Improving radioxenon background estimates based on nudging observations and machine learning

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INTRODUCTION AND MAIN RESULTS

This presentation provides insights into new approaches to the challenging task of detecting underground nuclear explosion signals. A combination of a data assimilation approach together with a machine learning algorithm are currently being explored in a new scientific project.

First results demonstrate the ability of the chosen data assimilation approach to improve radioxenon background fields but also point to expected challenges.

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BETXe PROJECT

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Introduction

Given the ever-present, global, and highly variable radioxenon background, nuclear underground tests are hard to detect in the IMS network because of uncertainties in:

- Emissions originating from a variety of well-known (or even unknown) nuclear facilities. Such emission profiles are mostly poorly known, except for a few stack emission sources with high accuracy in time and strength.
- Dispersion modelling, e.g., interpolation & parametrization errors (related to ATM) and the underlying meteorological input (Numerical Weather Prediction / NWP models).
- Nuclear explosion signals of well-contained nuclear underground tests. These are small signals and might show up delayed in measurements.

The **Xenon Background Estimation Tool Project** (XeBET) of the CTBTO explores and develops scientific computing methods for a software environment based on enhancing standard dispersion modelling with a novel approach and improving anomaly detections with machine learning. The usefulness of the approaches will be investigated for two assumed venting scenarios. Evaluation will be performed with case studies from the 2014 test data set, which was created for the 1st Nuclear Explosion Signal Screening Open Inter-Comparison Exercise 2021.

Methods

1. **Radioxenon data assimilation: "Nudging" with FLEXPART-LCM**

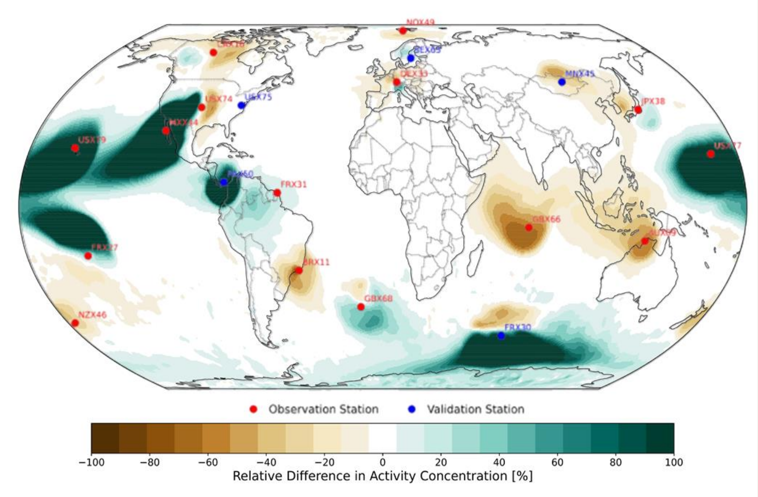
FLEXPART-LCM is a Lagrangian transport model for simulating trace gas and particle dispersion. The novel Linear Chemistry Module (LCM) fills the global atmosphere with particles. Emission information is not attributed to initialized particles, rather mass is attributed to the transported particles that cross (near) emission sources. *LCM includes a nudging module that gradually steers model simulations closer to observational data (e.g., of Xe-133) by applying mass adjustments near observations to reduce transport and emission errors.*

See the project companion poster **P2.3-286** for details.

2. Isolation Forest algorithm

This machine learning algorithm requires construction of features as input data using 1) single isotope information (more ambiguous) and 2) cross-isotope information (less ambiguous). *During the project the algorithm will be extended to also take nudging increments as input. The nudging increments should convey information about unusual adaptions of activity concentrations. The feasibility and subsequent effect of adding local meteorological information from the IMS sites as additional input will be explored.*

Results



Average, annual global impact of nudging Xe-133 observations on the predicted activity concentration field. Taken from *J. Fleisch (2025)* — Master's thesis in preparation.

Nudging reduces the bias in simulated concentrations locally, as reflected in the relative differences of nudged vs. unconstrained fields. *Strongest effects occur where 1) data are available (near IMS stations) and 2) over oceans, where lower variability makes nudging more representative across larger regions.*

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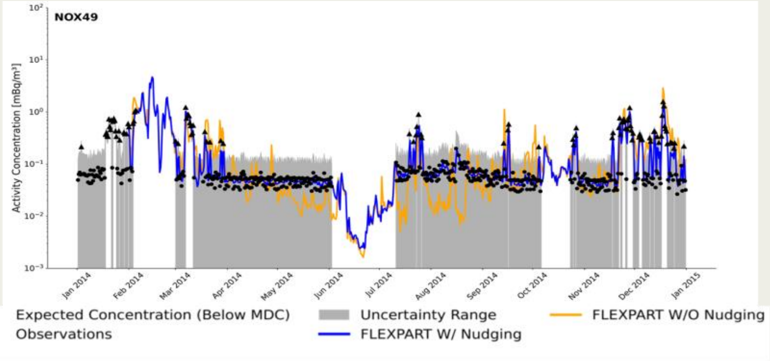
Results

Time series simulations of background Xe-133 concentrations at IMS sites reveal further insights into the impact of nudging. Nudging substantially improves simulated background concentrations at locations (e.g., NOX49) where observational data are assimilated.



Spitzbergen (NOX49) Xe-133 time series for 2014. Taken from *J. Fleisch (2025)* — Master's thesis in preparation.

Exploitation

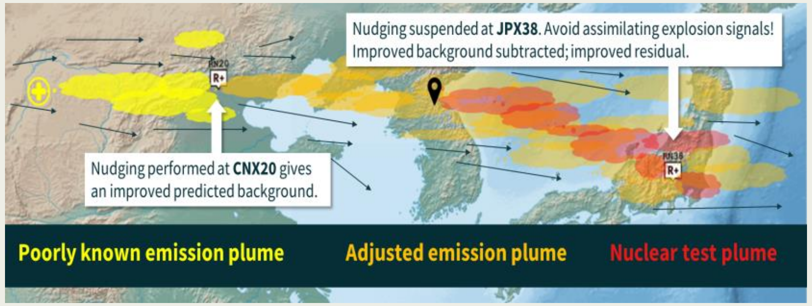
1. Assuming a prompt or slightly delayed release

Under this assumption nudging is suspended as soon as a mixture of background signals from known sources and explosion signals is predicted. The basic idea is to benefit from nudging at (an) upstream station(s) due to subsequently improved background signals from known sources at (a) downwind station(s) when calculating the residual between measurements and the predictions (see sketch under 2).

Exploitation

2. Assuming a delayed release

Prompt or slightly delayed venting is deemed unlikely (see DPRK tests). Machine learning incorporating relevant information (e.g., nudging increments) will be employed under this assumption. Nudging will not be suspended.



Example of a poorly characterized hypothetical civilian nuclear facility in China and westerly currents in combination with prompt venting following a hypothetical nuclear test performed in DPRK.

Challenges

- Sparseness of the IMS network
- Radioxenons are short-lived; nudged information will dissipate quicker compared to greenhouse gases.
- Ideally, the influence of emissions on nudging increments should be isolated. To get hold of the uncertainty in meteorological conditions, ensemble members from weather prediction models would be required to calculate mean or median nudging increments.

Conclusions

- Nudging of radioxenon background predictions to the IMS observation data, is one of a few general, essential approaches necessary to make promising progress in backtracking to known sources.
- The critical issue that remains is deducing the presence of explosion signals when nudging is suspended or in the process of nudging (via nudging increments).
- Preliminary findings indicate that nudging enhancements are largely confined to observational sites.
- Future work with FLEXPART-LCM will thus focus above all on improving the data assimilation approach. Potential enhancements of data assimilation include expanding the nudging influence via wider kernels. This, however, has challenges, risking the loss of spatial accuracy and model coherence. A hybrid strategy that combines nudging with more advanced flow-dependent or trajectory-based assimilation approaches may be an alternative.

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