Nudging: Making Background Predictions with Atmospheric Transport Modelling Sensitive to IMS Observations

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INTRODUCTION AND MAIN RESULTS

Radioxenon emissions originating from a variety of nuclear facilities (e.g. isotope production facilities) induce a variable, observable background signal in the noble gas part of the IMS network. This background poses a challenge for the verification regime of the CTBT because it may conceal detections resulting from nuclear test explosions. For the Xenon Background Estimation Tool project, scientific methods are explored to provide a confident identification of those well-established known sources. We clarify ‘nudging’, a basic data assimilation approach that calibrates particle masses towards IMS observations for more confident identifications. First project results are shown and discussed in poster P2.3-213.

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BETXe PROJECT

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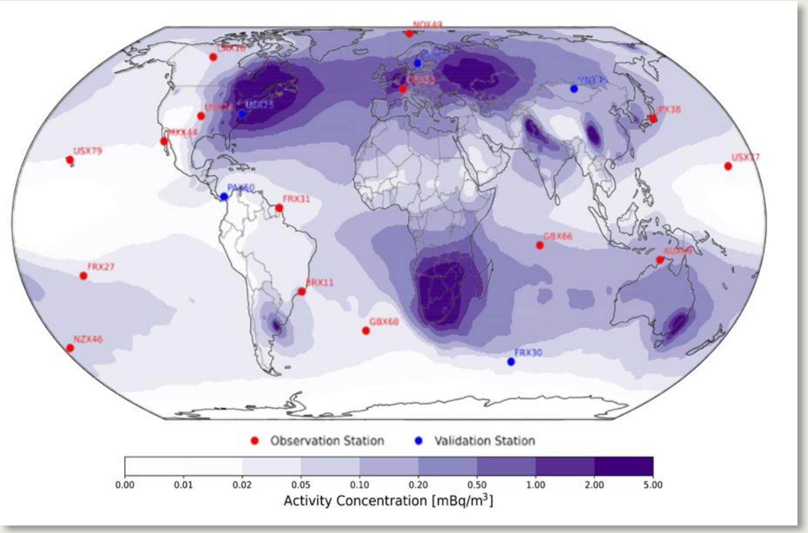
Motivation

Radioxenon emissions originating from a variety of well-established nuclear facilities (e.g. nuclear power plants) induce a variable and observable background that poses a challenge for the global monitoring of nuclear explosions because it may conceal signals resulting from a nuclear test explosion. Despite uncertainties in emission profiles from a variety of well-known (but also unknown) nuclear facilities, in dispersion modelling, and in the nuclear test explosion themselves less bias is required in background estimation so that noble gas detections can be screened out with more confidence.

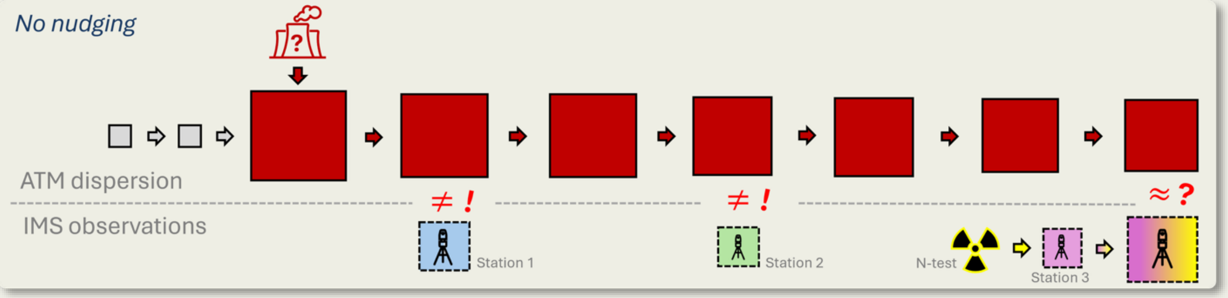


Map for 2014 showing the dispersion of activity concentration for ^{133}Xe induced by known emitters (nuclear power plants and medical production facilities). This annual average simulation (without nudging) peaks near sources and fades along transport routes. (J. Fleisch, 2025.)

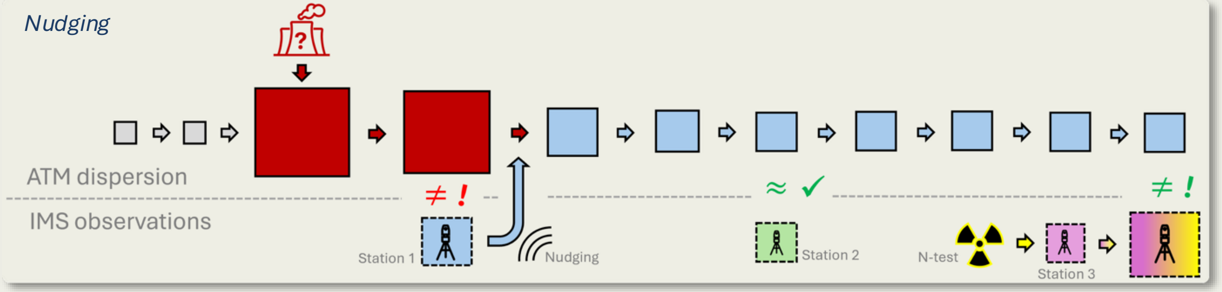
Methodology

CTBTO's Xenon Background Estimation Tool (XeBET) software project aims to explore and exploit scientific computing methods to confidently backtrack IMS noble gas detections to known emissions from nuclear facilities using atmospheric transport modelling (ATM) and machine learning. For the ATM part in the XeBET project, a novel approach called *nudging* is explored.

Nudging is a basic data assimilation technique used to gradually steer simulated dispersion of tracers closer to observational data by applying small, continuous adjustments. For CTBT verification, the dispersion pertains to the activity concentrations produced by FLEXPART, a Lagrangian transport and dispersion model suitable for the simulation of a large range of ATM processes. The latest instance of FLEXPART, version 11, contains the Linear Chemistry Module (LCM). In LCM, emission information is not attributed to initialized particles (as in the standard FLEXPART). Instead, the global domain is filled with particles while mass is attributed to the transported particles in the vicinity of emission sources. LCM includes a nudging module, which can be switched on and off during model runs, to adjust transported particle masses close to IMS stations.



Schematic of a basic no-nudging scenario; time and space flow to the right. An inadequately estimated mass (from a facility) is attributed to the (initial) simulated particle distribution but is not corrected for in IMS station 1. This eventually results in ambiguous comparisons in stations 2 & 3 (with or without an added nuclear test signal). The box size represents the concentration attributed, transported, and measured.



Same initialization as above but with nudging on. The observation of IMS station 1 is correcting the simulation, which will improve the comparisons downstream. The IMS observation in station 3 has an added signal by a nuclear test, which will now produce a confident residual due to less uncertainty in the ATM estimation.

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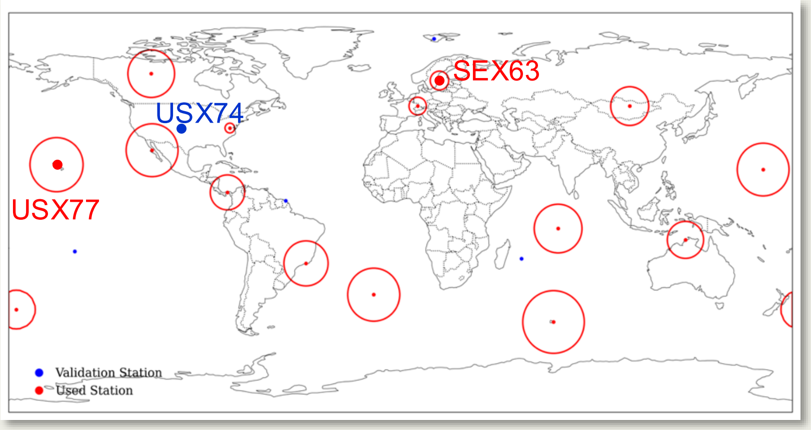
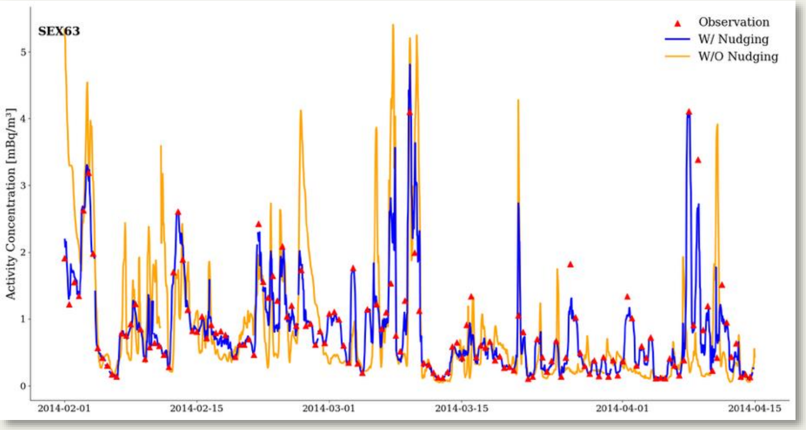
Methodology cont'd

- Each IMS observation is represented by a 4D kernel (space + time) in which simulated concentrations are 'Newtonian relaxed' toward the observation.
- Spatial kernel widths set the influence range in each direction; larger values = broader influence.
- Temporal kernel width determines how long before/after the observation time nudging is applied.
- Relaxation timescale controls adjustment speed: smaller values = faster correction. Nudging keeps the simulated SRS fields close to the observations of the IMS.

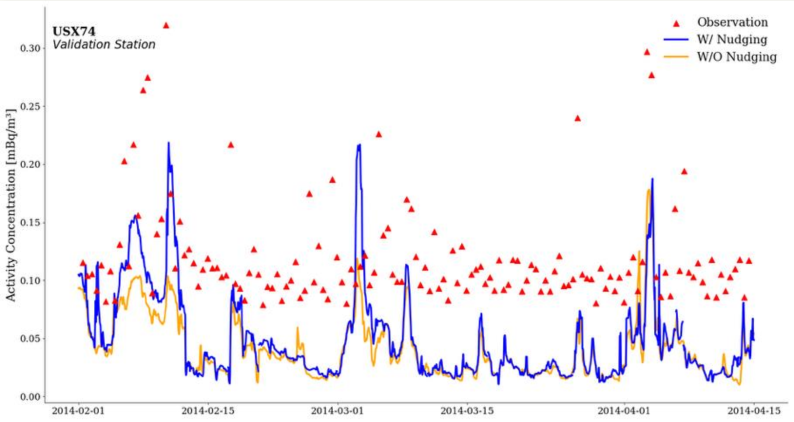


The nudging kernels in red; validation stations in blue. The strongest effect occurs where data are available (near IMS stations) and over oceans, where lower variability makes nudging more representative across larger regions. (J. Fleisch, 2025.)

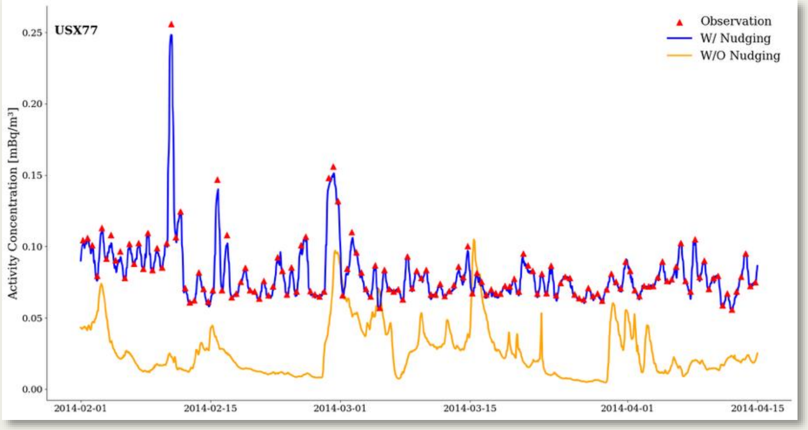
Examples



Time series for 2.5 months in 2014 for IMS station SEX63 with moderate nudging results. (J. Fleisch, 2025.)



Time series for 2.5 months in 2014 for IMS station USX74, a validation station. Validation stations are used to test the model generalization beyond nudged regions; selected for geographic and climatic diversity.



Time series for 2.5 months in 2014 for IMS station USX77 with promising nudging results. (J. Fleisch, 2025.)

Results

First nudging results of the XeBET project are shown and discussed in poster **P2.3-213.**

Conclusions

Nudging radioxenon ATM background predictions towards IMS observations aims to be one of a few promising approaches necessary to make progress in 'backtracking to known sources'. Nudging will serve as an extended ATM method in the XeBET project, next to machine learning methods for finding anomalies.

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