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INVERSE ATMOSPHERIC TRANSPORT MODELLING USING THE OPEN-SOURCE FREAR TOOL

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Abstract: An inverse modelling tool has been developed with the initial purpose of improving the verification of the Comprehensive Nuclear-Test-Ban Treaty. The tool is able to make inferences of source parameters (such as source location and release amount) given a set of airborne activity concentrations and their corresponding source-receptor-sensitivities obtained from atmospheric transport and dispersion modelling. The tool features several independent methods to perform the inverse modelling, including Bayesian inference and cost function optimisation. The tool can digest detections and instrumental non-detections and can take into account the possibility of misses and false alarms. An ensemble of atmospheric transport modelling can be provided for more rigorous estimation of the model uncertainty. Lastly, the tool features a flexible source parameterization, which was introduced to study the amount of Cs-137 released during resuspension from the wildfires in the Chornobyl Exclusion Zone in April 2020. Here, an overview of the open-source FREAR (Forensic Radionuclide Event Analysis and Reconstruction) tool is presented and some of its features are highlighted.

Key words: *inverse modelling, ATM, source reconstruction*

INTRODUCTION

Several countries operate high-volume air samplers that can measure traces of radioactivity in air for the purpose of environmental and treaty monitoring. Furthermore, a global network of ground-based measurement stations is set up to monitor for traces of radioactivity following clandestine nuclear testing, with the purpose of verifying compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT). If radioactivity is measured, its origin is sometimes known and can be confirmed for instance by direct atmospheric transport modelling. However, often the origin is unknown, in which case inverse atmospheric transport modelling can be used to determine the source location and release parameters.

For the purpose of CTBT monitoring, the open source inverse modelling tool Forensic Radionuclide Event Analysis and Reconstruction (FREAR) was developed (De Meutter and Hoffman, 2020). The tool makes use of observed airborne activity concentrations and associated source-receptor sensitivities obtained by atmospheric transport modelling to determine the unknown source parameters that can explain the observations. Besides treaty monitoring, the tool can also be used in the context of radiation protection.

INVERSE ATMOSPHERIC TRANSPORT MODELLING

Inverse modelling can formally be written as follows (Seibert, 2000):

$$\boldsymbol{y} = \boldsymbol{M}\boldsymbol{x} + \boldsymbol{\varepsilon} \quad (1)$$

where $\boldsymbol{y}$ is a vector of observations, $\boldsymbol{M}$ is a matrix containing the source-receptor sensitivities obtained from an atmospheric transport model for each geo-temporal release point and associated to each observation. The release at each geo-temporal release point is represented by the vector $\boldsymbol{x}$. Finally, $\boldsymbol{\varepsilon}$ represents the combined model and observation error.

Inverse atmospheric transport modelling involves determining $\boldsymbol{x}$ so that $\boldsymbol{Mx}$, the modelled observations, match $\boldsymbol{y}$ taken into account an estimate of the error $\boldsymbol{\varepsilon}$. Some atmospheric transport models such as the Lagrangian particle model Flexpart feature the possiblity to run backward-in-time (Seibert and Frank, 2004). If the number of possible geotemporal release points exceeds the number of receptors, it is computationally advantegeous to use the backward approach (Seibert and Frank, 2004). If the source location is known and originating from a point-like source, then the source-receptor sensitivities can be efficiently calculated forward-in-time.

FREAR & ITS KEY FEATURES

Given a vector of observations and associated source-receptor sensitivities obtained by an atmospheric transport model, FREAR determines the source parameters by solving equation (1). Some events of interest feature only a handful of trace detections. In such cases, the use of instrumental non-detections, when the observed quantity is below a detection threshold, can be particularly beneficial to further constrain the source parameters. FREAR can use not only detections but also instrumental non-detections (De Meutter and Hoffman, 2020).

Several methods are available for source reconstruction (De Meutter et al., 2024): two methods that solve equation (1), namely a cost function optimisation method and a Bayesian inference method; and two simpler methods that can be used to determine the (unknown) source location, based on the so-called Field Of Regard (Wotawa et al., 2003) and the Possible Source Region (Becker et al., 2007). An example of all four methods is shown in Figure 1 for a twin experiment with 8 fictitious detections of ^{137}Cs. The more elaborate Bayesian inference and cost function optimisation methods are able to constrain the source location, while the other two simpler methods give a crude estimate of the possible origin. The latter can be useful as a first guess, but also as a check for the more elaborate methods.

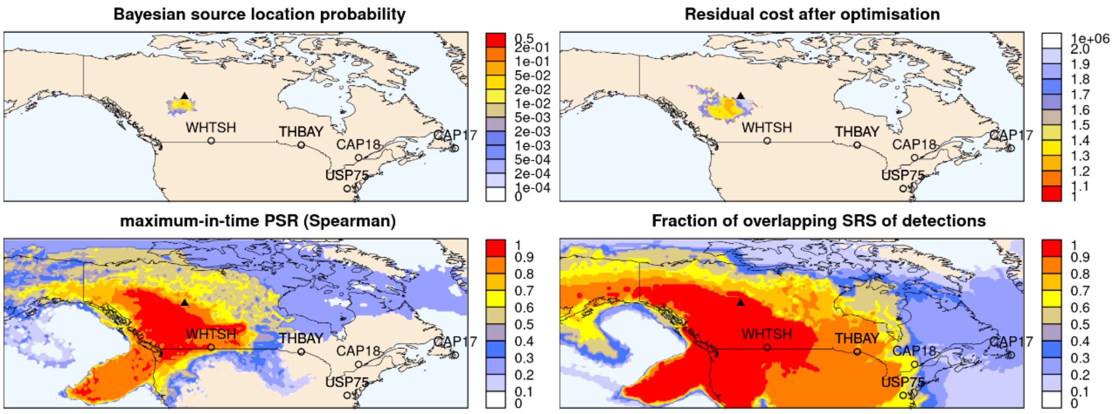

Figure 1. Source location estimate as obtained by four methods: (top left) source location probability obtained by Bayesian inference, (top right) residual cost following cost function optimisation, (bottom left) maximum-in-time correlation between the observations and the source-receptor sensitivities and (bottom right) fraction of non-zero source-receptor sensitivities. The true source location is marked by a black filled triangle. The locations of the measurement stations are also shown (circles and text labels).

The Bayesian inference and cost function optimisation methods allow for a comparison between the observed activity concentrations and the modelled activity concentrations using the source parameters found by FREAR. This allows one to check how well the inferred source parameters explain the observations. An example is shown in Figure 2 for the eight detections used in Figure 1.

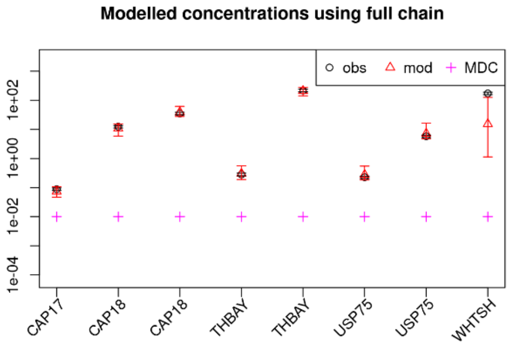

Figure 2. Comparison between the observed ^{137}Cs activity concentrations (black circles) and corresponding modelled activity concentrations (red triangles) following Bayesian inference. The minimum detectable concentration is also given (purple '+'-sign).

Finally, the Bayesian inference method provides a posterior distribution for each source parameter. An example of such posterior distributions is given in Figure 3 for five source parameters that explain the eight detections used in Figure 1 and 2.

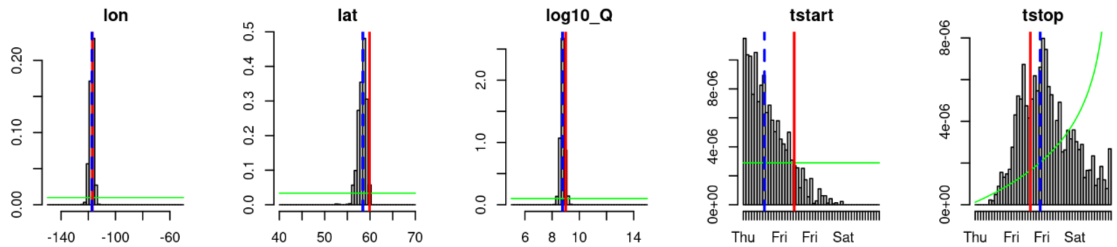

Figure 3. Posterior distribution for the source parameters following Bayesian inference. From left to right: longitude, latitude, log10 of the total release amount, start time of the release and end time of the release. For each source parameter, the prior distribution (green line), posterior median (blue dashed vertical line) and true value (red vertical line) are also plotted.

^{137}CS RELEASE FROM WILDFIRES

Resuspension of historically deposited ^{137}Cs through wildfires is a yearly reoccurring phenomenon. In April 2020, particularly strong wildfires occurred close to and within the Chornobyl Exclusion Zone. Several European countries measured slightly elevated levels of ^{137}Cs in the air (Masson et al., 2021). FREAR was used to determine the total ^{137}Cs resuspension. The huge variability of the location and timing of the wildfires was a particular challenge to determine the ^{137}Cs release. Within FREAR, several source parameterizations are available, such as the puff release for known or unknown location and the segmented release for known or unknown locations. However, these source parameterizations would poorly capture the spatio-temporal variation of the ^{137}Cs release. Therefore, a custom source parameterization was introduced following a study on the ^{137}Cs resuspension through wildfires in and near the Chornobyl Exclusion Zone (De Meutter et al., 2021). Release locations and timing were taken from the Global Fire Assimilation System that identifies wildfires and their intensity (Figure 4). Furthermore, the release was made proportional to the fire power and the historic ^{137}Cs contamination at that location. A total of 2985 fires were considered. It was shown that the source parameterisation taking into account the location of the wildfires, the fire power and the historic ^{137}Cs deposition leads to a better match with the observations (De Meutter et al., 2021).

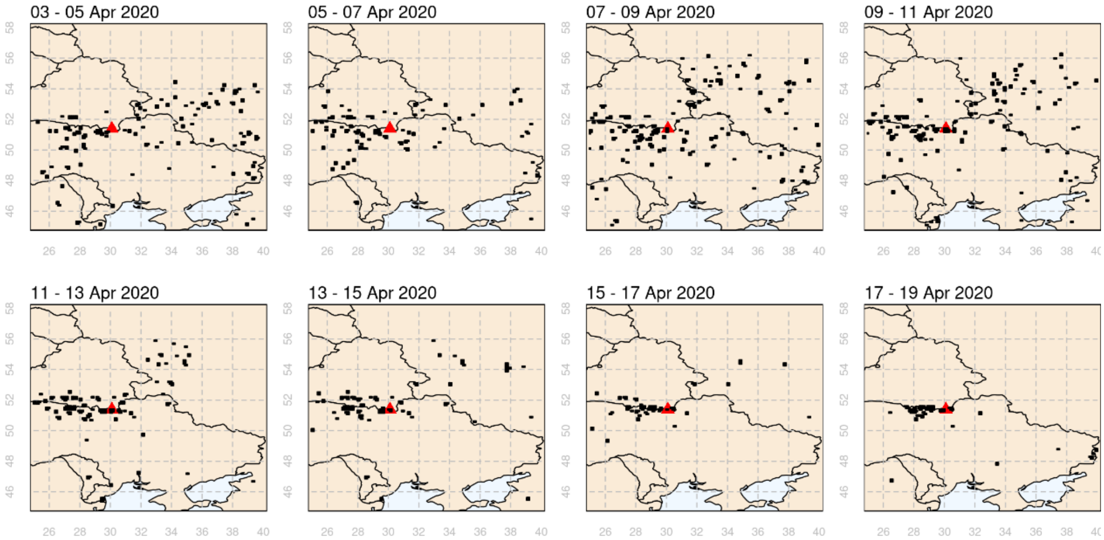

Figure 4. Maps showing the location of wildfires (black dots) as obtained by the Global Fire Assimilation System for 2-day periods from 3 April 2020 until 19 April 2020. The location of the former Chornobyl nuclear power plant is given by the red triangle.

SUMMARY AND OUTLOOK

The Forensic Radionuclide Event Analysis and Reconstruction tool FREAR combines observed activity concentrations and associated source-receptor sensitivities obtained by atmospheric transport modelling to determine the source parameters that explain the observed activity concentrations. The tool is useful for verifying compliance with the Comprehensive Nuclear-Test-Ban Treaty and for applications related to radiation protection. Further developments are foreseen to allow for the use of dry and wet deposition measurements for the inverse modelling. The tool can be downloaded from https://gitlab.com/trDMt2er/FREAR.

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