Contribution of Bayesian methods and uncertainty quantification to source location and interpretation of IMS radionuclide measurements

S. Generoso[1], M. Morin[1], P. Gross[1], S. Topin[1], P. De Meutter[2], I. Hoffman[3]

[1] The French Alternative Energies and Atomic Energy Commission (CEA), DAM, DIF
[2] Belgian Nuclear Research Centre (SCK-CEN)
[3] Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO)

INTRODUCTION AND MAIN RESULTS

- **Compare FREAR**(1) Bayesian inference and cost function with the operational in-house cost function (labelled “CEA Cost Function”) and Field of Regard (“CEA FOR”) methods.
- **Assess source term reconstruction in an operational context** with real detections due to known emissions.
- **Explore the use of meteorological ensemble data to quantify the model error** used as input of FREAR Bayesian inference.

- ✓ Good agreement between the different localisation methods.
- ✓ Bayesian inference adds the value of providing results with credible intervals.
- ✓ Need for a practical indicator of meteorological variability.

(1) Forensic Radionuclide Event Analysis and Reconstruction, an open source tool developed by Canadian and Belgium National Data Center : **De Meutter & Hoffman, 2020.** J. of Env. Rad., 218, 106225. **De Meutter, Hoffman, Delcloo 2024.** J. of Env. Rad., 273, 107372.

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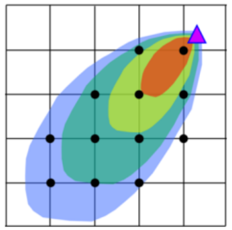
Method and data used

Radioxenon measured at the IMS monitoring station AUX04 in Melbourne (Australia) comes primarily from a single emitter, ANSTO, a medical isotope production facility in Lucas Height, about 650 km to the north-east.

From IMS ^{133}Xe data [2020-2024]. 9 plume events resulted in detected activity concentrations > 5 mBq/m^3. **From STAX(2) data.** Monitoring of radioxenon releases, on-site at ANSTO, are available for 7 of the 9 events. **GEFS ensemble meteorological data at 0.5°** to define model error based on meteorological uncertainties.

INVERSE MODELLNG



Monitoring station → Dispersion (ATM) → Possible sources (Localisation)

Four methods used in this study :

DETERMINISTIC APPROACH

- **Overlapping FOR** (Overlap of Field of Regards). Not used for release rate estimate.
- **CEA Cost Function.**
- **FREAR(1) Cost Function.**

PROBABILISTIC APPROACH

- **FREAR(1) Bayesian inference.** Currently in test.

ASSUMPTIONS ON THE PRIOR

FIELD OF REGARD (FOR)

- No assumption required, but used with an assumed maximum release (10^{14} Bq)

COST FUNCTION

- Assumptions required on the :
- ✓ **Geographic location** : A prior on the domain
- ✓ **Source size** : a range (a min and a max) for the amount released
- ✓ **A release period** (a start and stop date of the release + an assumption whether it is constant or variable with time)

BAYESIAN INFERENCE

- Same as the cost function + definition of errors (model, measurement)

DISPERSION calculated with

- ✓ FLEXPART with output grid 0.25°/6 hrs
- ✓ NCEP/GFS meteorological data at 0.25° and 6 hrs
- ✓ NCEP/GEFS (ensemble) data at 0.5° and 6 hrs

(2) **Friese J. et al., 2019,** High resolution stack data from fission-based Mo-99 production In: Science and Technology Conference, pp.24-28. June, Vienna , Austria (talk). https://ctnw.ctbto.org/ctnw/abstract/32769

Detailed analysis of one plume event : Map of likely area

IMS DATA USED IN THE LOCALISATION AUX04

START	^{133}Xe (mBq/m^3)	MDC (mBq/m^3)
12/12/2020 08:00	--	0.18
12/12/2020 20:00	0.16	0.15
13/12/2020 08:00	1.04	0.16
13/12/2020 20:00	10.01	0.17
14/12/2020 08:00	1.20	0.17
14/12/2020 20:00	1.83	0.21
15/12/2020 08:00	--	0.18

ATM AND LOCALISATION SET-UP

- Backward dispersion calculated for 5 days (11-16 Dec. 2020) with outputs (SRS fields) averaged over 6 hours.
- Assumed release date between 11 and 15 December, constant or variable (24-hour average).
- Comparison to STAX measurements from 11 to 15 Dec. 2020

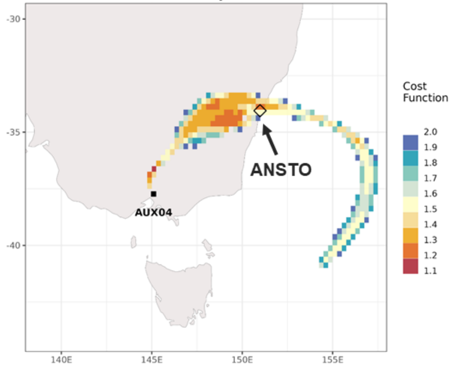
ACCUMULATED RELEASE at ANSTO 11-15 Dec 2020 (4 days)

Method	Bq/m³ [1]	
Cost Function Variable release (24hr release rate)	CEA **2.0x10⁹**	FREAR **1.5x10⁹** [2]
FREAR BAYESIAN[3] Rectilinear release [median & credible interval]	**2.7 [1.5-5.0]x10⁹**	
FREAR BAYESIAN + GEFS[3] Rectilinear [median & credible interval]	**2.1 [1.2-3.5]x10⁹**	
STAX measurement	**3.1x10⁹**	

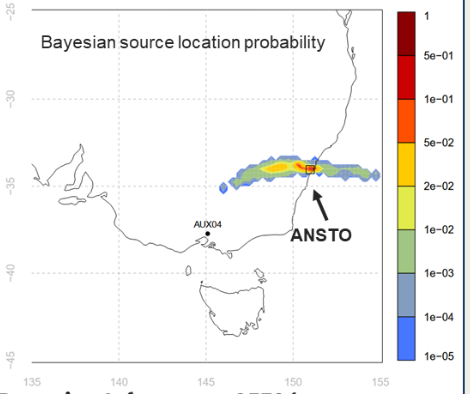
COMMENT

- Good localisation to the source
- Good agreement between the different methods.
- Non detections accounted for with the critical limit (= MDC/2)

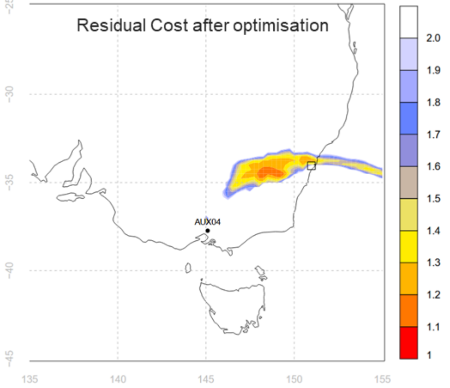
CEA Cost Function assuming a variable release (with a 24-hr resolution) from 11 to 15 Dec 20



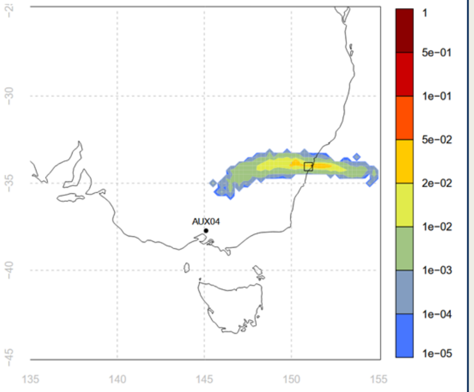
Bayesian Inference assuming a rectilinear release from 11 to 15 Dec 20



FREAR Cost Function assuming a variable release (24-hr) from 11 to 15 Dec 2020



Bayesian Inference + GEFS for srs error assuming a rectilinear release from 11 to 15 Dec 20



[1] As per request from ANSTO, data are reported in Bq/m³. The conversion was applied after the localisation (with outputs in Bq/h)
[2] At the closest location to ANSTO with cost function < 2
[3] The values reported are obtained at ANSTO exact location with the FREAR option « fixed location »

ANSTO : Australia's Nuclear Science and Technology Organisation
IMS : International Monitoring System
ATM : Atmospheric Transport Modelling
SRS : Source Receptor Sensitivity

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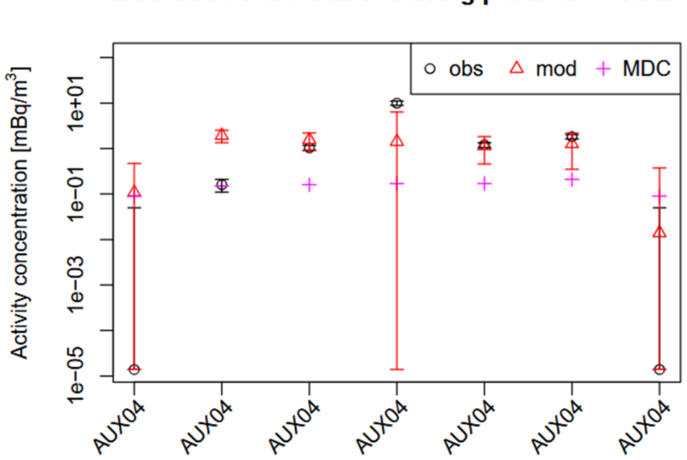
Bayesian Inference

Example : assuming a rectilinear release from 11 to 15 Dec 20



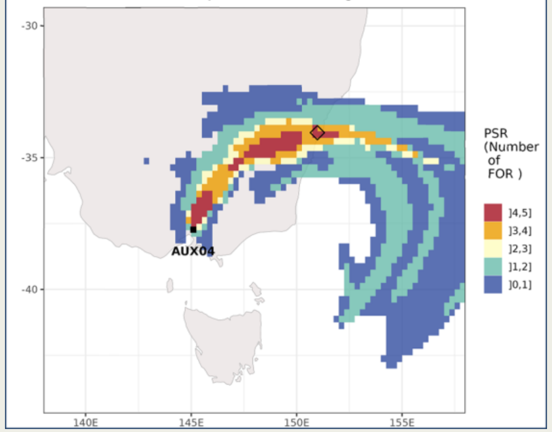
Comment

- Automatically calculated and plotted in FREAR
- Rapid check of the performance of the calculated source term
- Bayesian inference returns results associated to probability : plotted (in red) are the median and the 95% credible interval.

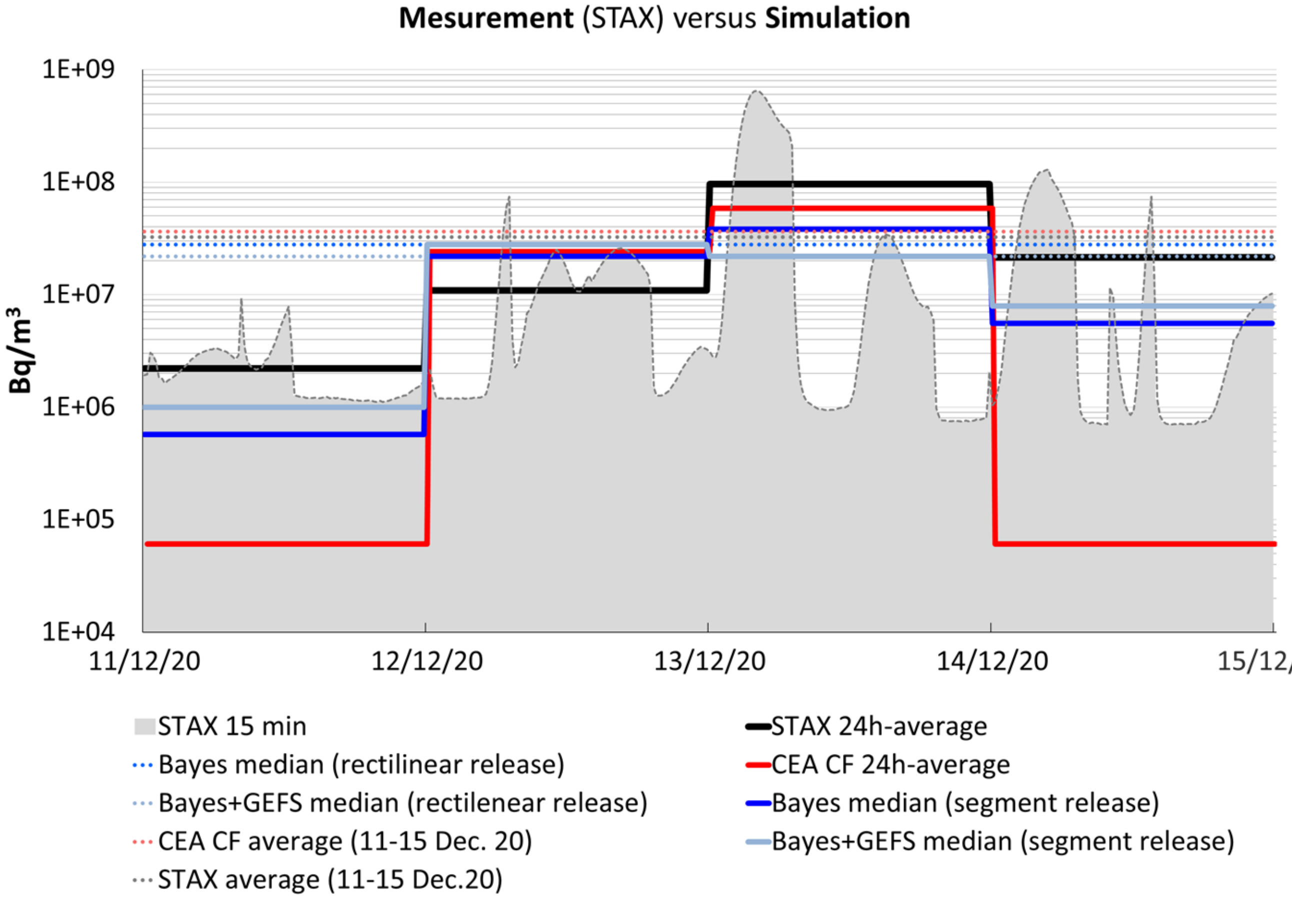
Map of likely area from FOR

for the same detection episode

as an overlap of Field of Regards (FOR)



Detailed analysis of one plume event : Calculated release at ANSTO versus measurement



Comment

- On average, all methods return a fair/good agreement with the measurements

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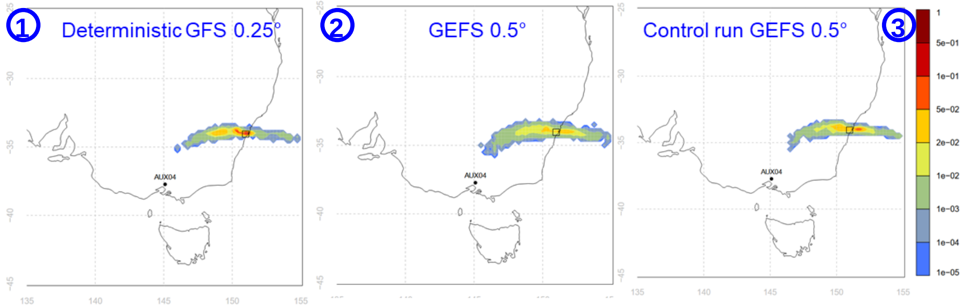
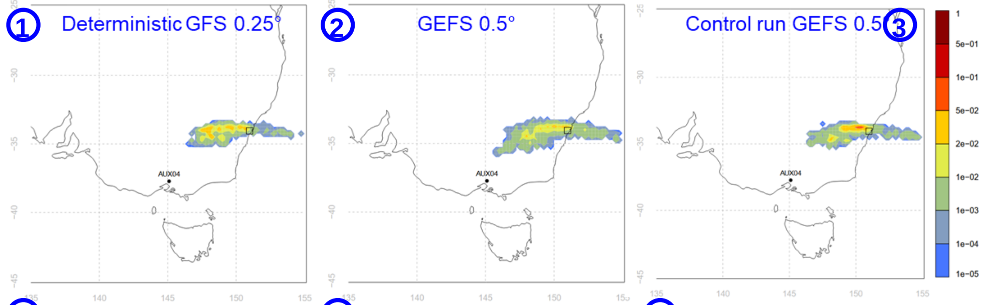
Detailed analysis of one plume event : Use of ensemble meteorological data

Sensitivity of likely release area to the meteorological field used

Bayesian source location probability
Rectilinear release
(24-hour resolution) from 11 to 15 Dec. 2020



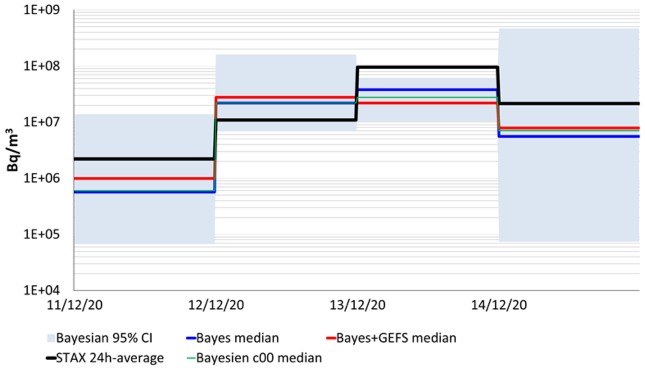
Bayesian source location probability
Segment release
(24-hour resolution) from 11 to 15 Dec. 2020



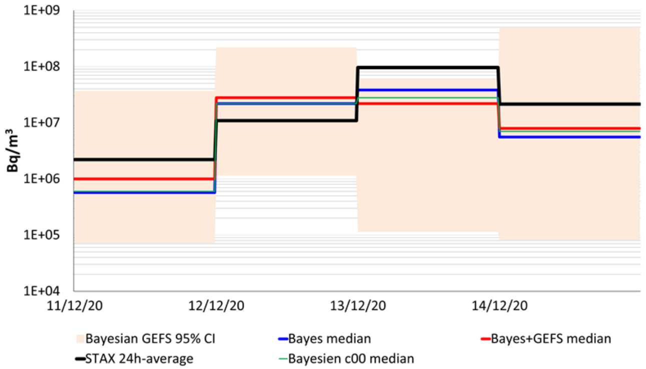
1. *FREAR applied to SRS calculated with GFS 0.25° and a model error set as 50% of the SRS values*
2. *FREAR applied to SRS calculated with GFS 0.25° and a model error set as the spread of GEFS ensemble (option "fitInvGamma")*
3. *FREAR applied to SRS calculated with GEFS control run 0.5° and a model error set as 50% of the SRS values*

Sensitivity of the calculated release rate to the model error definition

Error on SRS fields set to 50%



Error on SRS fields with GEFS ensemble
(FREAR option fitInvGamma)



Summary and lessons learnt

The case study presented is an ideal real-case to test the performance of the localisation methods used at NDCs since the monitoring station in Melbourne (Australia) measures mostly background from one single contributor, whose actual emissions are known. Seven ideal plume events have been identified in 2020-2024.

The detailed analysis of one plume event is presented and show overall good or fairly good agreement between the different methods, both in terms of likely release area and of release rate estimates.

The clear added, practical benefit of the Bayesian inference is that it provides results with credible intervals.

On the other hand, the use of Bayesian inference requires expertise. As such, it may be useful to use first a PSR/FOR or a cost function, to help constrain the priors (geographic, source size, release period) required by the Bayesian approach. To that end, an interactive (rather than automated) use of the Bayesian inference for locating radionuclide source may be preferred.

The sensitivity analysis to the model error presented in this work (fixed or according to the spread of the meteorological ensemble) is a preliminary study, and will be further explored.

The method presented will be applied to the six other identified events.

NDCs : National Data Centres
SRS : Source Receptor Sensitivity