40:00	Cs-137	8,86	3,20	1	Background level extrapolated from stockholm station	UTC	uBq/m3	uBq/m3	%
Sweden	Kiruna	67,84	20,42	09/09/2024 09:40:00	16/09/2024 04:45:00	Cs-137	4,3	3,00	1	Background level extrapolated from stockholm station	UTC	uBq/m3	uBq/m3	%
Sweden	Kista	59,4	17,95	30/08/2024 10:30:00	07/09/2024 17:28:00	Cs-138	5,5	5,00	1	Background level extrapolated from stockholm station	UTC	uBq/m3	uBq/m3	%
Sweden	Kista	59,4	17,95	07/09/2024 17:28:00	15/09/2024 22:19:00	Cs-138	2,3	4,00	1	Background level extrapolated from stockholm station	UTC	uBq/m3	uBq/m3	%
Sweden	Umea	63,85	20,34	02/09/2024 08:00:00	09/09/2024 10:34:00	Cs-137	2,25	5,60	1	Background level extrapolated from stockholm station	UTC	uBq/m3	uBq/m3	%
Sweden	Umea	63,85	20,34	09/09/2024 10:34:00	16/09/2024 10:30:00	Cs-137	6,2	4,00	1	Background level extrapolated from stockholm station	UTC	uBq/m3	uBq/m3	%
Sweden	Gavle	60,67	17,19	02/09/2024 12:00:00	09/09/2024 17:30:00	Cs-137	5,29	3,40	1	Background level extrapolated from stockholm station	UTC	uBq/m3	uBq/m3	%
Sweden	Gavle	60,67	17,19	09/09/2024 17:30:00	16/09/2024 12:30:00	Cs-137	2,2	5,00	1	Background level extrapolated from stockholm station	UTC	uBq/m3	uBq/m3	%
Sweden	Visby	57,61	18,32	03/09/2024 13:00:00	09/09/2024 09:00:00	Cs-137	9,78	3,40	1	Background level extrapolated from stockholm station	UTC	uBq/m3	uBq/m3	%
Sweden	Visby	57,61	18,32	09/09/2024 09:00:00	16/09/2024 07:30:00	Cs-137	0,4	14,00	1	Background level extrapolated from stockholm station	UTC	uBq/m3	uBq/m3	%
Sweden	Ljungbyhed	56,08	13,22	02/09/2024 08:25:00	09/09/2024 09:00:00	Cs-137	5,04	3,30	1	Background level extrapolated from stockholm station	UTC	uBq/m3	uBq/m3	%
Sweden	Ljungbyhed	56,08	13,22	08/09/2024 09:00:00	16/09/2024 08:10:00	Cs-137	0,2	24,00	1	Background level extrapolated from stockholm station	UTC	uBq/m3	uBq/m3	%
Norway	Stavanger	58,88	5,63	30/08/2024 10:15:00	06/09/2024 09:33:00	Cs-137	0,2	38,00	0,3	Normal level / background level extrapolated from Svanhovd and V	UTC	uBq/m3	uBq/m3	%
Norway	Østerås	59,94	10,6	02/09/2024 09:29:00	09/09/2024 11:46:00	Cs-137	3,3	14,00	0,3	Elevated level / background level extrapolated from Svanhovd and V	UTC	uBq/m3	uBq/m3	%
Spain	Madrid	40,41	-3,69	26/08/2024 00:00:00	05/09/2024 00:00:00	Cs-137	0,266	0,17	0,3	Normal level / Absolute uncertainty	UTC	uBq/m3	uBq/m3	%
Spain	Bilbao	43,26271	-2,9253	13/08/2024 00:00:00	20/08/2024 00:00:00	Cs-137	0,19	0,08	0,3	Normal level / Absolute uncertainty	UTC	uBq/m3	uBq/m3	%
Spain	Bilbao	43,26271	-2,9253	20/08/2024 00:00:00	27/08/2024 00:00:00	Cs-137	0,246	0,08	0,3	Normal level / Absolute uncertainty	UTC	uBq/m3	uBq/m3	%
Spain	Bilbao	43,26271	-2,9253	27/08/2024 00:00:00	03/09/2024 00:00:00	Cs-137	0,171	0,08	0,3	Normal level / Absolute uncertainty	UTC	uBq/m3	uBq/m3	%
Spain	Bilbao	43,26271	-2,9253	03/09/2024 00:00:00	10/09/2024 00:00:00	Cs-137	0,194	0,08	0,3	Normal level	UTC	uBq/m3	uBq/m3	%
Spain	Bilbao	43,26271	-2,9253	10/09/2024 00:00:00	17/09/2024 00:00:00	Cs-137	0,35	0,08	0,3	Normal level	UTC	uBq/m3	uBq/m3	%

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}$$

Minimization of the cost function $\mathcal{J}$:

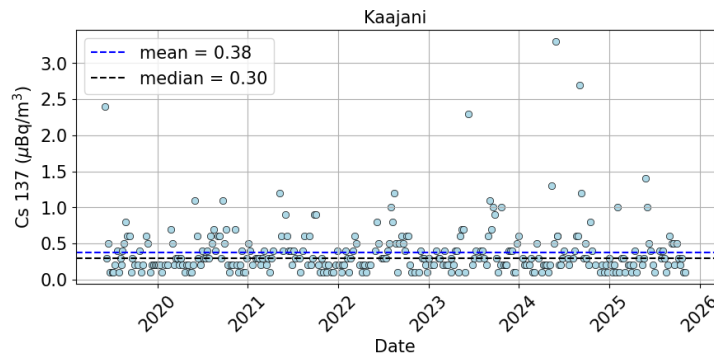
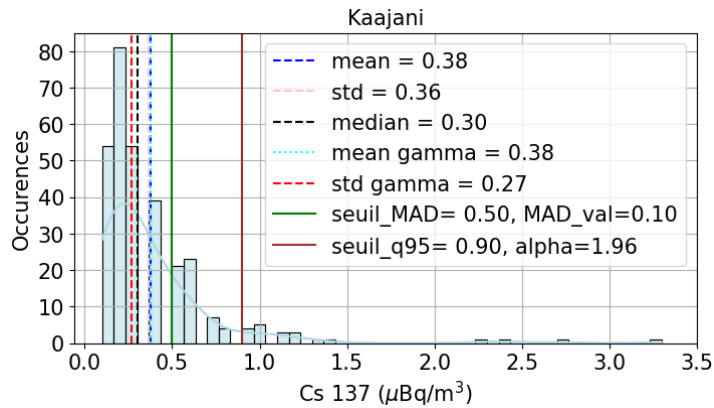
$$\mathcal{J}(x) = \|y - Hx\|_{R^{-1}}^2 + \|x - x_b\|_{B^{-1}}^2$$

Résolution numérique :

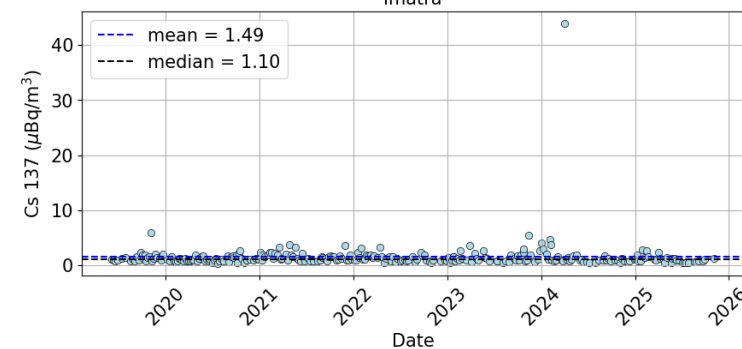
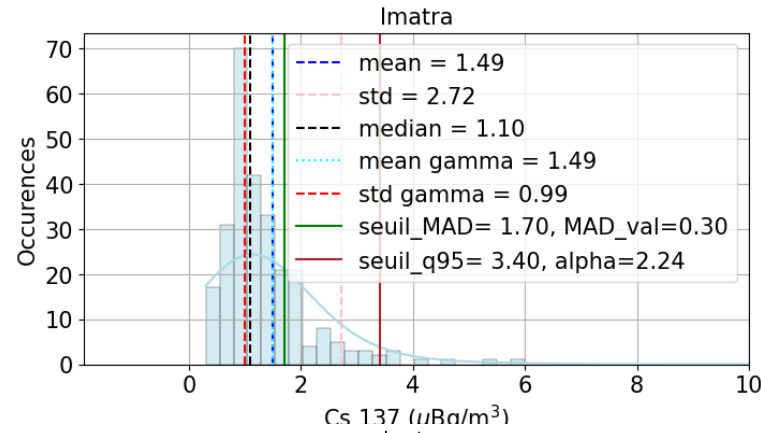
- $N_{\text{var}} > N_{\text{obs}}$: computationally expensive solution; additional constraints are required
- $N_{\text{var}} < N_{\text{obs}}$: solved using a gradient descent algorithm, specifically the **L-BFGS-B** method

Observation processing

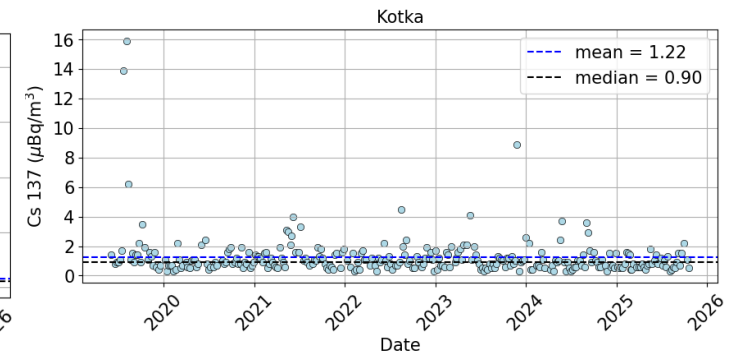
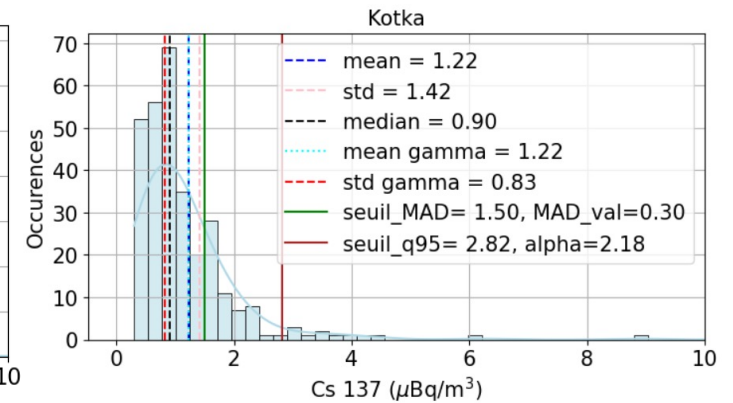
- 2019 - 2025
- 304 observations



- 2019 - 2025
- 268 observations



- 2019 - 2025
- 302 observations



Scatter plot (top) and histogram (below) of volumetric activities for (Kaajani, Imatra, et Kotka) in Finland.

Observation processing

Decision threshold calculation (TD)

Gamma distribution

- Estimation of the distribution parameters through gamma-distribution fitting
- calculation of the decision threshold based on the 90% target quantile of the fitted gamma distribution

$$TD = q_{\text{target_quantile}}$$

Mediane Absolute Deviation (MAD)

- Estimation of the MAD from the dataset
- Calculation of the decision threshold based on a standard-deviation equivalent

$$TD = \text{Background} + k \cdot \text{MAD}$$

$$\text{where } \sigma = K \cdot \text{MAD}$$



Background (BL) soustraction

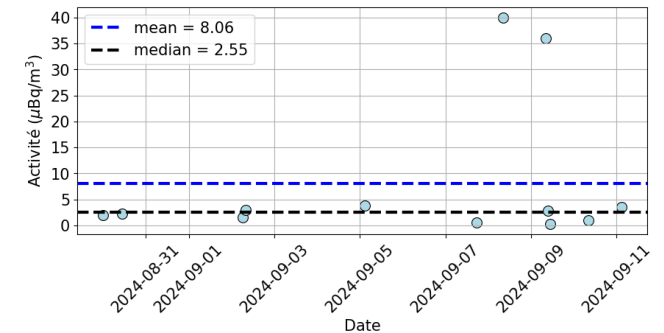
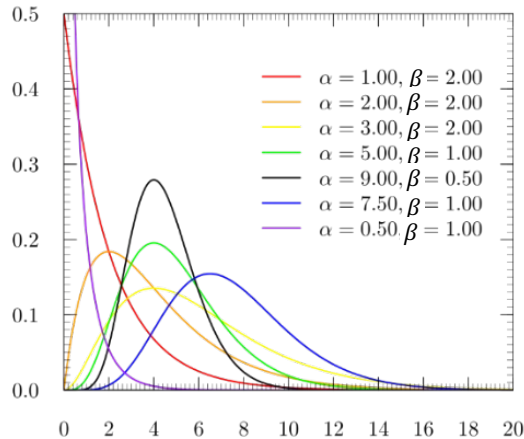
Concentration > TD

YES

NO

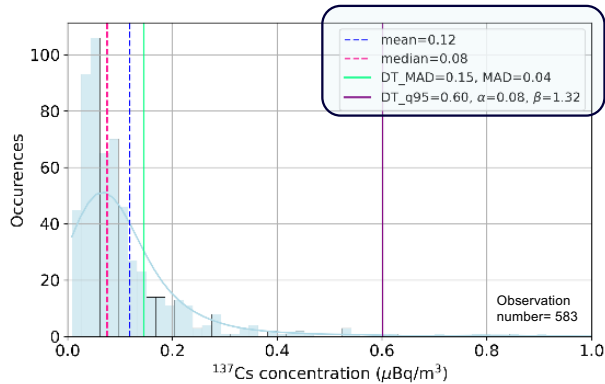
Concentration
=
Concentration - BL

Concentration = 0

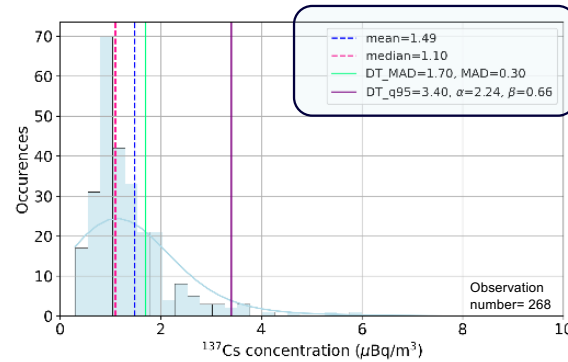


Observation processing

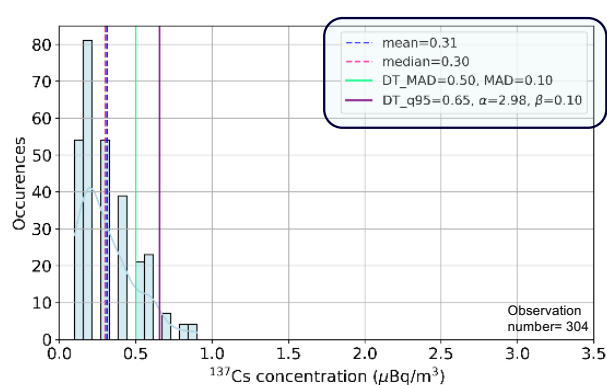
OPERA TGD Network - France



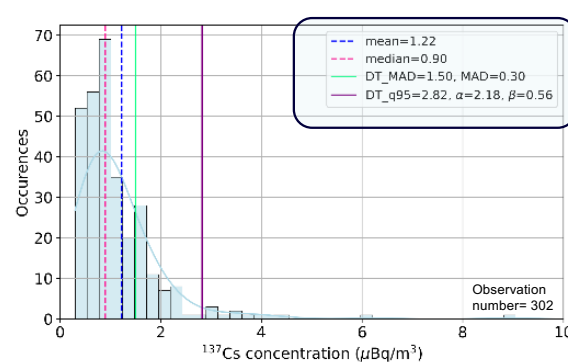
Imatra Network - Finland



Kaajani Network - Finland



Kotka Network - Finland



Limitations :

- The estimated parameters differ from one station to another for both the Gamma and MAD approaches
- Ideally, these parameters should be characterized individually for each station, when statistics allow ,to ensure an accurate background-level subtraction.

Addressing the limitations :

Gamma law

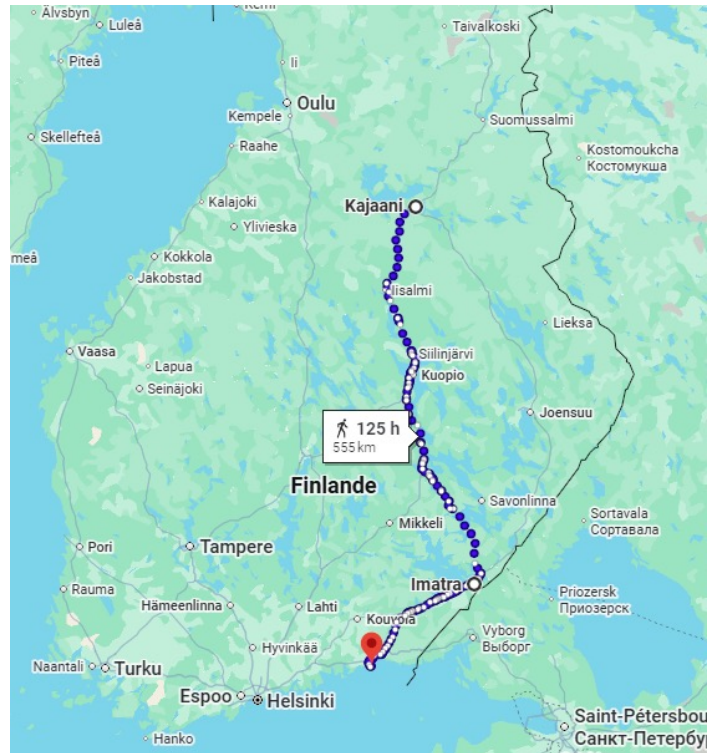
1. Assume a fixed shape parameter $\alpha = 2$ for all European stations.
2. Estimate β from the Background Level using:
$$\beta = BL/\alpha$$
3. Decision threshold for each station

MAD law

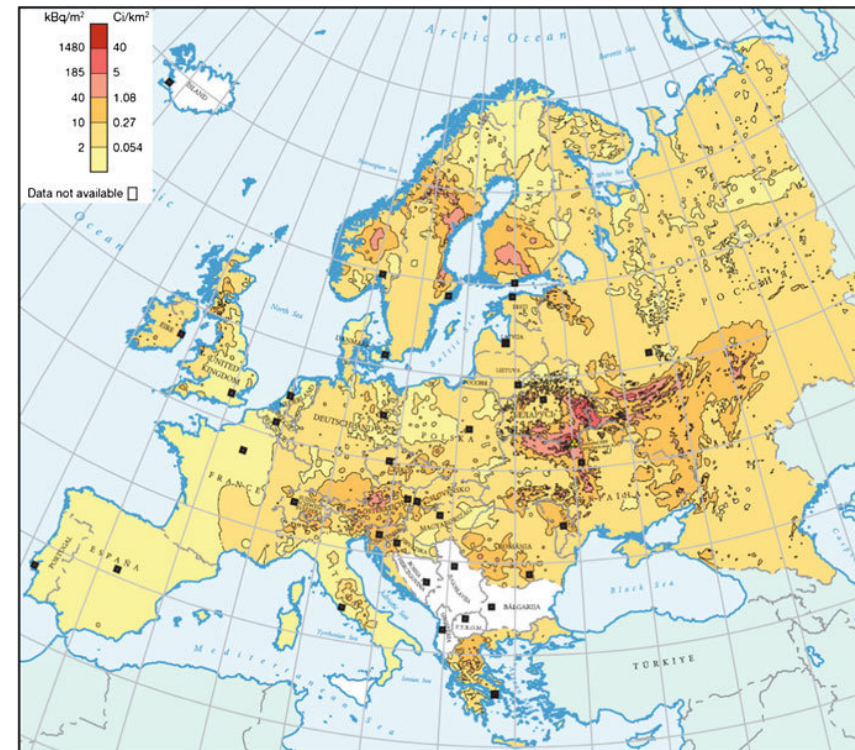
1. Assume a constant MAD = 0.1 for all European stations.
2. Decision threshold for each station

Histogram of volumetric activities for all monitoring stations in France and for the Imatra, Kajaani, and Kotka stations in Finland

Observation processing



Location of Kajaani, Imatra and Kotka according to Google Maps



Distribution map of Cs-137 in Europe (IAEA)

→ The background level of Cs 137 varies from one station to another.