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SOURCE ALLOCATION BASED ON ATMOSPHERIC TRANSPORT MODELLING OF RADIONUCLIDE PLUMES: CHALLENGES AND NEW DEVELOPMENTS

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ABSTRACT

Identifying the source of radioactive detections at the International Monitoring System (IMS) stations is both challenging and central to the CTBTO mandate. Atmospheric Transport Modelling (ATM) calculations provide the link between IMS radionuclide detections and a potential source of emissions, including atmospheric, underground, and underwater nuclear explosions. The additional challenge related to source localization is that both remote and nearby sources might contribute to an elevated level of radionuclide detected at an IMS station. In case of radioxenon, this challenge is magnified by the presence of a radioxenon background from known sources. Radioxenon can be produced either during a nuclear explosion (forming an important tracer to prove the nuclear character of an explosion) or be emitted by nuclear facilities. The regular operational releases of radioxenon from nuclear installations contribute significantly to both the global and regional background. In the Northern Hemisphere radioxenon background at most of the IMS stations is dominated by the contribution of nuclear power plants. For some stations, simulated concentrations above the detection limit may include observable contributions from up to 19 different sources per daily sample (samples are sensitive to 80 or more possible sources of radioxenon). Thus, understanding the radioxenon background at the radionuclide stations of the IMS network is vital for improving the verification capability of the CTBTO. This presentation provides an overview of the new developments aimed at improving the source allocation method e.g., using the ensemble modelling for the backward ATM, more accurate estimation of radioxenon background or a method for identifying samples associated with the same release event.

INTRODUCTION

The Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) developed the International Monitoring System (IMS), which is a global system of monitoring stations based on three waveform verification technologies — seismic, hydroacoustic and infrasound, and the complementary radionuclide technology. The latter is the only one capable to confirm whether an explosion detected and located by the others is indicative of a nuclear test. The radionuclide network comprises 80 stations, of which 72 are certified. The aim of this radionuclide network is the global monitoring of radioactive aerosols and radioactive noble gases, supported by atmospheric transport modelling (ATM) to track measurements back to their possible source regions.

Assisting Member States in identifying the source of radioactive detections at IMS stations is both challenging and central to the CTBTO Preparatory Commission mandate. ATM calculations provide the link between IMS RN detections and potential sources of emissions, including both atmospheric and underground nuclear explosions. Treaty monitoring requires an evaluation on a sample by sample basis and this is much more challenging than getting an average close to right. With regard to the latter, significant progress has been made. For example, using the average sampling values in the Southern Hemisphere as a metric gave reasonable bounds on average facility emissions (Eslinger et al., 2014).

To meet the needs of the CTBT verification system, the IDC aims to establish a world-class ATM system (ATM pipeline). In order to address the inherent uncertainties of the ATM simulations associated with the dynamics of the atmosphere, the PTS cooperates with the World Meteorological Organisation (WMO) and its Regional Specialised Meteorological Centres (RSMCs) in the field of dispersion modelling. However, it should be noted that the WMO cooperation is only used for a very low fraction of samples that are highlighted by the sample categorization scheme. The ATM products for all other samples are routinely generated by the CTBTO in-house ATM pipeline.

The IDC takes all opportunities to validate its results against results from other institutes which work in the field of ATM. The IDC participated in three international model comparisons (the so-called ATM Challenges) in 2015, 2016, and 2019. The results of these exercises indicate that the performance of the CTBTO simulations is very good (Eslinger et al. 2016; Maurer et al. 2018, 2022), in most cases above the average and occasionally on the top. The second ATM challenge highlighted the importance of high-quality meteorological fields. Even from around 17 000 km away from the source or even after 8-13 days of travel time, the plume timing of the measured samples can be satisfactorily reproduced when the simulations are done using advanced and validated ATM driven by high quality meteorological fields (Maurer et al. 2018). The satisfactory reproduction of individual samples even around 17 000 km away from the source mentioned above highlights that the challenge needed for CTBT monitoring, with a sample-by-sample comparison between measurements and simulations, can be met with proper data and under favourable conditions.

This presentation discusses the current methods and the new developments aimed at improving the source allocation method.

THE ATMOSPHERIC TRANSPORT MODELLING (ATM) OPERATIONAL SYSTEM

The ATM operational system deployed and used at the CTBTO produces source receptor sensitivity (SRS) fields, which specify the location of the air masses prior to their arrival at any radionuclide station of the International Monitoring System (IMS) network. The current ATM operational system is based on a Lagrangian Particle Dispersion Model, FLEXPART (Stohl et al. 2005) driven by the global meteorological fields provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction (NCEP) at a resolution of 0.5 degrees.

Operationally, the ATM system is used in backward mode (i.e., from the receptor’s location) to compute SRS fields for each sample at all radionuclide measurement locations. The ATM results are stored as ASCII files, including the information about coordinates (latitude, longitude), time step and SRS values. A backward simulation is the method of choice when a source is unknown. In special cases, such as announced nuclear explosive testing by the Democratic People's Republic of Korea (DPRK) or the Fukushima nuclear accident, when a source location is suggested (e.g., as a result of a seismic event localization) forward modelling is done. The ATM is then used in forward mode to predict which of the IMS radionuclide stations are likely to be affected by a potential radioactive release.

If an IMS station detects an elevated level of radionuclides in a particular sample, ATM calculations performed in a backward mode are used to identify the origin of air masses. In many cases, detections of radionuclides occur at a single station, without nearby stations measuring a signal. In this case, a simple Field of Regard (FOR) concept is used to determine the location of a release across a broad area. An example of FOR is illustrated in Figure 1.

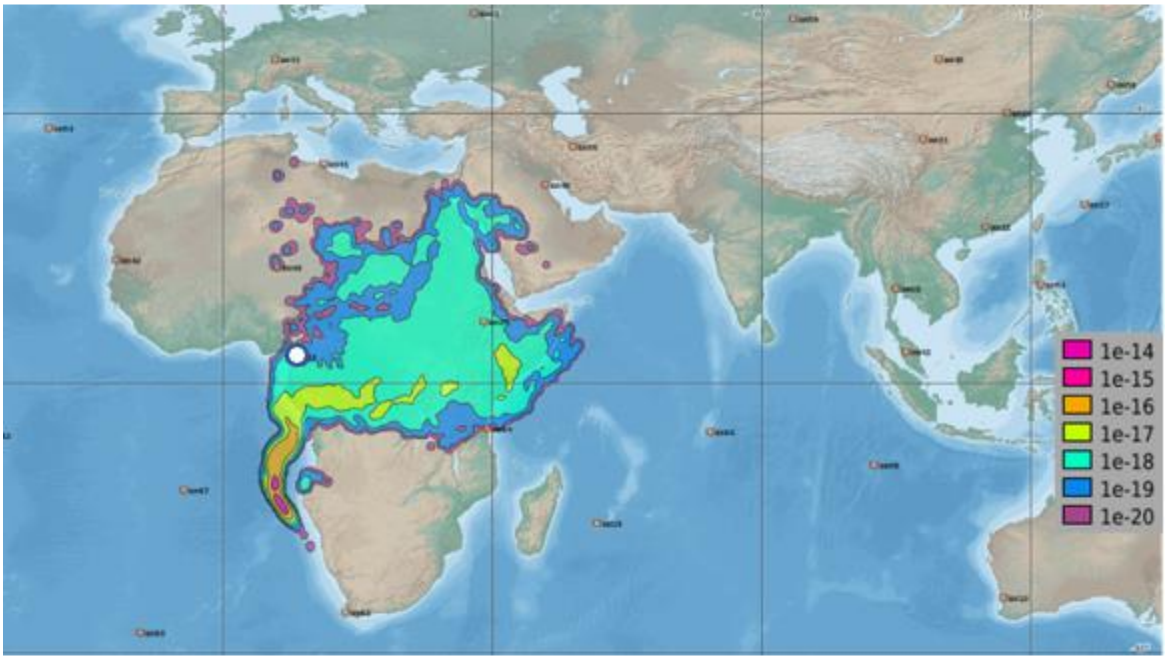

FIG. 1. Example of the static Field of Regard (FOR) image, for the IMS station in Cameroon (white dot, RN13). Snapshot taken on 2 April 2023. The coloured area marks the region where, according to the ATM backward simulations, the air masses were 9 days prior to the arrival at the IMS station.

On some occasions, multiple detections might occur at one or more IMS stations. Depending on the nature of these detections and on prevailing meteorological conditions, it is possible that all these detections come from a unique source, and thus the possible source region (PSR) concept can be used that provides a more precise possible source location. More details can be found in Kuśmierczyk-Michulec et al., (2023).

CHALLENGES IN SOURCE LOCALIZATION

The challenge related to source localization is that both remote and nearby sources might contribute to an elevated level of radionuclide detected at an IMS station. In case of radioxenon, this challenge is magnified by the presence of a radioxenon background from known sources.

Radioxenon is a fission product with a high fission yield. It can be produced either during a nuclear explosion, forming an important tracer to prove the nuclear character of an explosion, or be emitted by civil industrial nuclear facilities, e.g., nuclear power plants or isotope production facilities. The regular operational releases of radioxenon from nuclear installations contribute significantly to both the global and regional background (e.g. Kalinowski and Tuma, 2009; Saey, 2009; Wotawa et al., 2010; Achim et al., 2016; Gueibe et al., 2017, Kuśmierczyk-Michulec et al., 2022; Kalinowski, 2023). This is clearly visible in the region of East-Asia (see Fig. 2). Radioxenon background at most of the IMS stations located there is dominated by the contribution from nuclear power plants. For some stations, simulated concentrations above the detection limit may include observable contributions from up to 19 different sources per daily sample; at the same time the sample being sensitive to 80 or more possible sources of radioxenon (Kuśmierczyk-Michulec et al., 2022). Figure 3 illustrates this effect.

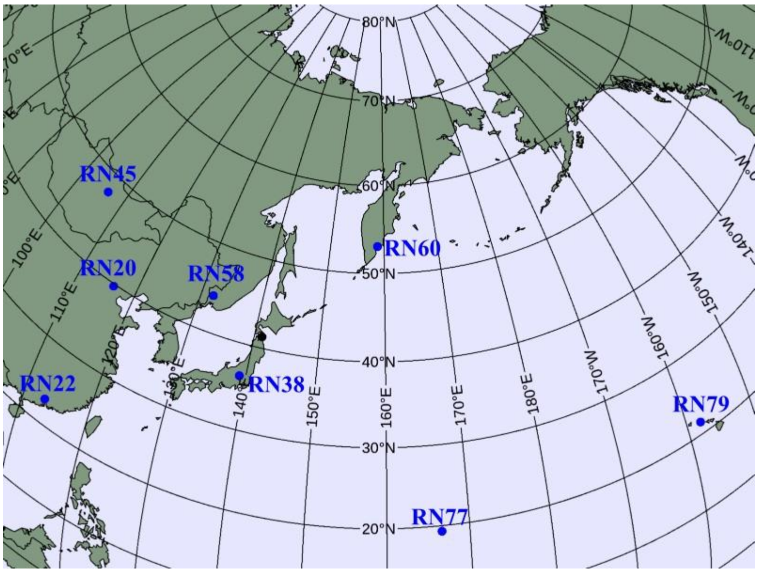

FIG. 2. Map showing the region of East-Asia.

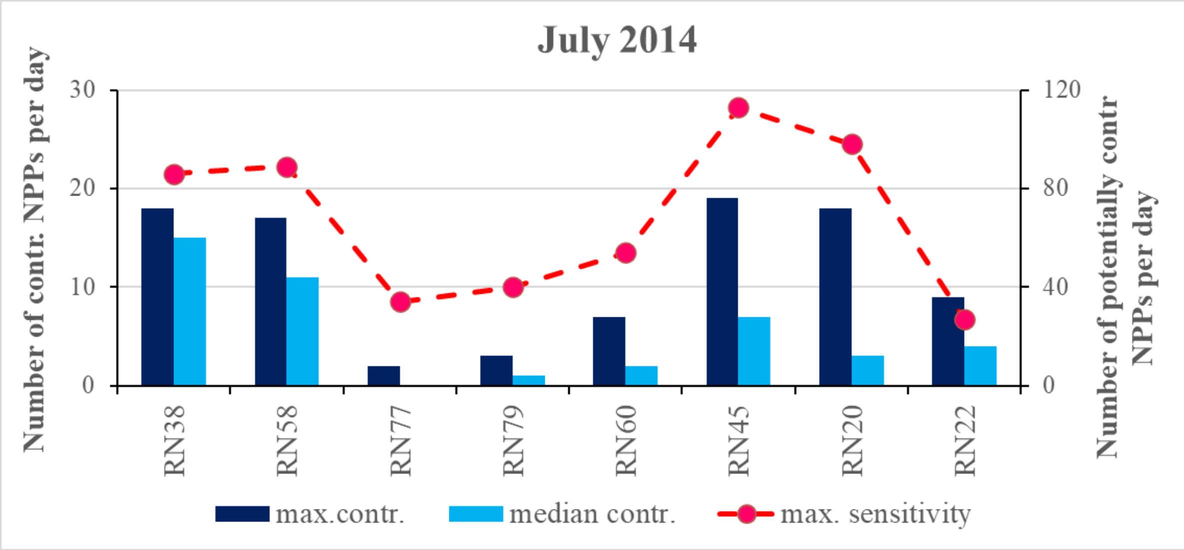

FIG. 3. Number of sources that could contribute to the daily samples at the IMS measurement stations located in the region of East-Asia, as simulated by the ATM system in July 2014. For illustration purpose, in addition to the maximum (dark blue) and median (light blue) number of sources with observable contribution to the daily sample, also the maximum number of radioxenon sources to which a daily sample was sensitive, is shown (red). For more details, please see Kuśmierczyk-Michulec et al.,(2022).

NEW DEVELOPMENTS

The identification of a sample associated with a nuclear test is a challenging task for the CTBTO because of the presence of a noble gas background in the constant evolving atmosphere. This background is caused by nuclear power plants, nuclear research reactors, and medical isotope production facilities and contributes to samples collected by the IMS noble gas systems. To address this problem, in 2021, the IDC initiated a project, through funding from the EU Council Decision VIII, to conduct an exercise called: “1st Nuclear Explosion Signal Screening Open Intercomparison Exercise 2021”. The Exercise was based on a subset of a comprehensive radioxenon test data set produced for the whole year of 2014, with hypothetical nuclear underground and underwater explosion signals added to IMS observations. The exercise considered three levels of participation requiring different levels of expertise whereby the last and most advanced level considered location and source strength as additional metrics to detection, screening, and timing. International experts have proposed their own screening methods and procedures to identify radioxenon events not consistent with civil background.

The evaluation results summarized in the final report, will be used as a guideline in two follow-up projects: Xenon Background Estimation Tool (XeBET) project and Source Term Estimator Tool (STE) Project. The aim of the XeBET project is to deliver an aggregation of scientifically developed ideas into a software prototype (Schoemaker et al, 2023). The purpose of the STE project is to estimate more efficiently and with greater certainty where a nuclear event was located and what its strength was. Work on the STE project will be done in close cooperation with the XeBET project, which provides a better estimation of the radioxenon background as input to STE.

A more ambitious objective for future enhancements is the reconstruction of the atmospheric radioxenon concentrations by assimilating the emission inventory and the IMS observations and producing a best fit of simulated concentrations to these input data. Ideally, the activities collected in IMS samples can be explained with known sources and residual concentrations can be highlighted as potentially coming from an unknown source. The purpose is to implement a flag called ATM backtracking to known sources which has to be reported by the IDC for each radioxenon sample. It is also foreseen to develop an ATM method for characterization of the key source parameters of an event (probability of the start time, duration of a release from a given location, source strength) as an input for hypothesis testing for an observation being possibly caused by a nuclear explosion. Whatever can be automated will enter the standard IDC products including a data fusion tool. The more sophisticated enhancements will be implemented in expert technical analysis.

Furthermore, these new developments will also include sample association, a method for identifying samples associated with the same release event. One of the key approaches, is based on analysis of isotopic ratios of radioxenon (Kijima et al., 2023; Liu et al., 2023). This is useful for confining the possible source region and applying the PSR method.

It is anticipated to explore machine learning algorithms to identify an anomalous observation inconsistent with previous observations and known sources.

SUMMARY

This paper provided an overview of different projects and activities aiming at overcoming challenges related to source allocation.

DISCLAIMER

The views expressed in this study are those of the authors and not necessarily represent the views of the CTBTO Preparatory Commission.

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