Atmospheric Transport Modelling (ATM) in support of radionuclide monitoring: an overview of operational capacities.

Generoso S., Achim P., Gross P., Morin M., Topin S.

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11 September 2025

Generoso S., Achim P., Gross P., Morin M., Topin S.

Outline

A BRIEF INTRODUCTION

Atmospheric Transport Modelling (**ATM**) in the context of CTBTO

- ➢ Main two objectives
- ➢ Main two challenges

FROM STUDIES TO OPERATIONAL CAPACITIES

An overview of studies conducted over the last ten years, presented at past SnT

- ➢ How they have supported the verification work of National Data Centres (**NDCs**)

OPERATIONAL CAPACITIES

TODAY

- ➢ Examples of progress made over the last ten years, from ~ 2013 (3rd DPRK) to today

PERSPECTIVES

- ➢ Some highlights from SnT2023 and SnT2025

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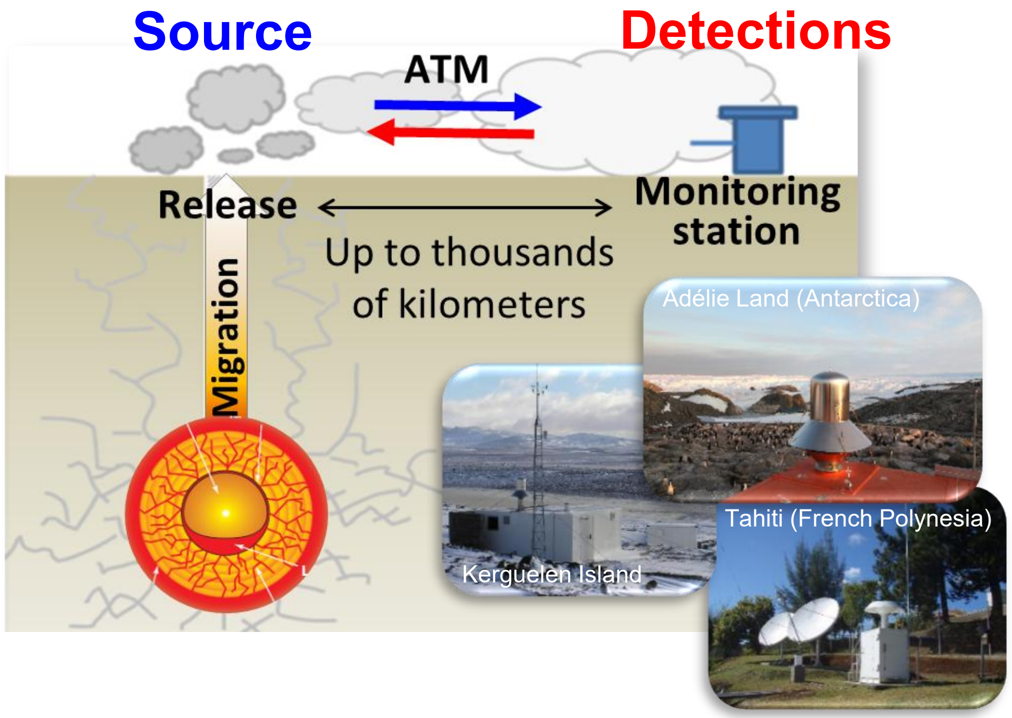
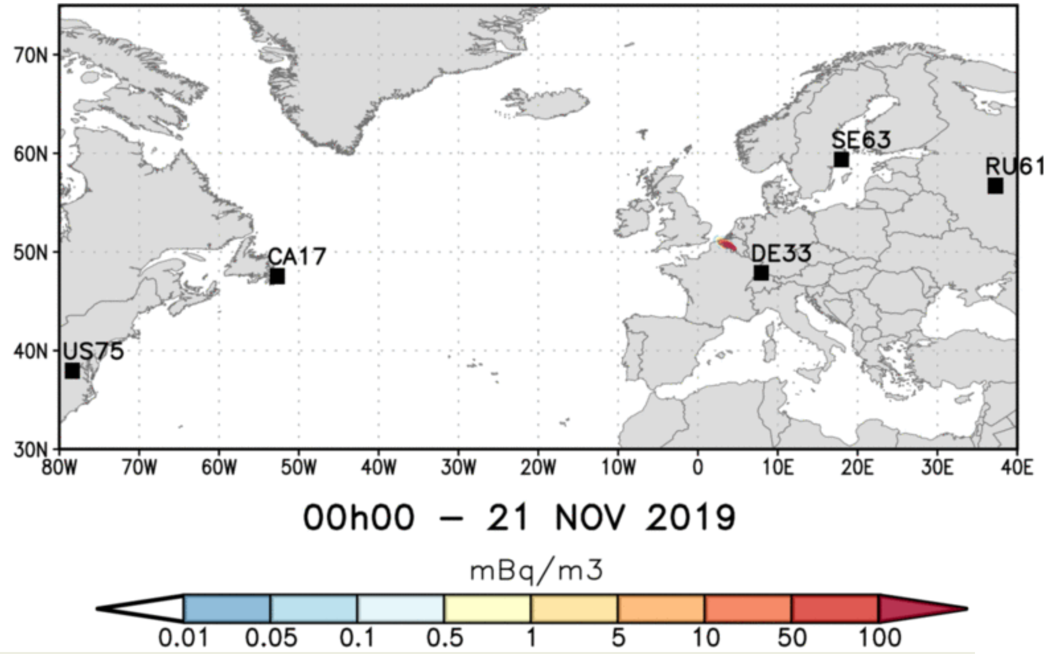
ATM in the context of CTBTO



Atmospheric dispersion of a fictitious release of ^{133}Xe calculated over 8 days



✓ ATM is used in NDCs to help discriminate the origin of the radioactivity detected on the International Monitoring System (**IMS**), be it particles or nobles gases, and provide :

- **Source localisation** (release location, amount and date)
- Contribution of background sources

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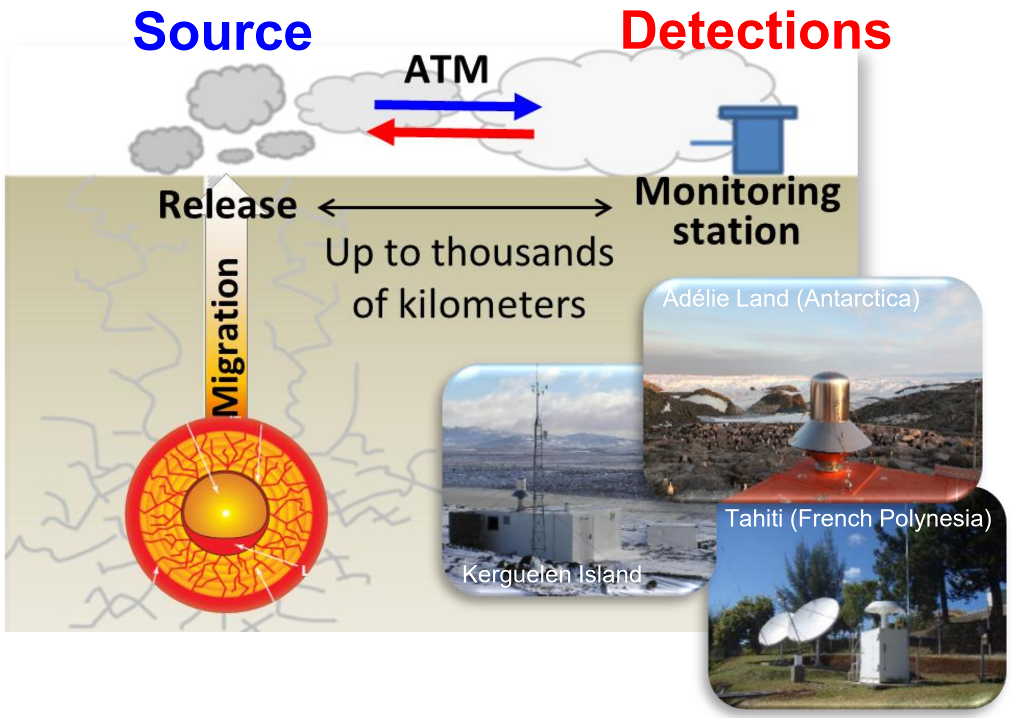
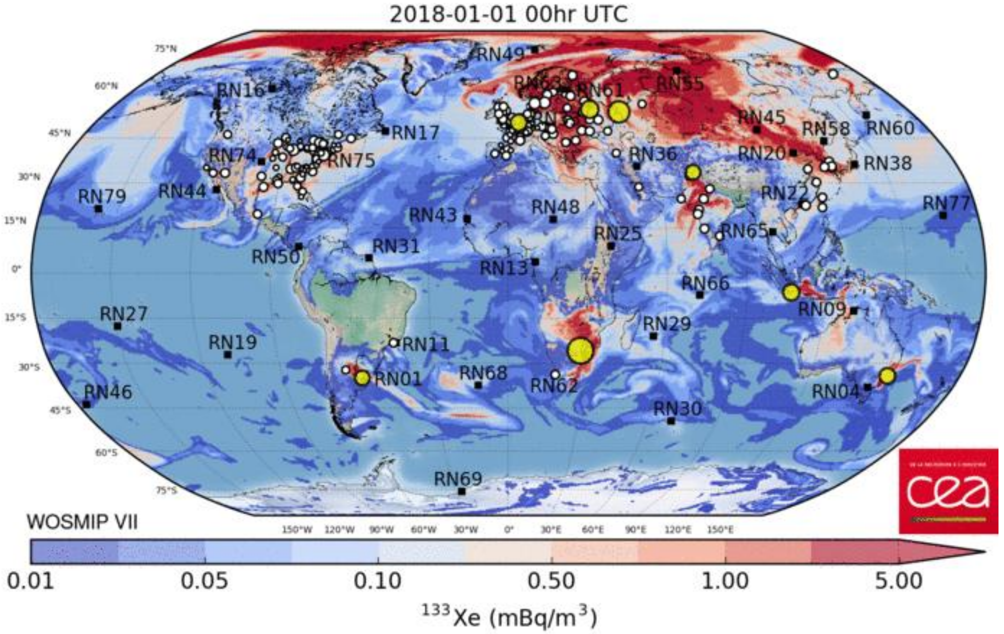


Expected industrial background of ^{133}Xe calculated with a priori emissions



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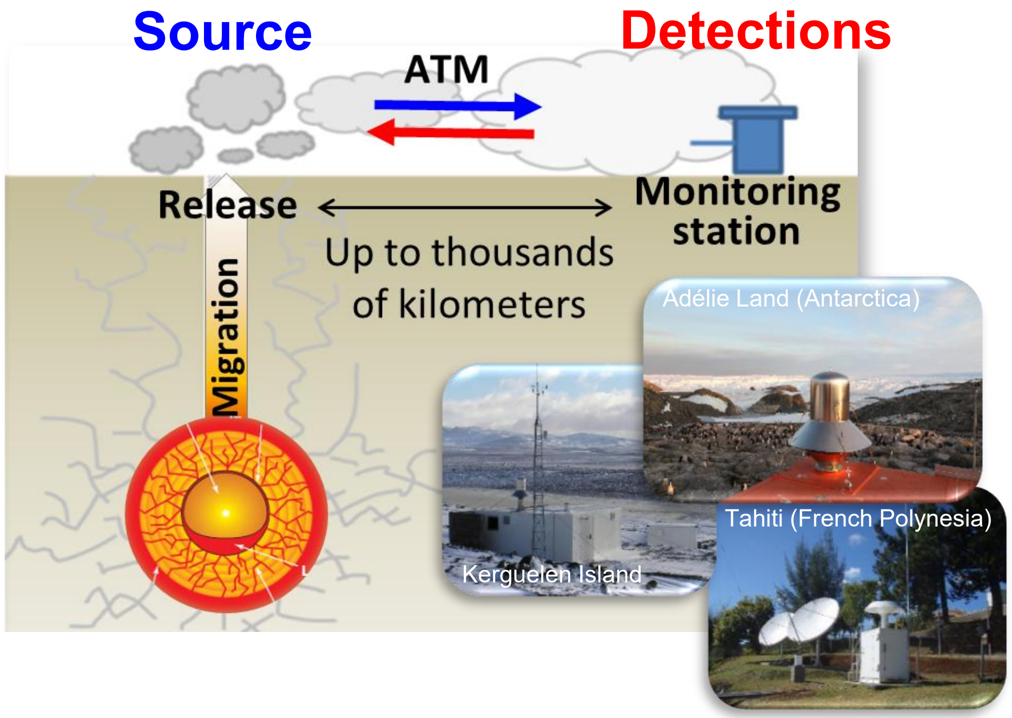
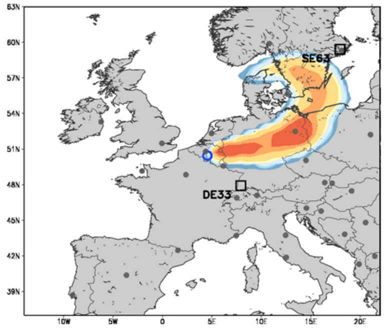


FORWARD

Meteorological data → DISPERSION CODE → CONCENTRATIONS

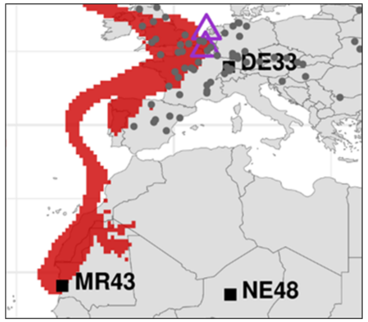
Description of sources → DISPERSION CODE



BACKWARD

Meteorological data → DISPERSION CODE | LOCALISATION CODE → SOURCE LOCALISATION

Detections → DISPERSION CODE | LOCALISATION CODE



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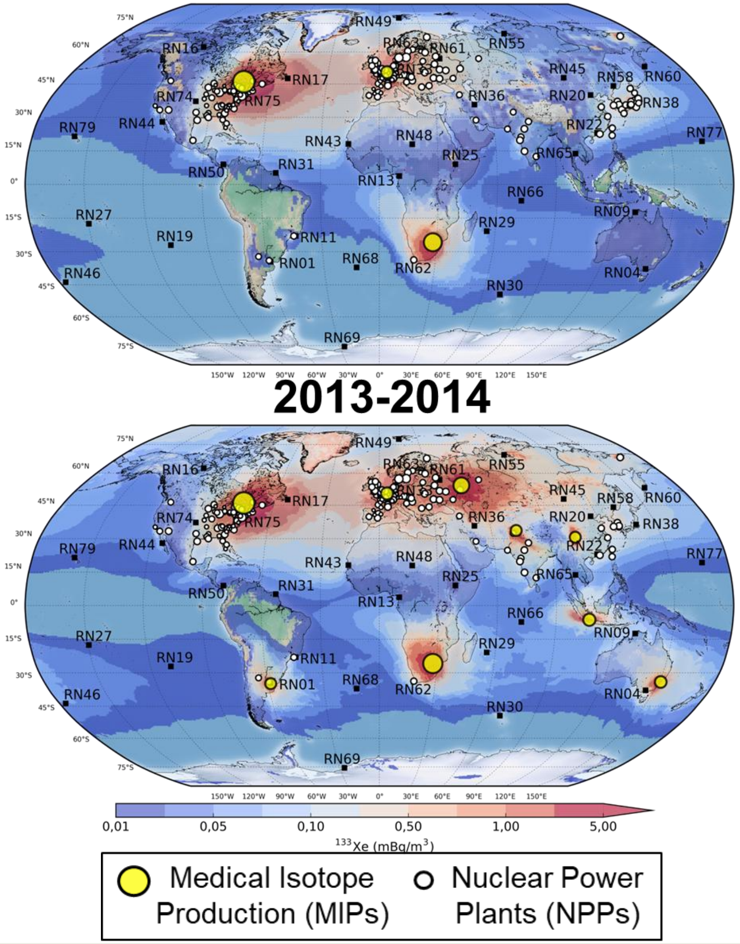
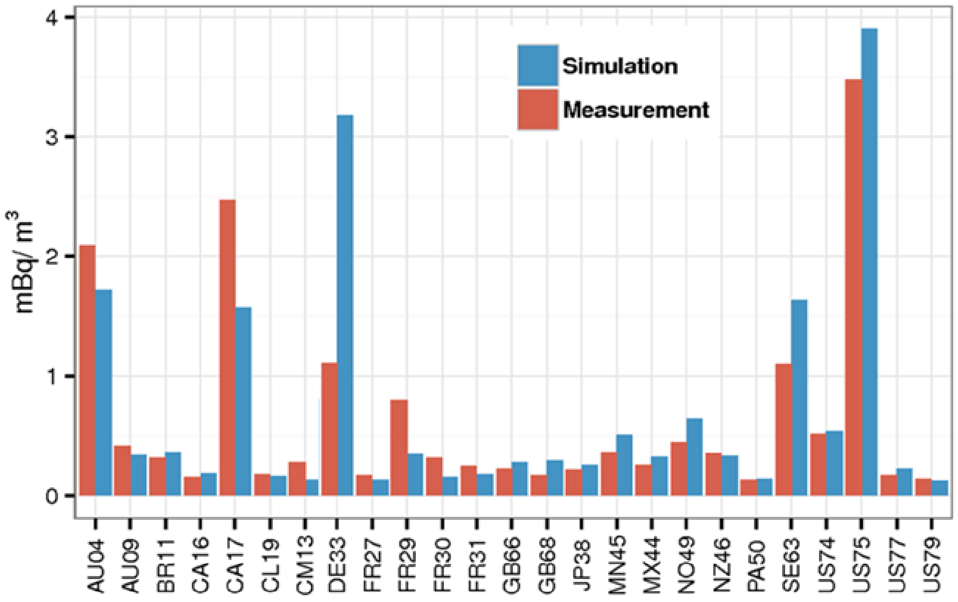
The challenge of industrial radioxenon background

Achim et al., SnT 2011
Achim et al., SnT 2015





FROM MEASUREMENTS

^{133}Xe from industrial activities is regularly detected worldwide by the IMS and could interfere with the detection of releases from nuclear tests.

FROM ATM IN ~ 2010-2013

Simulation reproduces, on average, the global distributions of the measured background, factoring in the main medical isotope production facilities and nuclear power plants worldwide. Daily variability remains a challenge.

ACHIM ET AL. 2016 *J. of Geophys. Res. Atmos.*
WOTAWA ET AL 2010 *Pure Applied Geophysics*

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The challenge of uncertainty in ATM

Reducing uncertainties

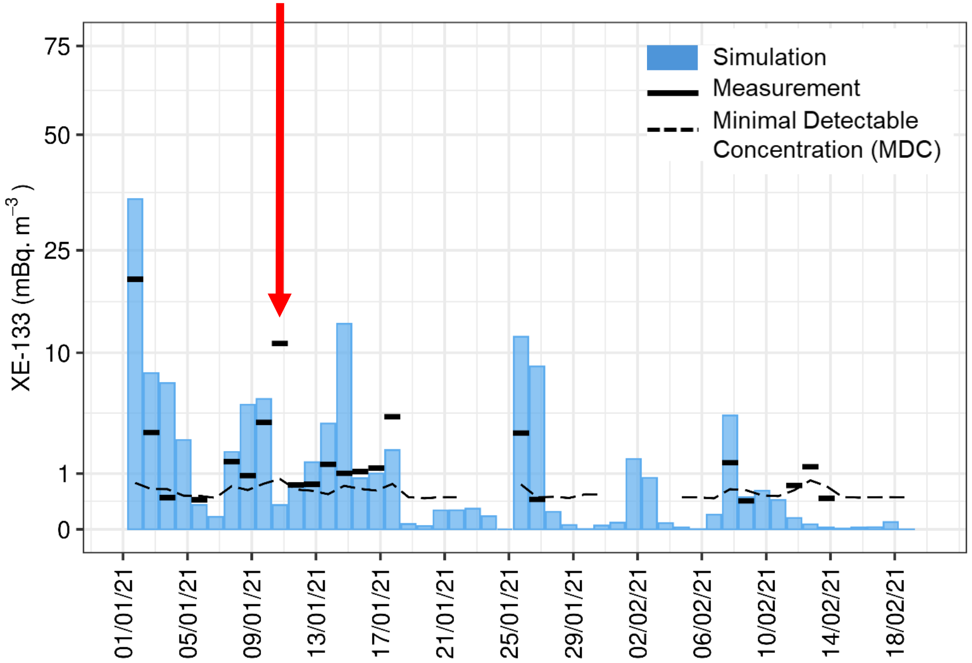
Take into account data, physics, process to better represent, e.g.

- ➢ Emissions
- ➢ Meteorological information,
- ➢ Model description (deposition, radioactive decay, etc.)

Mekhaimr and Wahab 2019
Sources of uncertainty in atmospheric dispersion modeling in support of Comprehensive Nuclear–Test–Ban Treaty monitoring and verification system
Atmospheric Pollution. Research

See an example in
Adenis et al., SnT 2025 *(P2.3-296)*

Missing source ?
Meteorological uncertainty ?
Model uncertainty ?



*Simulated versus measured **concentrations** at IMS station DEX33 (Germany)*

Quantifying uncertainties

Provide a quantitative information on the certainty of the results, e.g.

- ➢ Confidence, credible intervals
- ➢ Probability of occurrence
- ➢ Range of values, “Error bars”

From ATM in ~ 2013

A discrepancy in simulation results remains a challenge to attribute to a missing source, model or meteorological uncertainty in an operational context.

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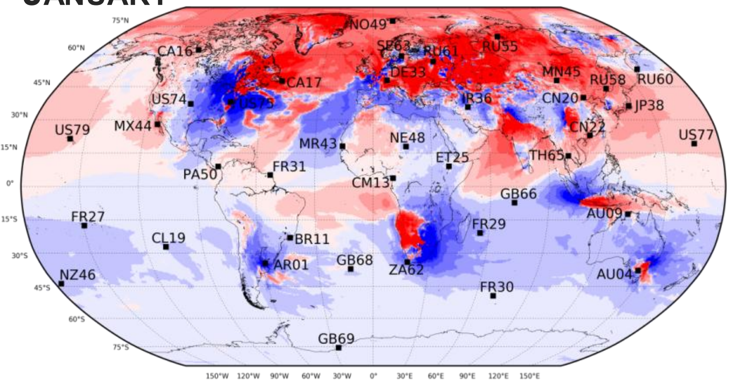
FROM STUDIES TO OPERATIONAL

Ke03

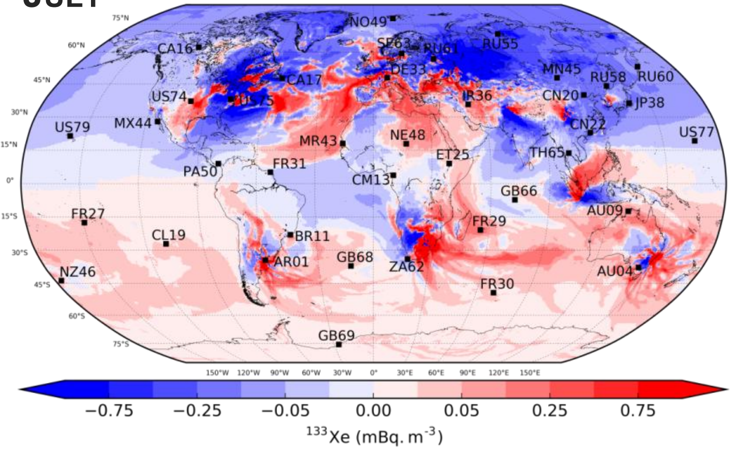
Industrial ^{133}Xe background : from global to seasonal distributions

Generoso et al., SnT 2017

JANUARY

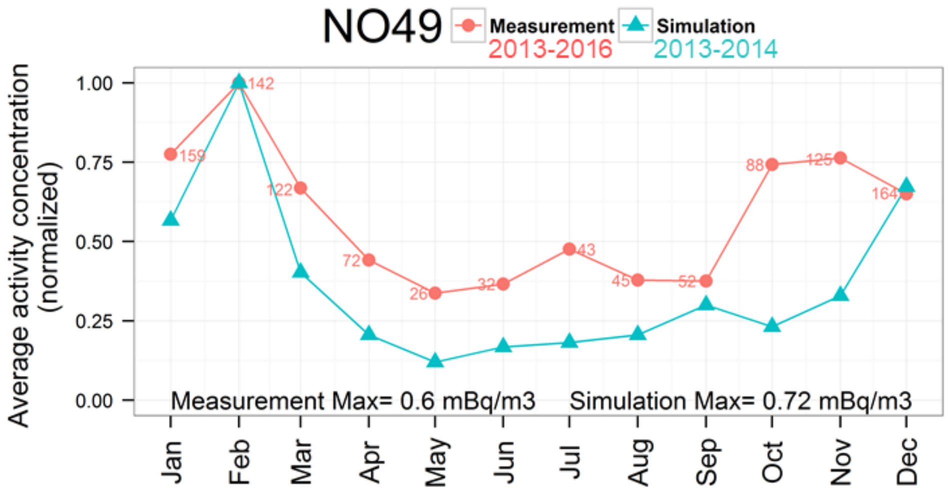


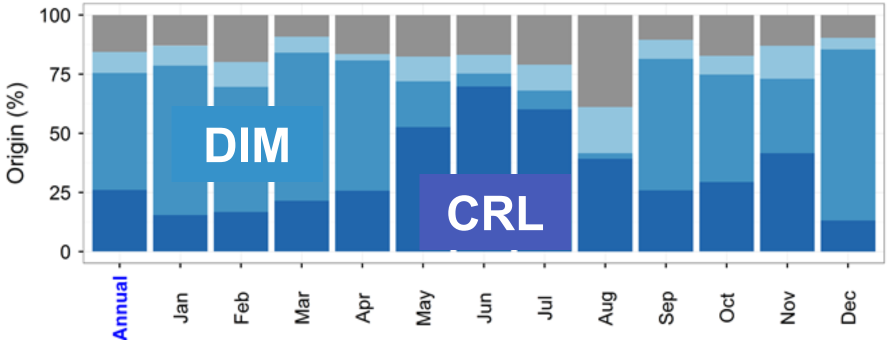
JULY



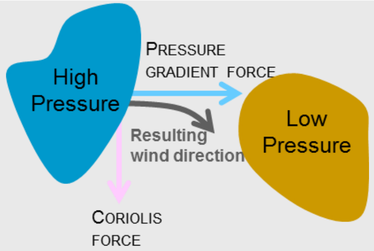
Monthly – annual means

GENEROSO ET AL. **2018** *J. of Geophys. Res. Atmos.*





SCHEMATIC OF THE ATMOSPHERIC CIRCULATION



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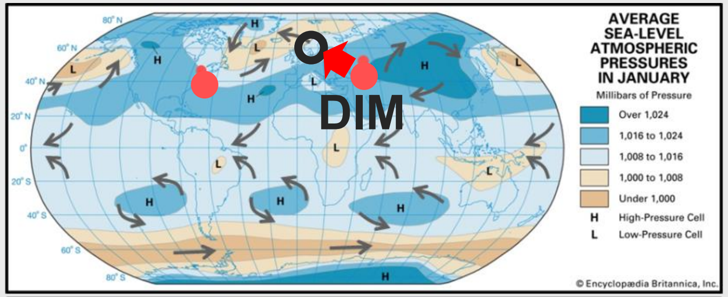

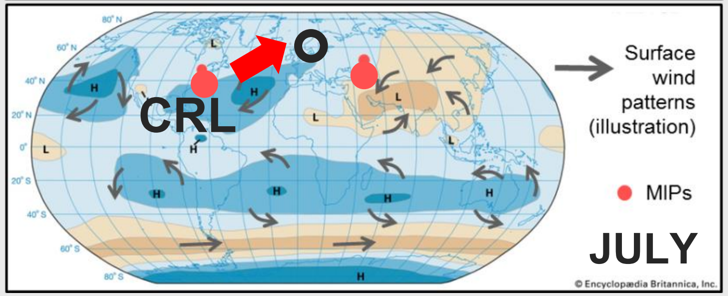

At first order, the seasonal variations of the atmospheric circulation explain the variability of ^{133}Xe measured and the variability of contributors. This knowledge helps build a pattern of “usual” or expected detections.

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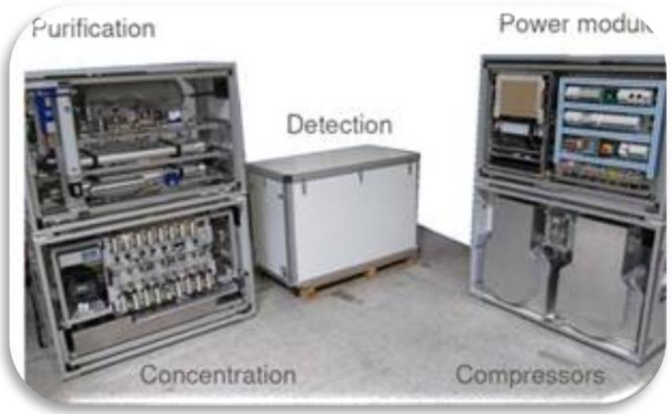
FROM STUDIES TO OPERATIONAL

Ke03

Industrial ^{133}Xe background : Evidence of secondary and local contributions

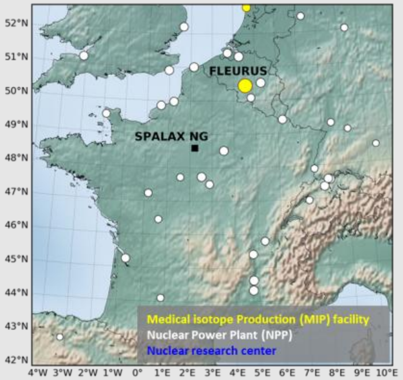
Achim et al., SnT 2021

Six months of SPALAX NG data near Paris (Oct. 2018 - Apr. 2019) as part of the system qualification process by the CBTO.



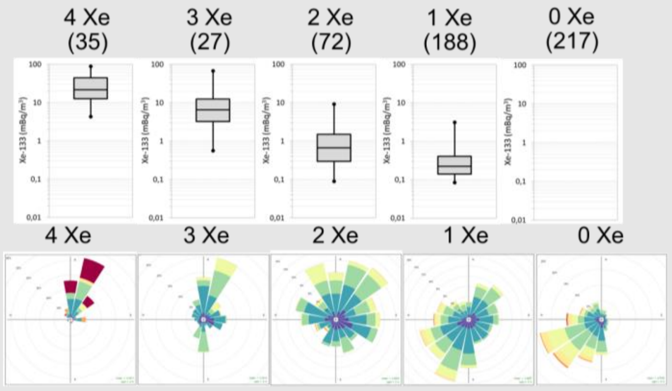
TOPIN ET AL 2020 *J. of Env. Rad.*
ACHIM ET AL 2021 *J. of Env. Rad.*

➔ Unprecedented number of multi isotope detections



Confirmation of Fleurus facility as the main source of multi isotope detections with large levels of ^{133}Xe in Paris area.

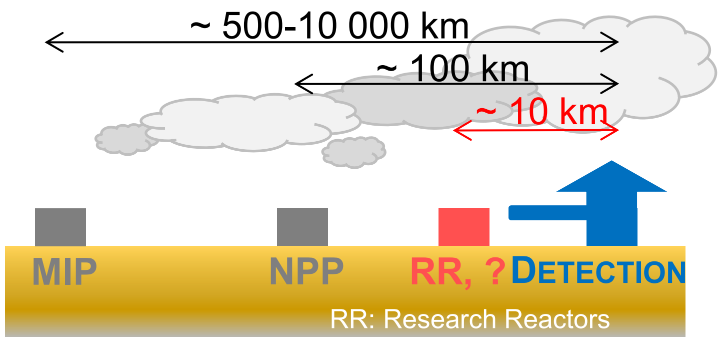
Distribution of ^{133}Xe activity concentrations for spectra sorted by number of detected isotope



Dominant wind direction : direct pathways from Fleurus | No dominant : worldwide background | Not related to Fleurus

➔ Detections of events such as ^{131m}Xe measured alone, not related to Fleurus medical isotope production.

Multiple scale Atmospheric transport



NG systems reveal events undetected before and suggest the contribution of local sources that remain a challenge to identify.

See Ringbom et al., SnT 2025 (P3.6-394)
Liljegren et al., SnT 2025 (O3.6-547)
Goodwin et al., SnT 2025 (O3.6-799)

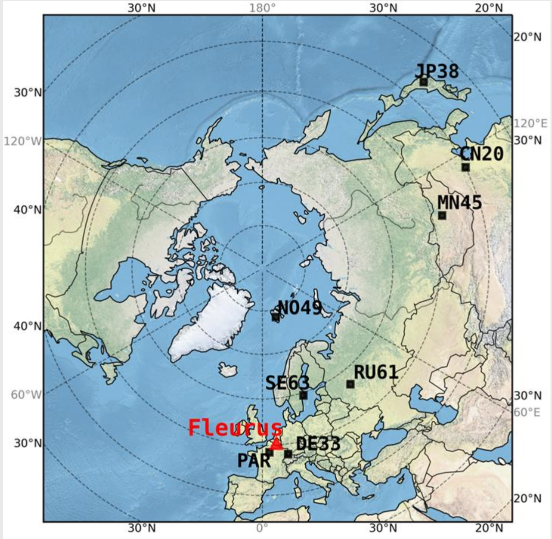
Industrial ^{133}Xe background : Reducing uncertainties in emissions

Friese et al., SnT 2019 (PNNL)

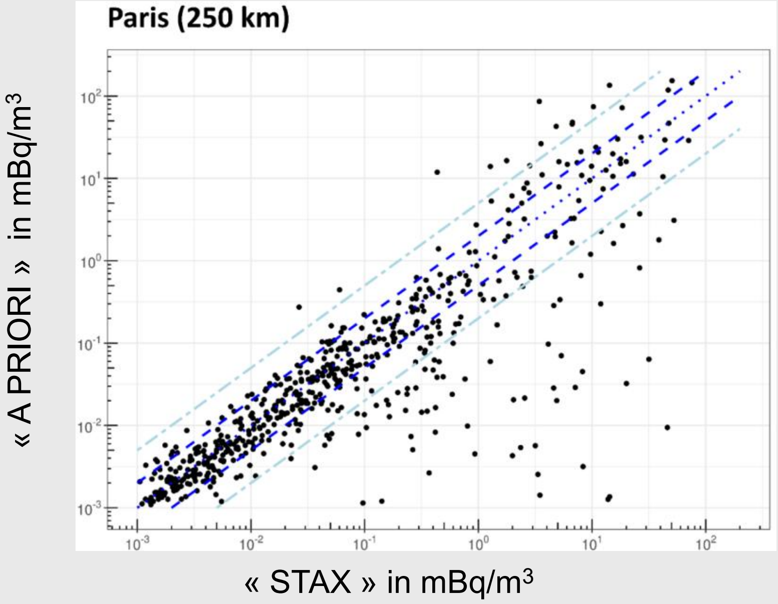
STAX Source Term Analysis of Xenon

Voluntary partnerships with facilities to monitor and provide real emission data to NDCs, led by PNNL
www.wosmip.org/stax

Simulations with/without Fleurus (Belgium) real emissions over a period of 1 year (June 2020-April 2021)



GENEROSO ET AL. 2022 *J. of Env. Radioactivity*



The knowledge of real emissions reduces uncertainties in ATM and allows to “fix” one degree of uncertainty to focus on the others, such as meteorological uncertainties, and this is an invaluable insight to validate ATM.

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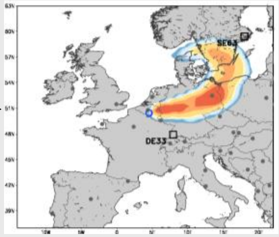
Industrial ^{133}Xe background : Quantifying meteorological uncertainty

Generoso et al., SnT 2023

DETERMINISTIC APPROACH (NCEP/GFS)

Meteorological data → Dispersion Code →



→ **1 result**

ENSEMBLE APPROACH (NCEP/GEFS)

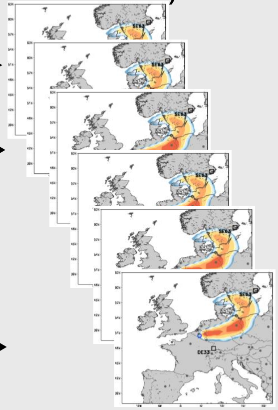
Meteo. data « Control » c00 → Dispersion Code →

Meteo. data « Control » p01 → Dispersion Code →

. . .

Meteo. data « Control » p30 → Dispersion Code →

31 simulations

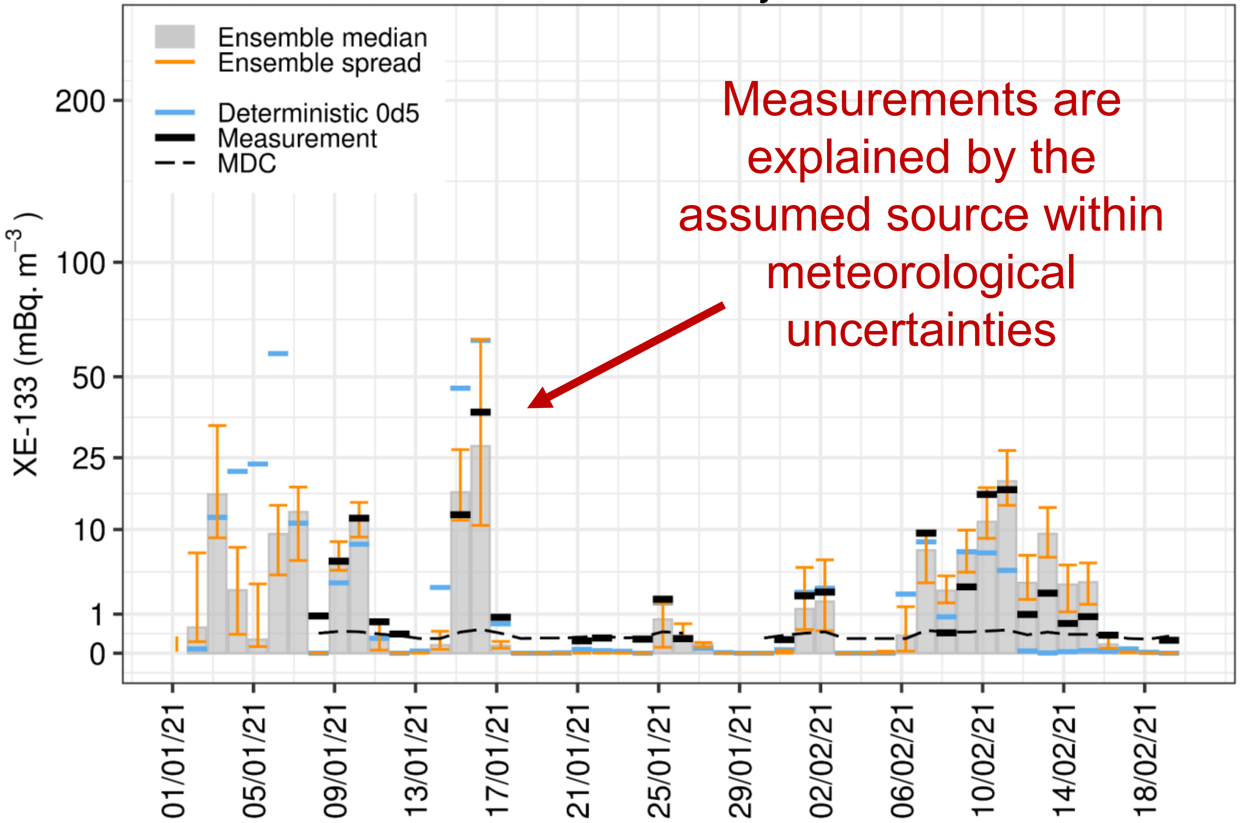


→ **A set of results. All equiprobable**

which differ (only) in the input meteorological data, "perturbed" to represent the range of uncertainties

MAURER ET AL. 2021 *J. of Env. Rad.*
DE MEUTTER & DELCLOO. 2022 *J. of Env. Rad.*
LEADBETTER ET AL. 2022 *Atmos. Chem. and Physics*

Simulated versus measured activity concentrations ***at Paris***



Simulations include only one source of background (Fleurus with STAX real emission data)

Ensemble methods allows to quantify uncertainty, which is decisive for discrimination with ATM results.

GENEROSO ET AL. 2023 *J. of Env. Radioactivity*

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FROM STUDIES TO OPERATIONAL

Ke03

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Generoso et al., SnT 2023

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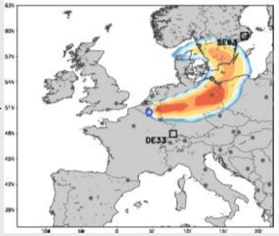

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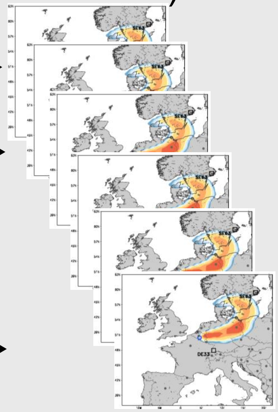

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MAURER ET AL. 2021 *J. of Env. Rad.*
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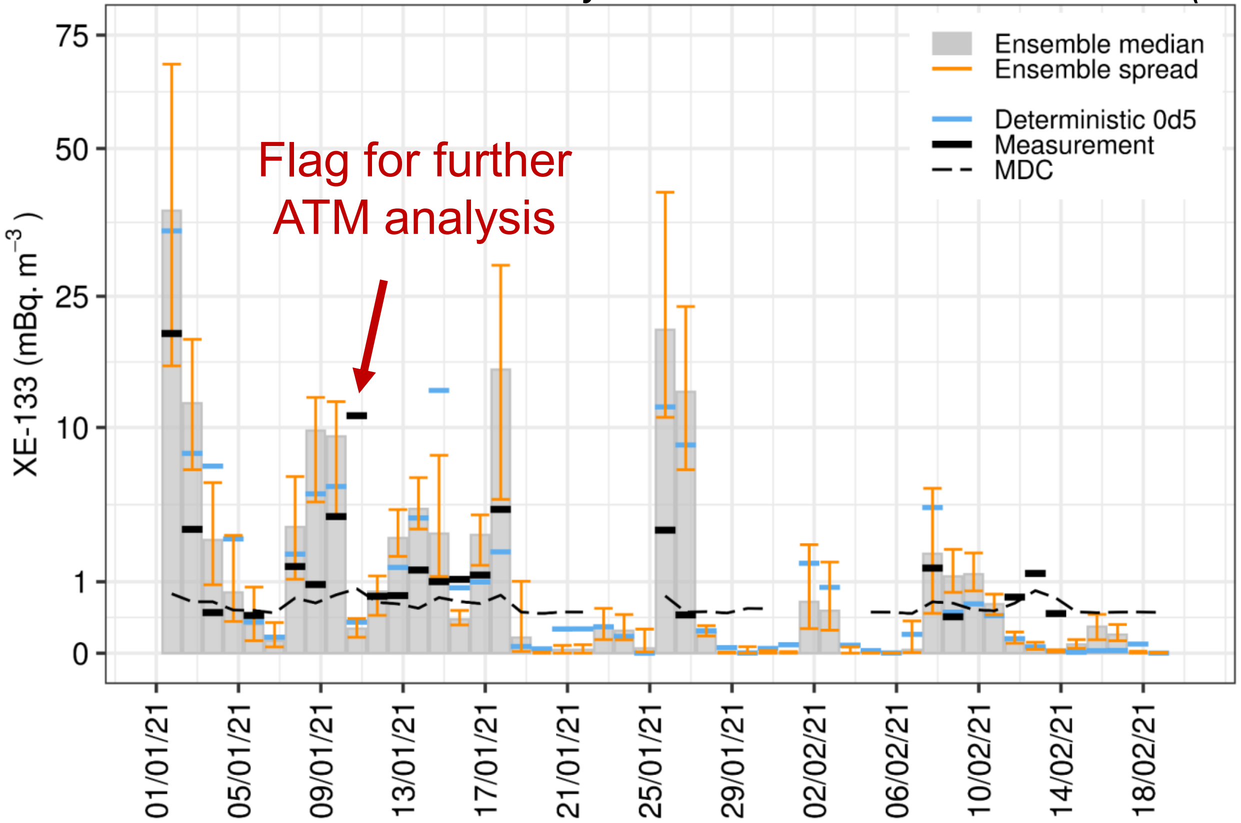
LEADBETTER ET AL. 2022 *Atmos. Chem. and Physics*

Simulated versus measured activity concentrations at ***IMS DEX33*** *(Germany)*



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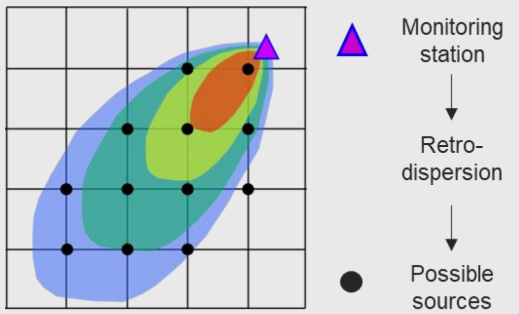
FROM STUDIES TO OPERATIONAL

Ke03

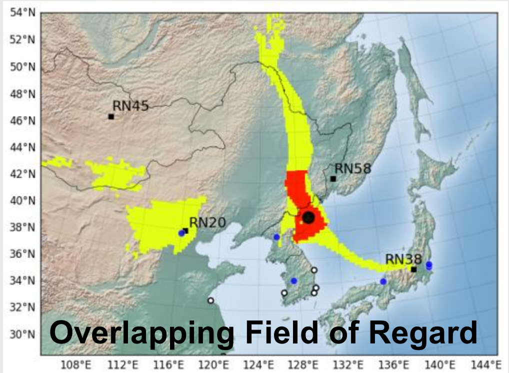
Localisation : from overlapping plumes to statistical optimisation

De Meutter et al., SnT 2019 (SCK-CEN)
De Meutter et al.,SnT 2023 (SCK-CEN)
Generoso et al., SnT 2025 (P3.6-347)



Which possible sources is most probable ?

DETERMINISTIC	PROBABILISTIC
FOR/PSR Cost Function	**Bayesian inference**



Localisation with Possible Source Region (correlation)

Localisation with Cost function

Localisation with Bayesian inference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A. Ringbom, A. Axelsson, M. Aldener, M. Auer, T.W. Bowyer, T. Fritioff, I. Hoffman, K. Khrustalev, M. Nikkinen, V. Popov, Y. Popov, K. Ungar, G. Wotawa


www.nature.com/scientificreports
SCIENTIFIC REPORTS
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Source localisation and its uncertainty quantification after the third DPRK nuclear test
Pieter De Meutter, Johan Camps, Andy Delcloo & Piet Termonia


Journal of Environmental Radioactivity 273 (2024) 107372
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ELSEVIER
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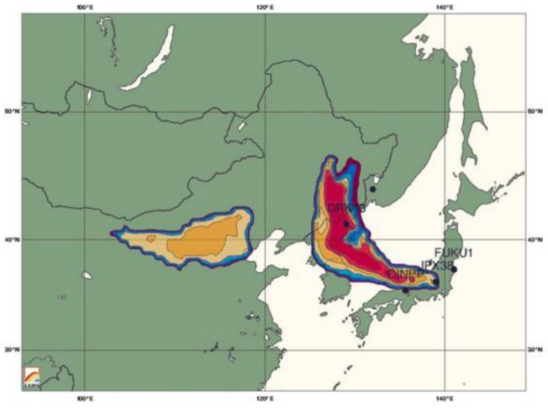
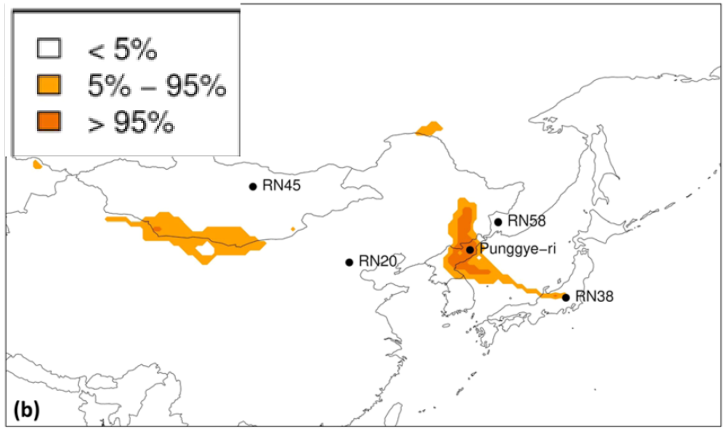
Pieter De Meutter *, Ian Hoffman, Andy W. Delcloo



FROM RINGBOM ET AL 2014, *Journal of Env. Radioactivity*



FROM DE MEUTTER ET AL 2018, *Scientific Reports*

Source localisation now also relies on statistical optimisation, enabling reconstruction of source terms and uncertainty quantification.

DE MEUTTER ET AL 2024, *Journal of Env. Radioactivity*

cea

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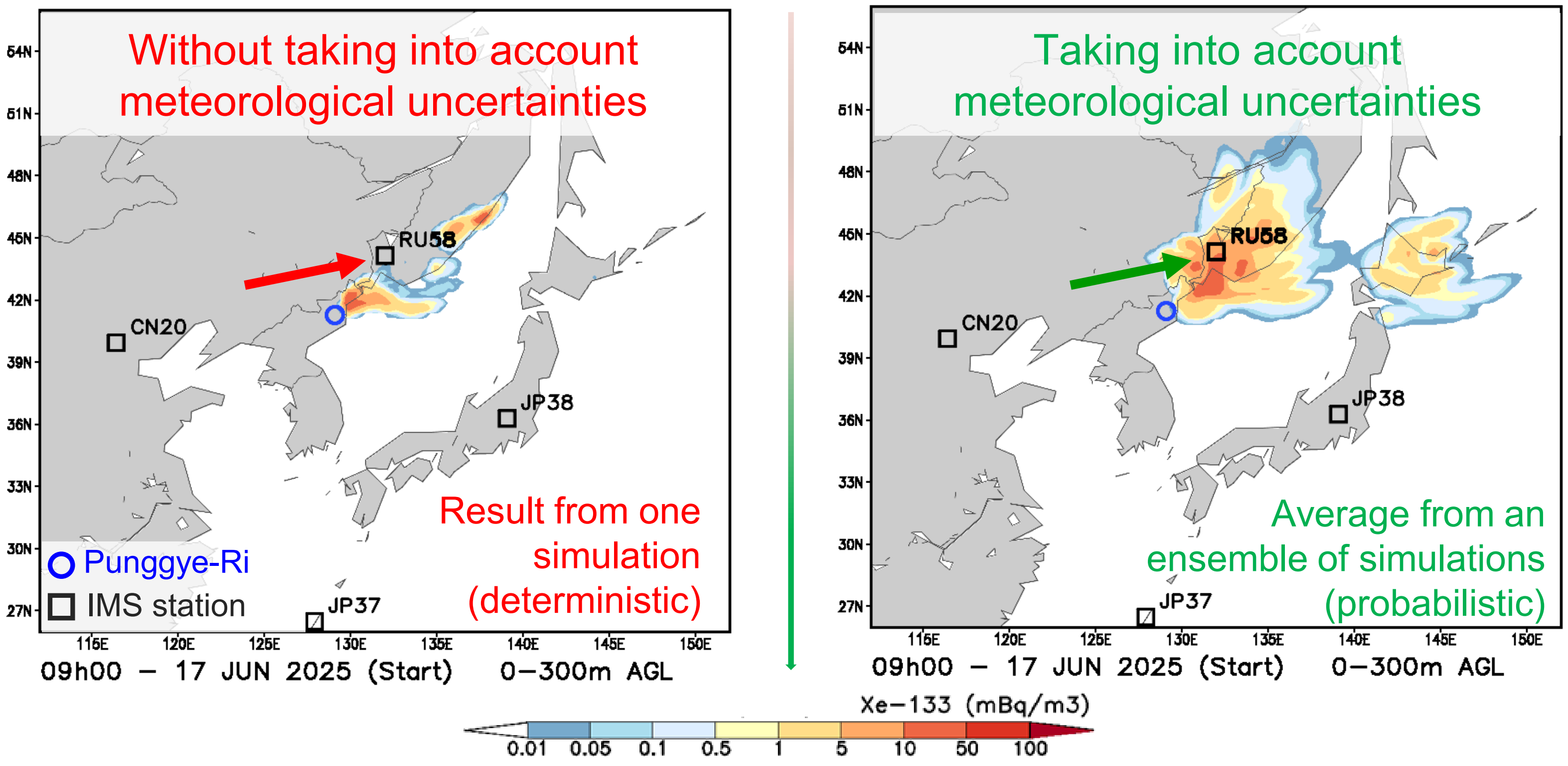
Uncertainty quantification : automated & real-time simulation triggered by waveforms

2013

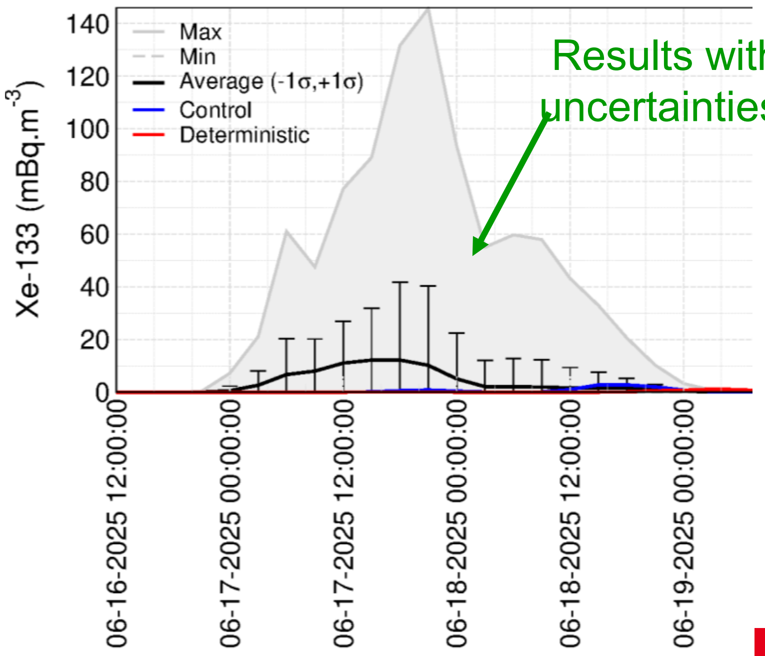
2025

Atmospheric dispersion of a fictitious release from Punggye-Ri, triggered by seismic location and taking into account meteorological uncertainties

Position of the plume of ^{133}Xe 39 hours after the fictitious release



Predicted activity concentrations at RN58



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Industrial ^{133}Xe background : automated & real-time simulation

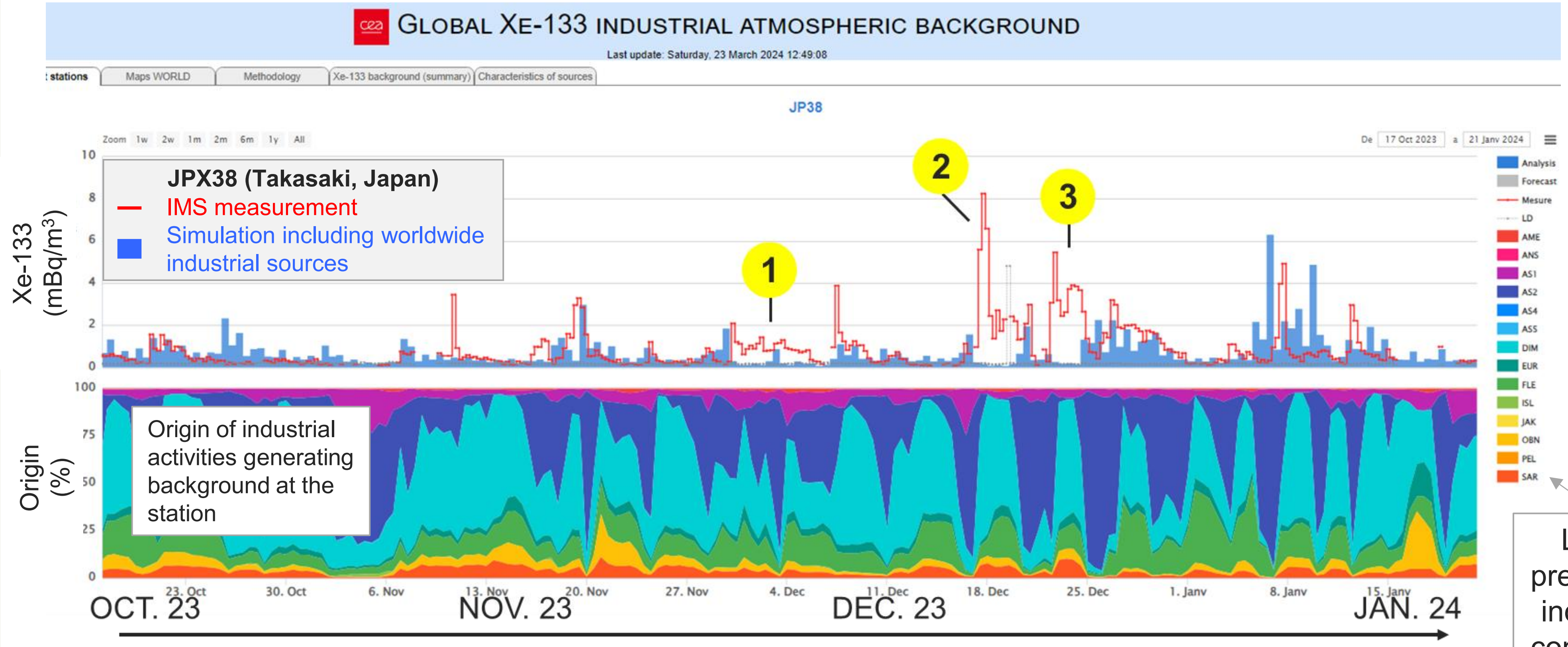
2013

Not available in real-time

Categorisation of ^{133}Xe detection based on predicted industrial background, calculated at every IMS station in real-time (automated)

2025

Available in real-time and with 4-day forecast



List of predefined industrial contributor

Events labelled 1 2 3 are not attributed to usual industrial activities
=> Further ATM and localisation analysis is conducted.

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Localisation with statistical optimisation : map of likely area

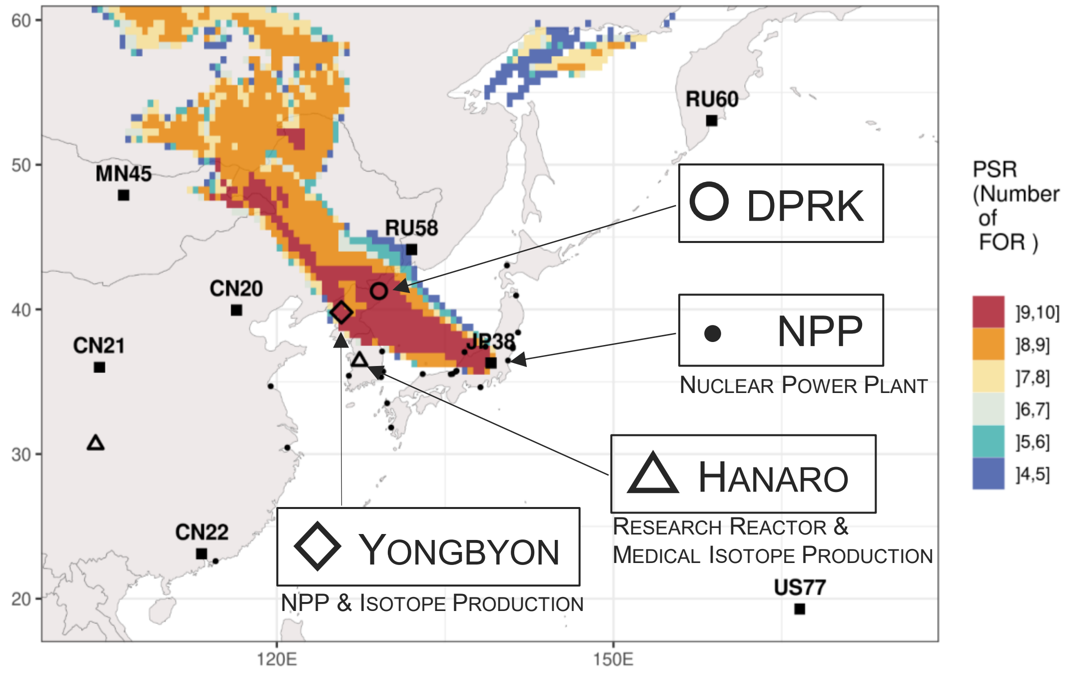
2013

Localisation with overlapping FOR

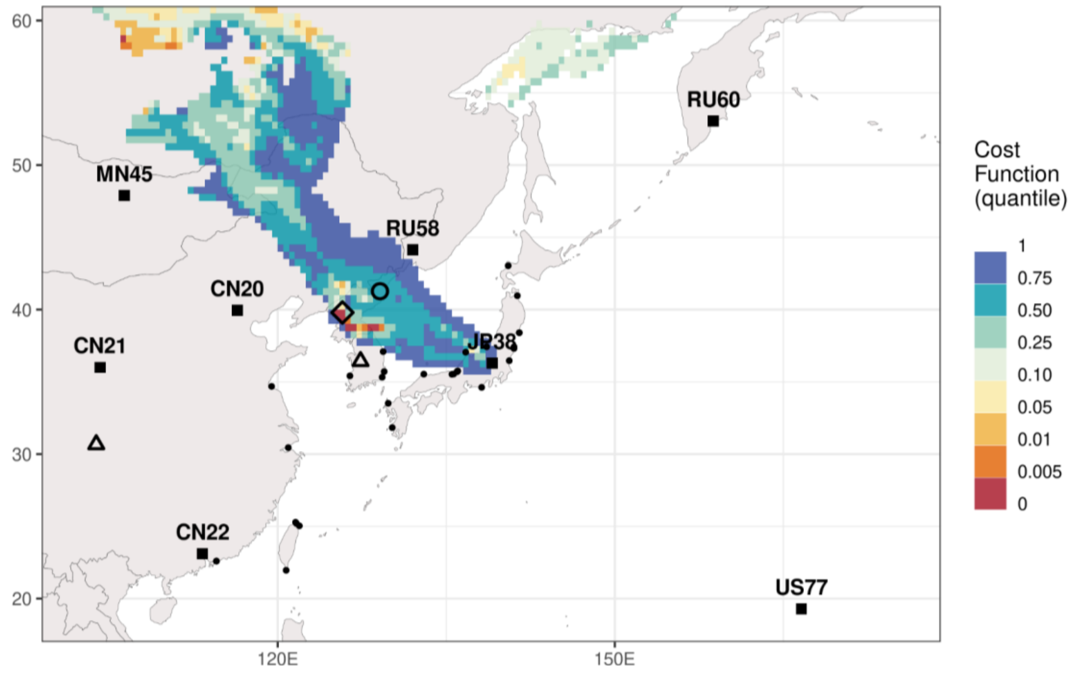
Example of detection event at JPX38 (Takasaki, Japan) labelled 3

2025

Localisation with statistical optimisation



CEA Overlapping Field of Regards



CEA Cost Function (statistical optimisation)

See **CHESTER ET AL 2025,** Investigating anomalous radioxenon detections on the International Monitoring System related to a significant source in East Asia, **SUBMITTED TO *J. of Env. Rad.***

See also Ross et al., SnT 2025 (P2.3-646)

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Localisation with Bayesian inference: Release estimate

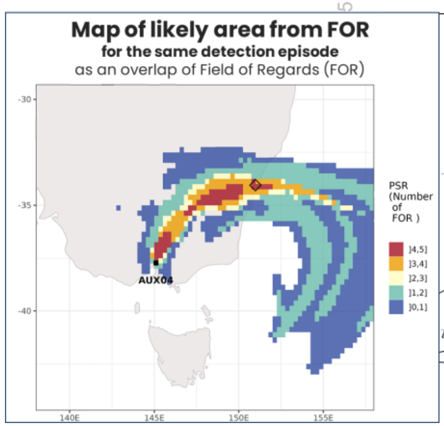
2013

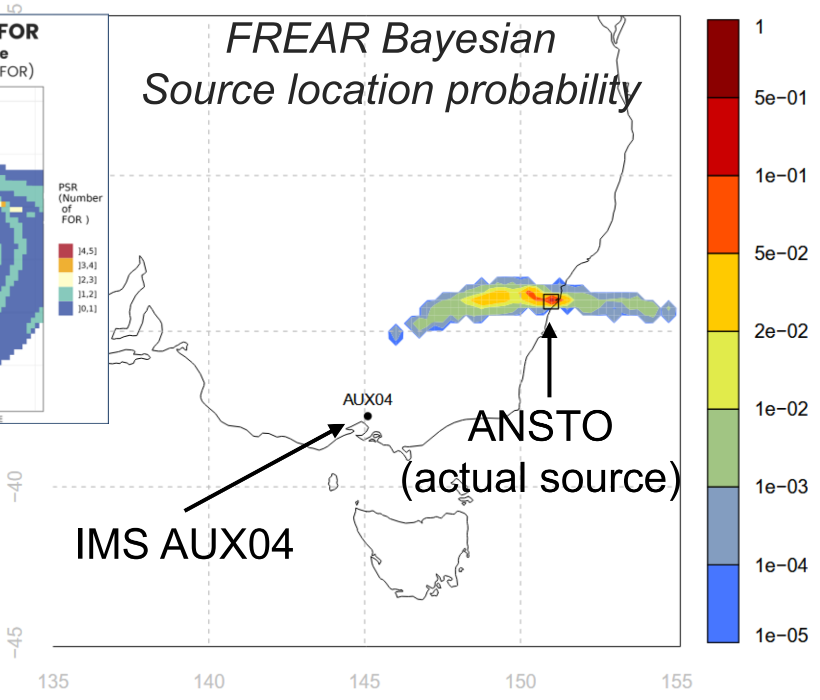
Localisation with overlapping FOR

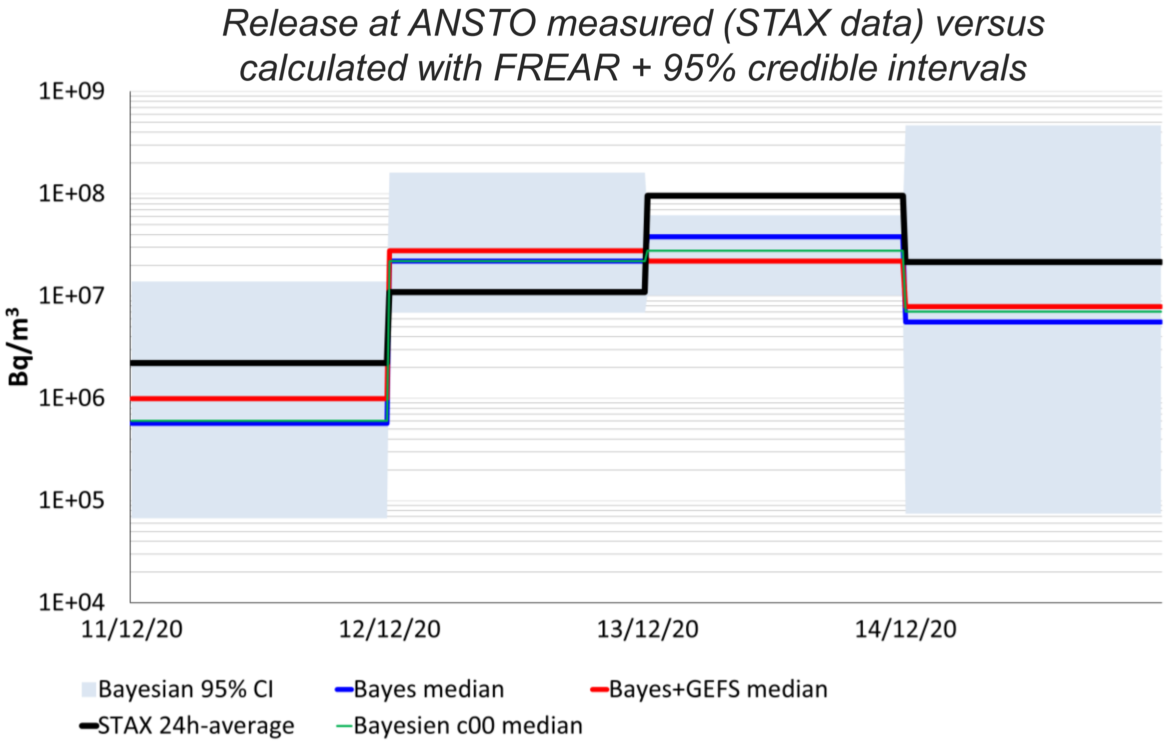
Example of event detected at AUX04 (Melbourne, Australia), for which real emissions are known (STAX data from ANSTO medical isotope production)

2025

Localisation with statistical optimisation







FREAR software :
DE MEUTTER & HOFFMAN. 2020. *J. of Env. Radioactivity*
DE MEUTTER, HOFFMAN & DELCLOO. 2024. *J. of Env. Radioactivity*

Generoso et al., SnT 2025 (P3.6-347)

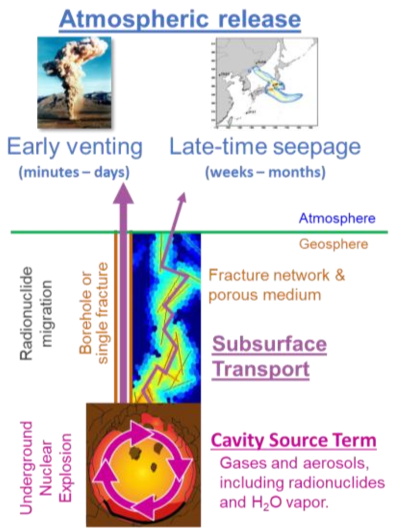
Atmospheric Transport Modelling (ATM) in support of radionuclide monitoring: an overview of operational capacities.

Generoso S., Achim P., Gross P., Morin M., Topin S.

PERSPECTIVES

Ke03

Coupling ATM and subsurface transport



Pili et al., SnT 2023

STM_toolkit: a Radionuclide Source-term Modeling Package for Rapid Scenario Determinations at the French NDC

Pili et al., SnT 2025 *(P2.3-204)*

Coupling condensation with decay-chains: A refined model for the calculation of the radioxenon source term produced by underground nuclear explosions

Pili et al., SnT 2025 *(P2.3-203)*

SATEx: Ground truth for the atmospheric detectability of xenon emitted from an underground cavity

Support from Machine learning

Liljegren, SnT 2025 *(P3.6-559)*

Radioxenon **sample association** using a machine learning approach

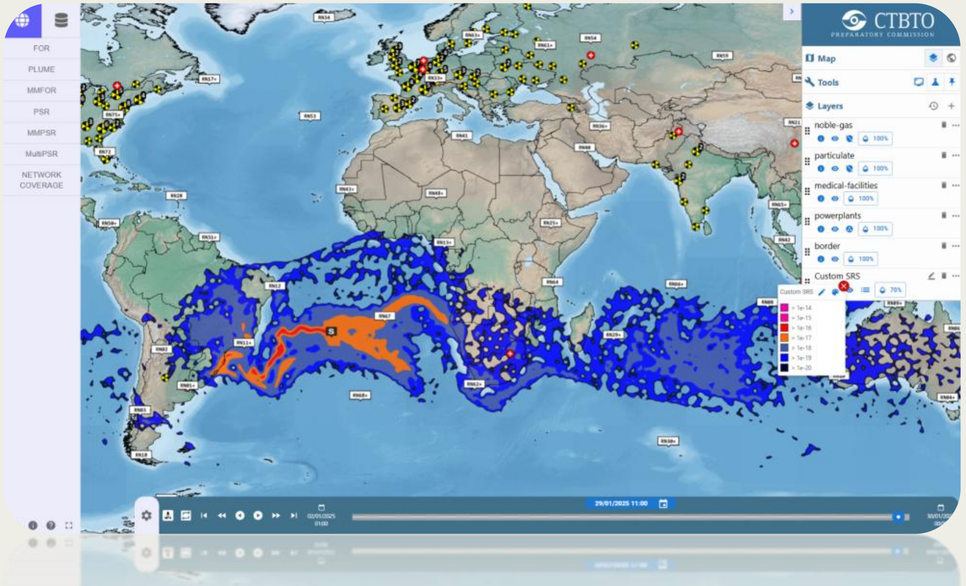
Lucas, SnT 2023

Machine Learning Enhanced **Detection of Radionuclide Anomalies**

Atik, SnT 2025 *(P2.3-748)*

Characterization of ^{133}Xe atmospheric civil source distribution using graph models on simulated data

Providing ATM capacity to NDCs across the globe



Screenshot of **CTBTO WebGrape** Internet Based Service

Tipka, SnT 2025 (CTBTO) *(P4.1-720)*

Schoemaker, SnT 2025 (CTBTO) *(P2.3-286)*

Krysta, SnT 2025 (CTBTO) *(P1.1-557)*

PANEL 11 SEPT 17:00

"Gender, Geography, Generations: How NDCs Shape the World Today and Tomorrow"

Generoso S., Achim P., Gross P., Morin M., Topin S.

Conclusions

IN BRIEF

✓ Atmospheric Transport Modelling (**ATM**) is up and running in National Data Centres and at the International Data Centre and fulfil its role in supporting radionuclide monitoring

STUDIES FOR OPERATIONAL CAPACITIES

✓ Ensemble/probabilistic methods to quantify uncertainties in ATM
✓ Characterization of the radioxenon background

OPERATIONAL CAPACITIES TODAY

✓ Source localisation and source term reconstruction with statistical optimisation, Bayesian inference
✓ Contribution to sample categorisation based on the expected levels of background

FACING CHALLENGES

➢ Radioxenon background: A new picture with new generation systems data & new sources
➢ Uncertainty quantification in operational context : a need for a practical indicator ?