Approaches for Estimating Radioxenon Background Variations, Anomalies, and Explosion Signals in Modeled and Measurement Data

Presenter

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Team (alphabetical order)

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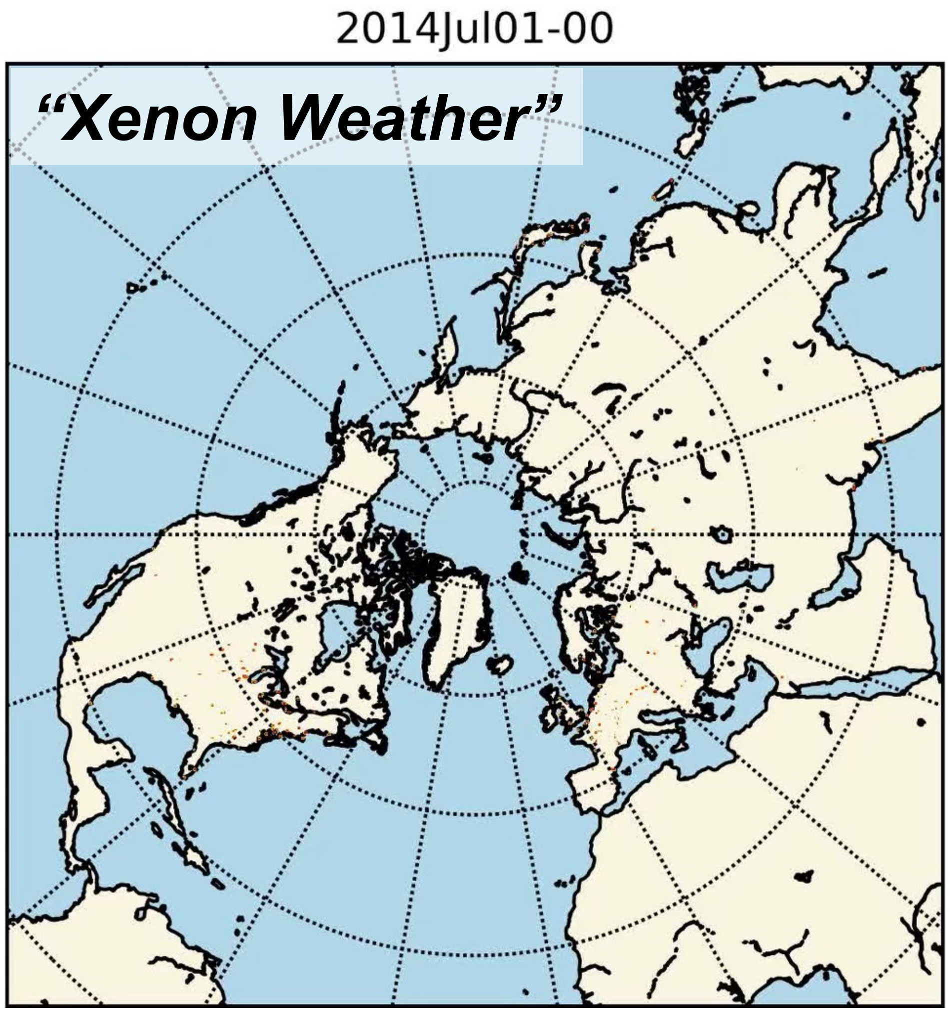
Background Radioxenon is Highly Variable in Space and Time



Movie of Xe-133 released from 200 facilities on 2014 July 01 and tracked for two weeks. Colors show near-surface logarithmic activity concentrations.

Extracting nuclear test signals from the radio-xenon background is like finding a needle in a haystack.

Advances in modeling and algorithms may help find the needle.

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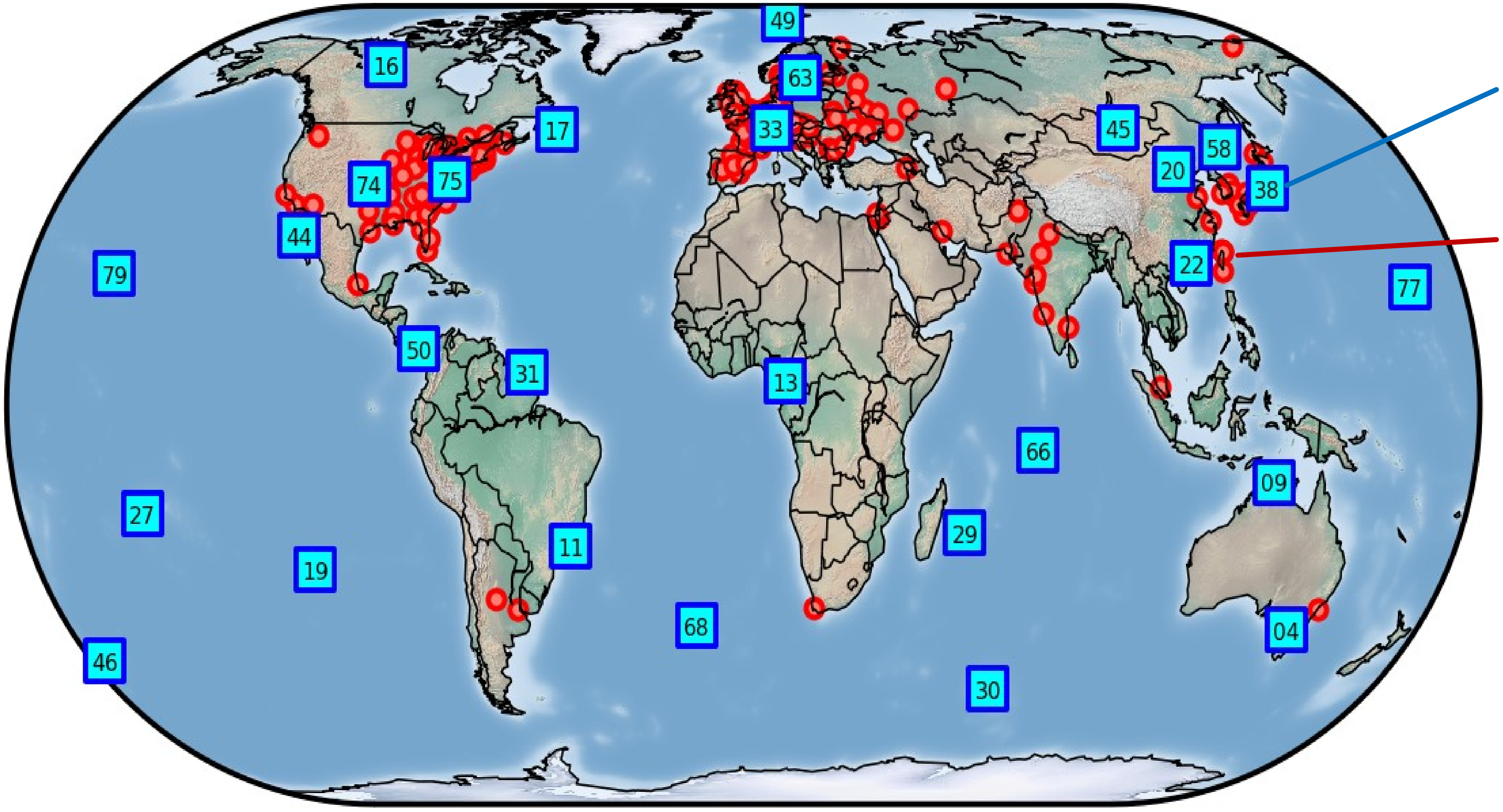

RN stations

Potential background xenon sources (nuclear power plants, research reactors, and medical isotope facilities)

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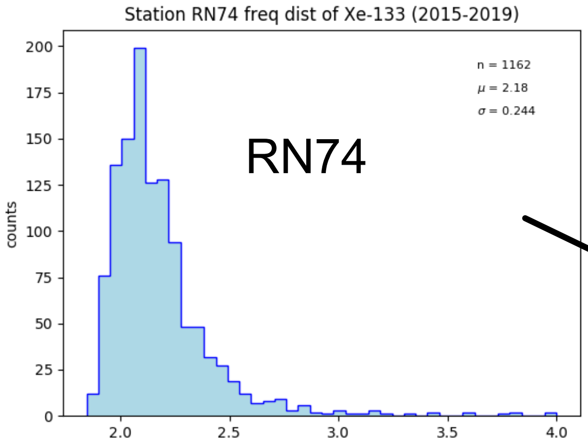
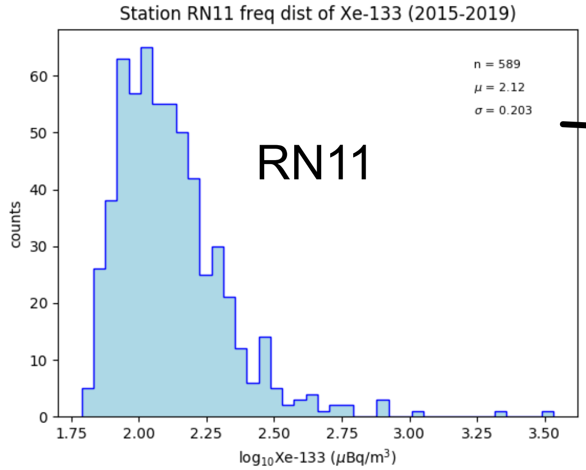
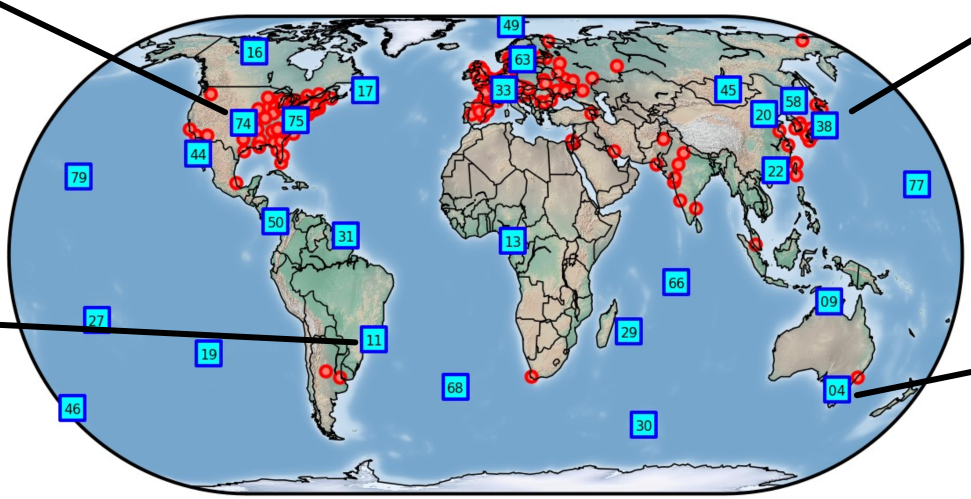
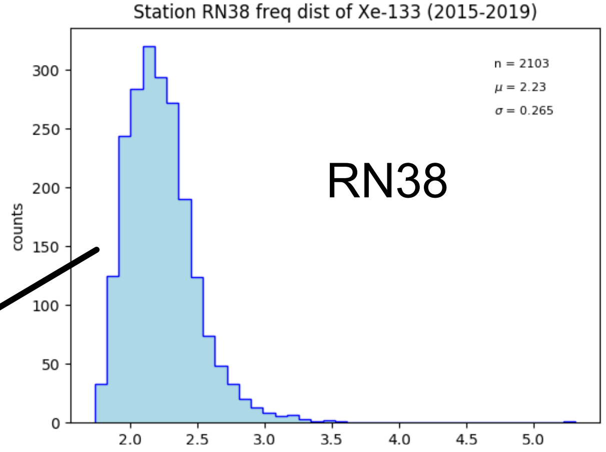
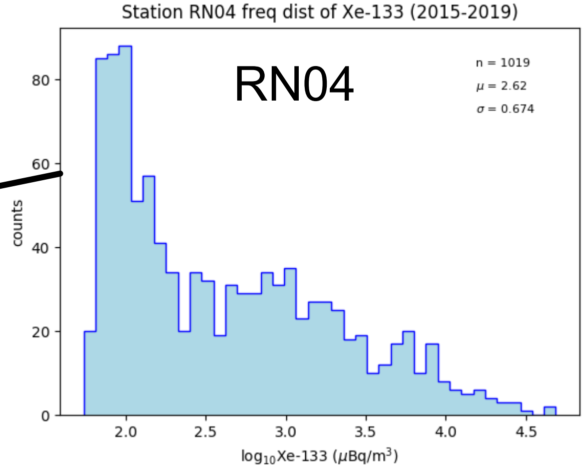




Radioxenon variability at IMS stations depends on proximity to sources, changes in meteorology, topography, and land properties, and other factors.



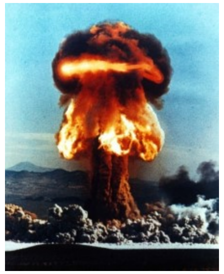


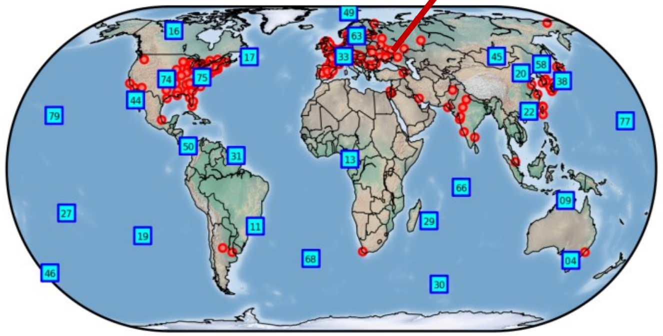


Frequency distributions of Xe-133 over the period 2015-2019.

Atmospheric Models Can Be Used to Estimate Background Xenon

Xenon Sources

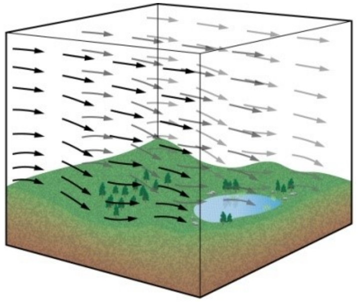




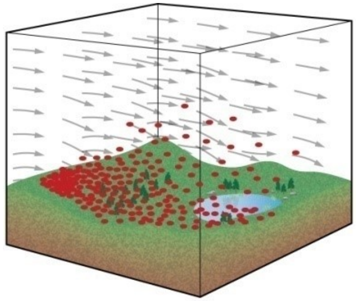
Xenon emission rates at facilities are typically not measured and can represent a large source of model uncertainty.

Atmospheric Models

Meteorology



Atmospheric transport



ECMWF
EUROPEAN CENTRE FOR MEDIUM RANGE WEATHER FORECASTS

GFS
Global Forecast System

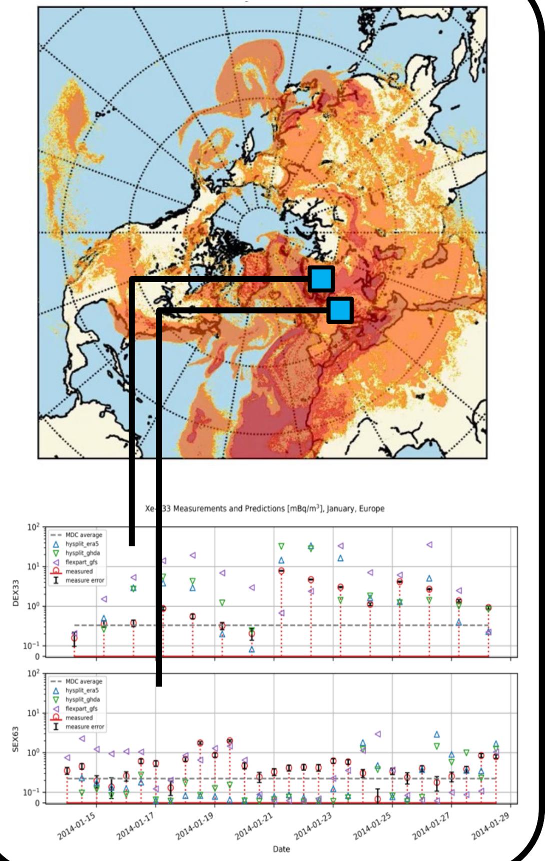
NATIONAL CENTERS FOR ENVIRONMENTAL PREDICTION
NCEP

HYSPLIT
AIR RESOURCES LAB

FLEXPART

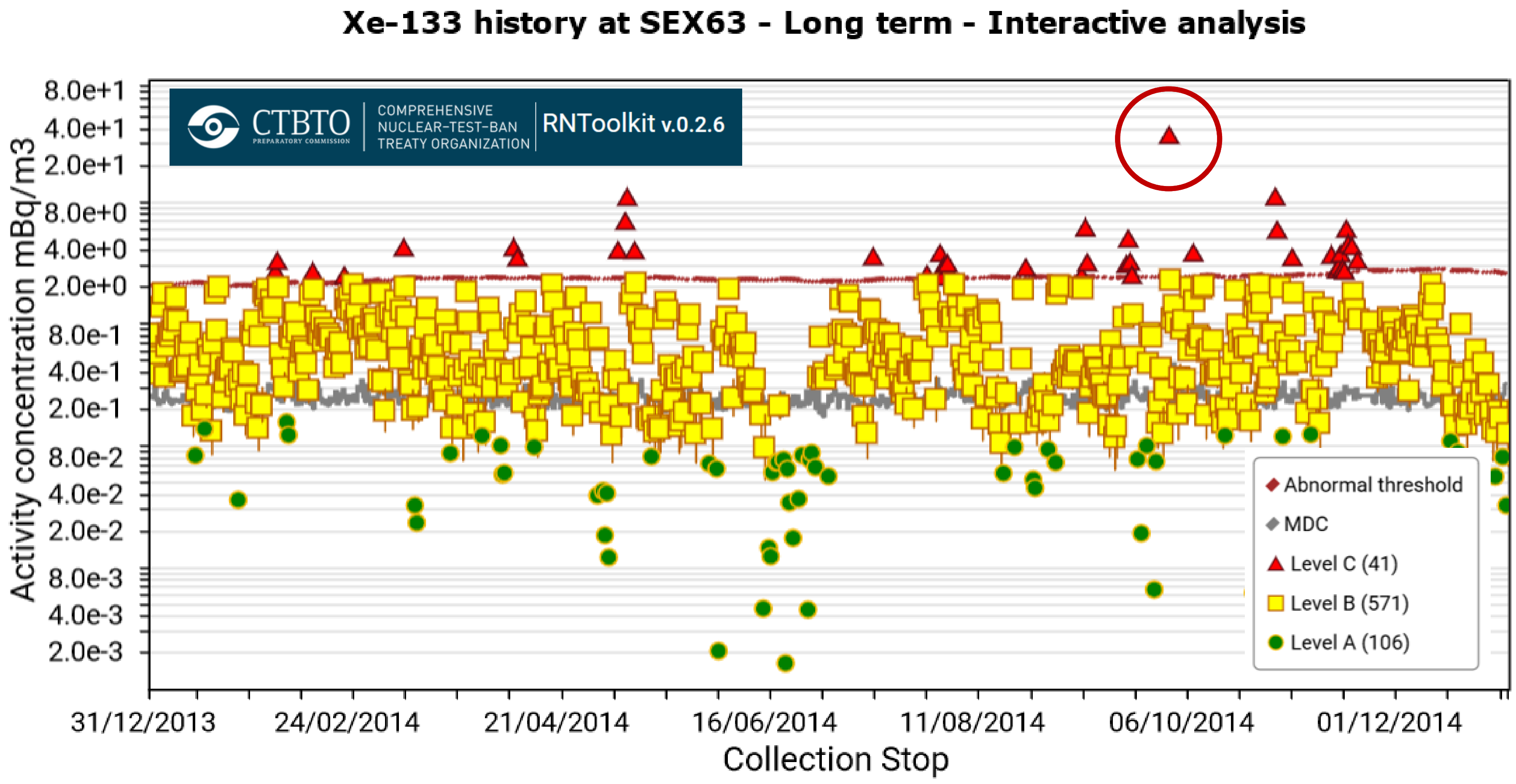
HYSPLIT
AIR RESOURCES LAB

Xenon Signals



Inverse Modeling

Identifying Xenon Anomalies in Measurements

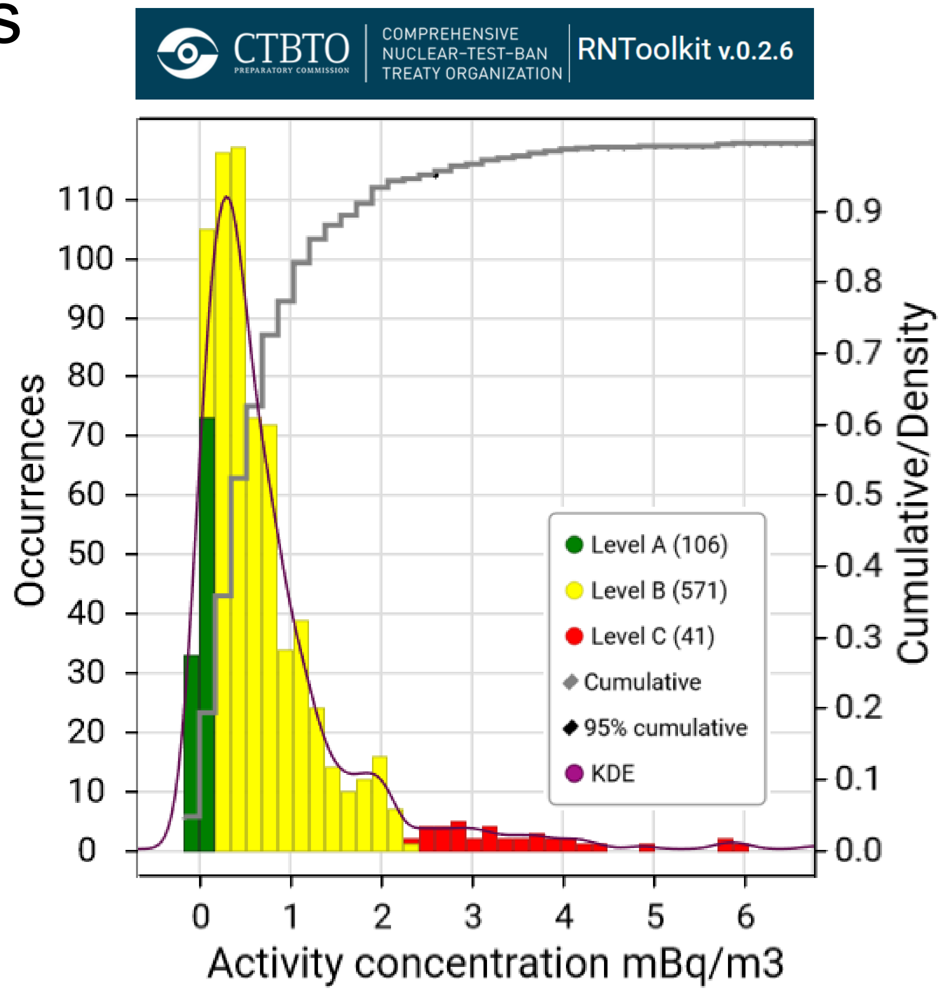


To distinguish explosion signals from background sources, it is important to quantify the size and frequency of xenon anomalies.

Identifying Xenon Anomalies in Measurements

Anomalies can occur in multiple dimensions
- One or more Xe isotopes
- One or more IMS stations

Quantile Scores
- Empirical and easy to compute in one dimension, but challenging in higher dimensions



Outlier/Novelty Detection Algorithms
- Time series methods
- Machine learning approaches
  - Local Outlier Factor
  - Random Isolation Forest

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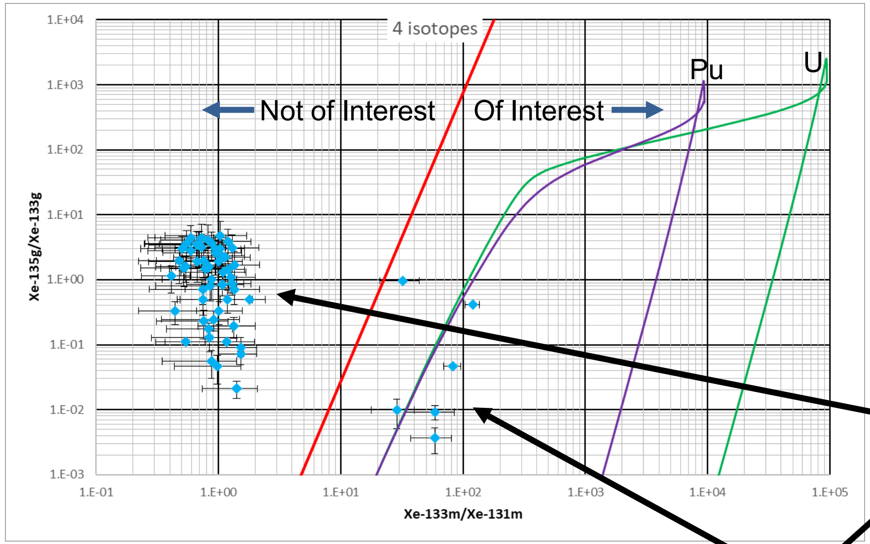
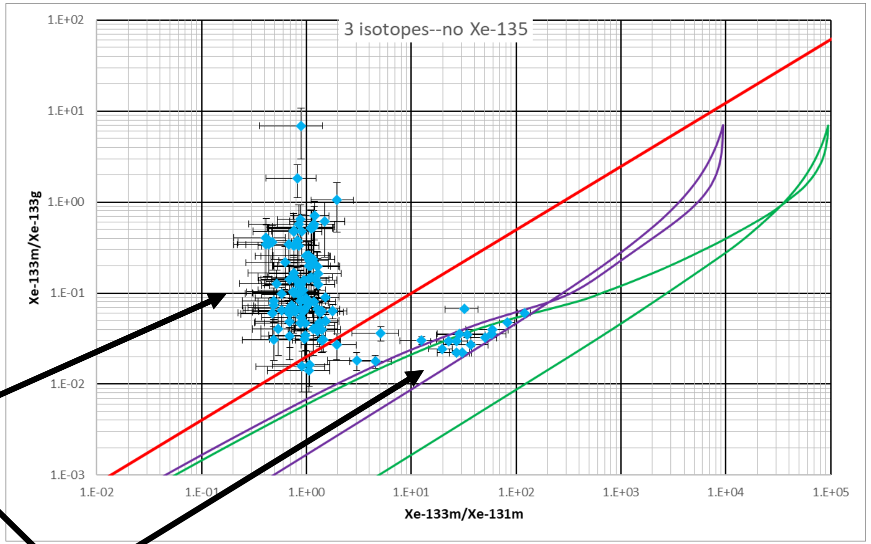
Example of Identifying Xe-133 Signal Injections in January 2014

	true positive rate	false positive rate
q50	0.924	0.115
q75	0.847	0.066
q90	0.784	0.036
q95	0.72	0.017
q96	0.716	0.015
q97	0.686	0.011
q98	0.657	0.008
q99	0.623	0.004

There is a tradeoff between true positives and false positives versus the quantile threshold.

Identifying Xenon Anomalies in Measurements

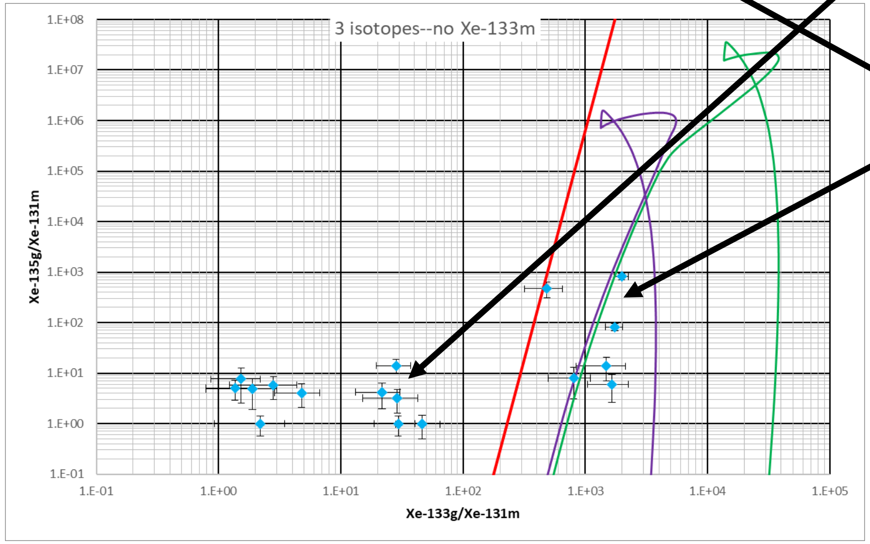


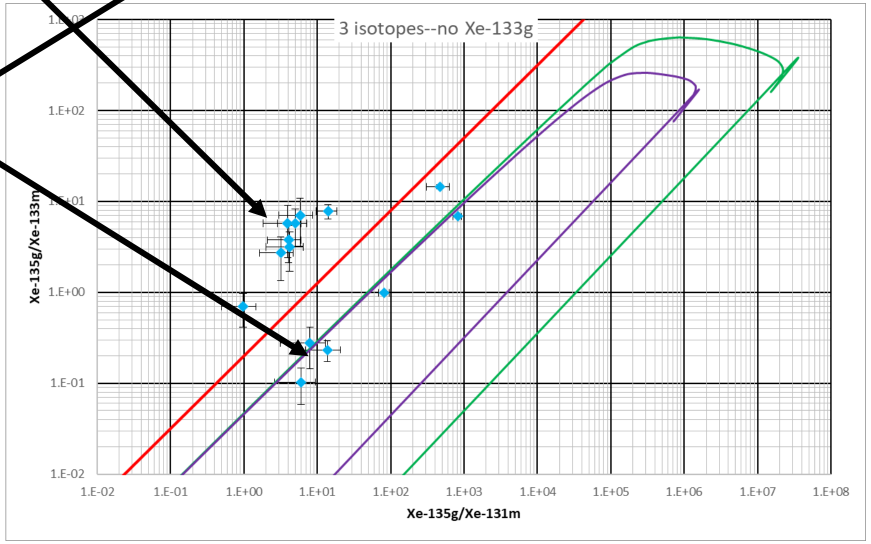


Xenon Ratios help identify anomalies

Xenon Samples not of interest

Xenon Samples of interest





Requires detecting multiple isotopes

With fewer isotopes can use MDC

Identifying Xenon Anomalies in Measurements

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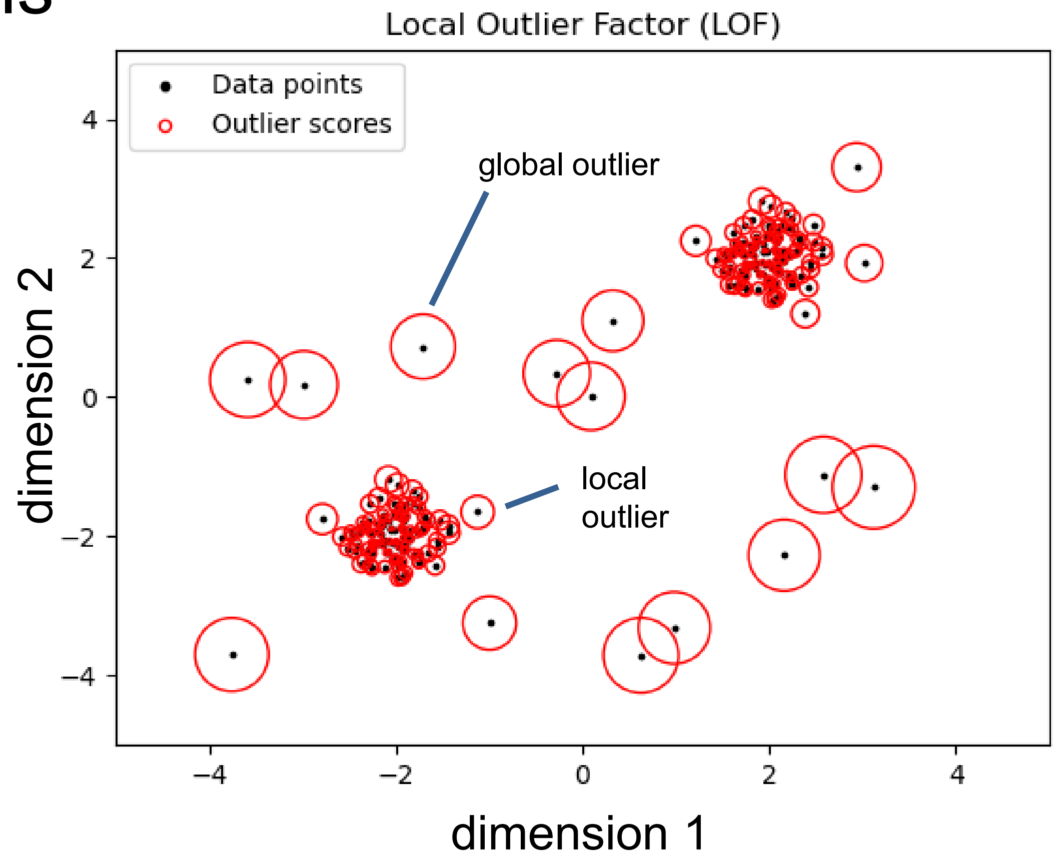

Image modified from scikit learn

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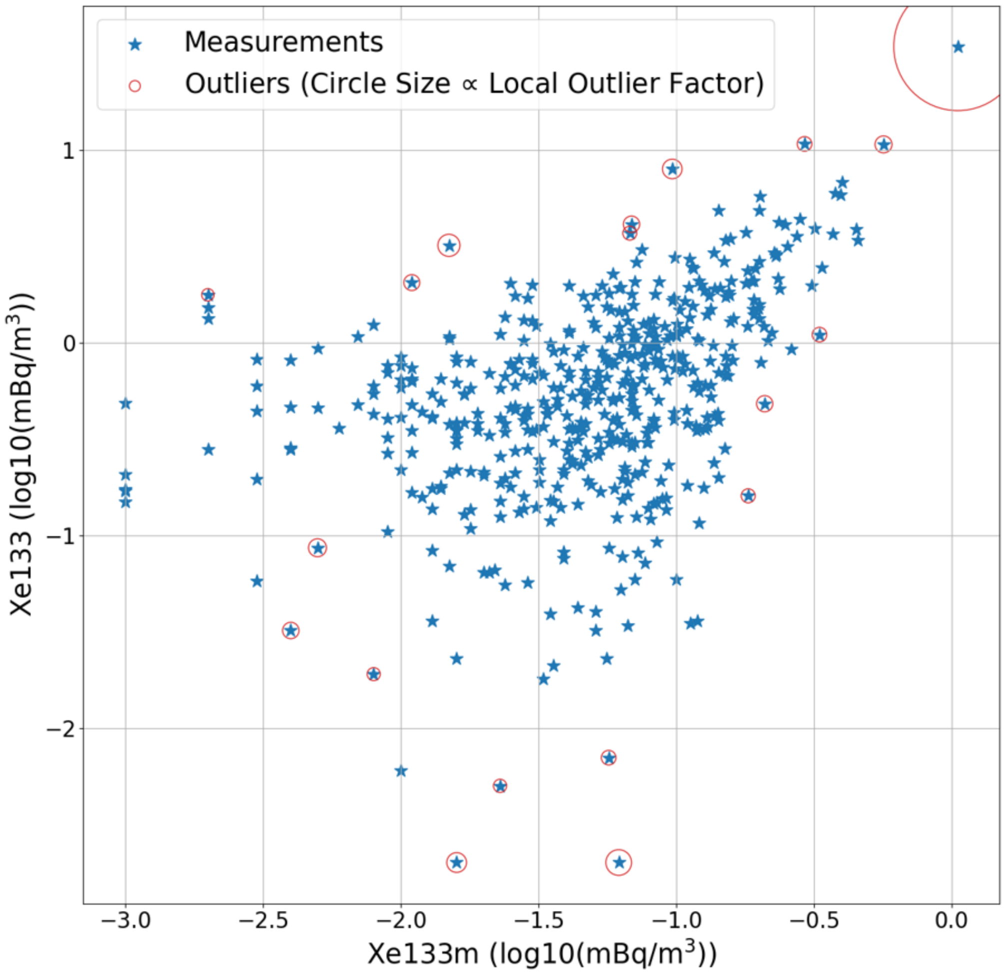
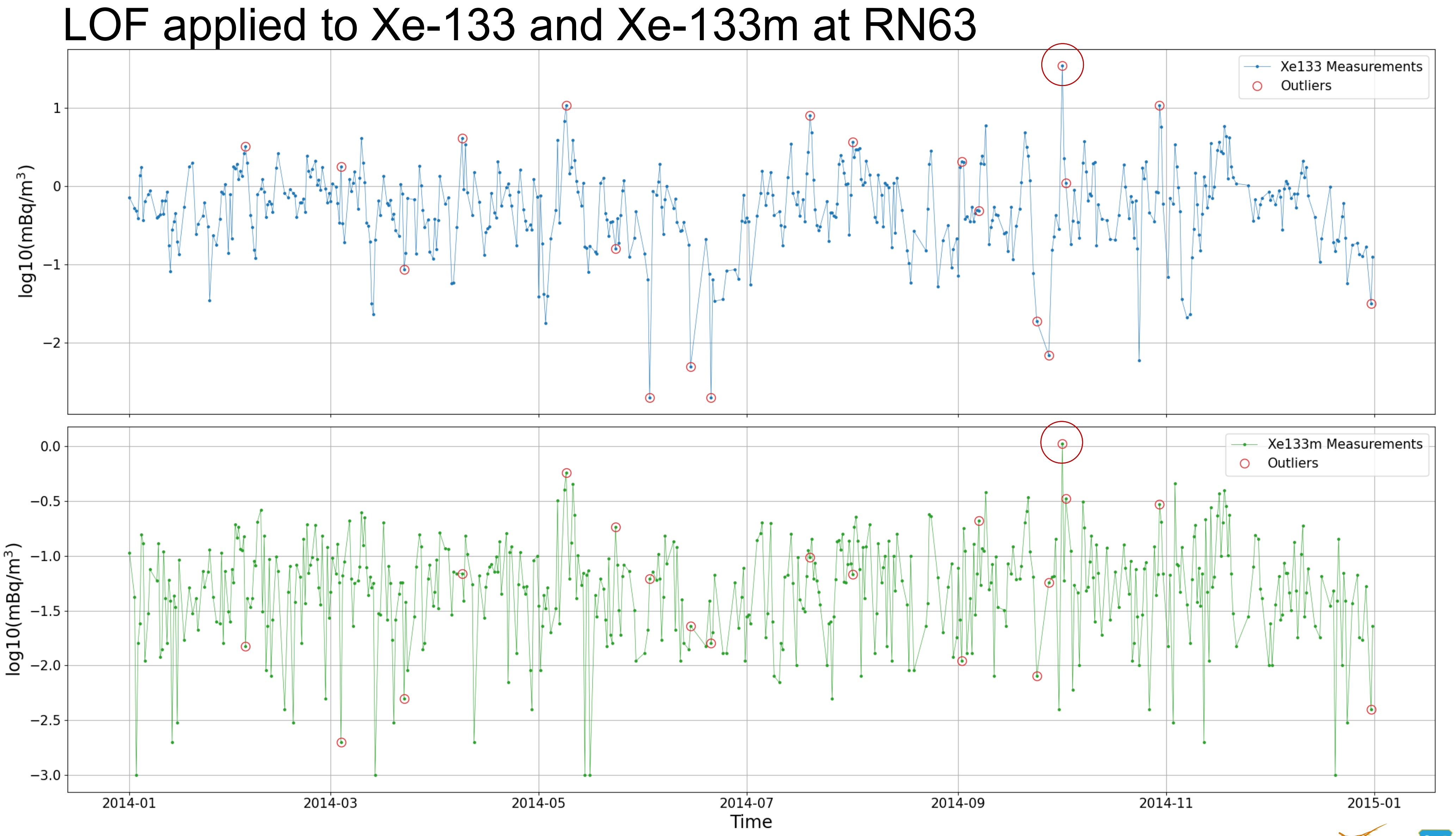
LOF applied to Xe-133 and Xe-133m at RN63 for 2014



Identifying Xenon Anomalies in Measurements



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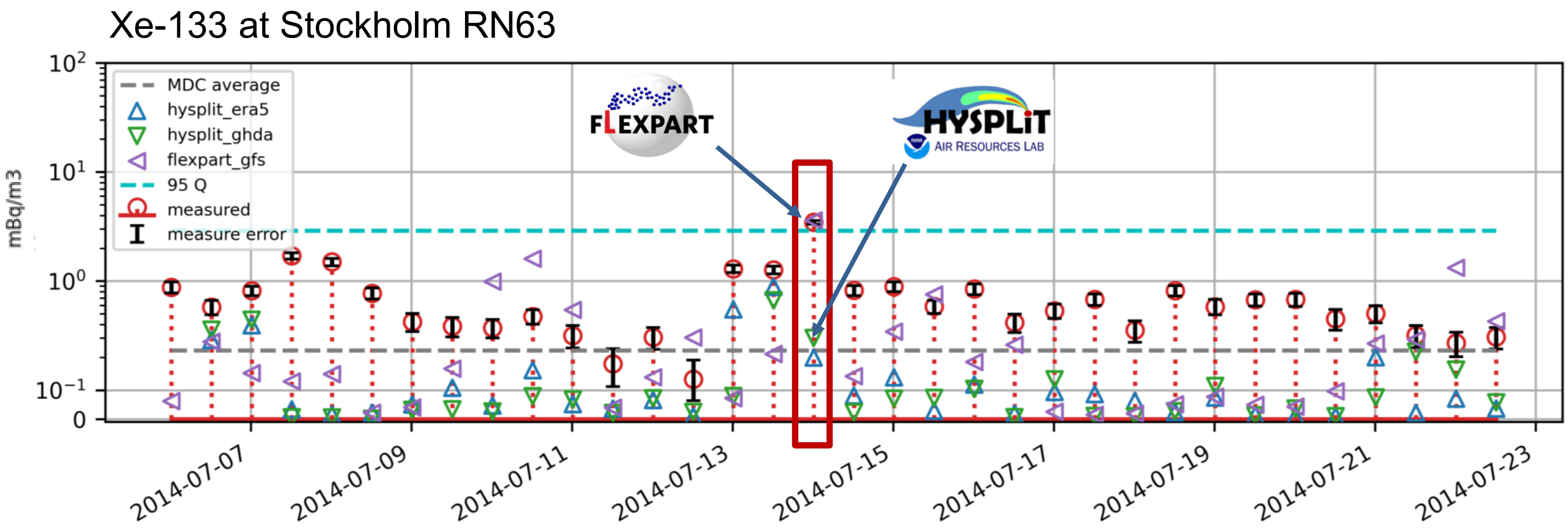
Identifying Anomalies With Measurements & Atmospheric Models



- Both models tend to underpredict Xe-133 during this period.
  - A case of low emissions or a bias in the atmospheric models?
- There was an elevated collection on 14 July at the 97th percentile.
- FLEXPART matches the elevation, HYSPLIT does not.
- Is the elevated collection an anomaly of interest?

Identifying Anomalies With Measurements & Atmospheric Models

Regression methods can be used to combine ensembles of models, correct for model biases and errors, and provide predictions of IMS collections with uncertainty.

CTBTO PREPARATORY COMMISSION INTERNATIONAL MONITORING SYSTEM $\approx F($ HYSPLIT AIR RESOURCES LAB, FLEXPART $)$

$$\boldsymbol{Y_{IMS}} = \boldsymbol{F}(Hysplit_1, Hysplit_2, \ldots, Flexpart_1, Flexpart_2, \ldots)$$

Train on data for previous periods ➔ Apply to collections of interest

Other predictors can be incorporated, like collections from different IMS stations, environmental variables, categorization levels, etc.

Identifying Anomalies With Measurements & Atmospheric Models

Bayesian Ridge Regression for Xe-133 at RN63

Robust to outliers, easy to train, and provides uncertainty estimates.

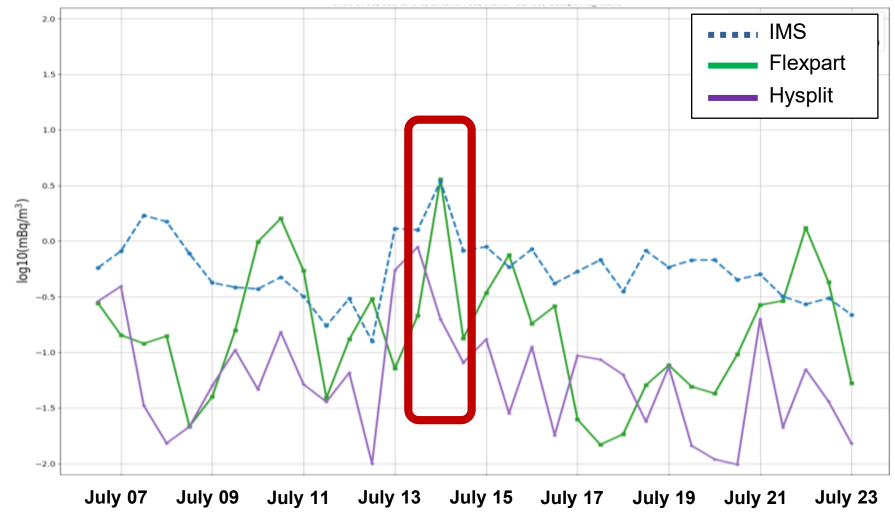
Elevated collection on 13-14 July lies within the regression prediction uncertainty.

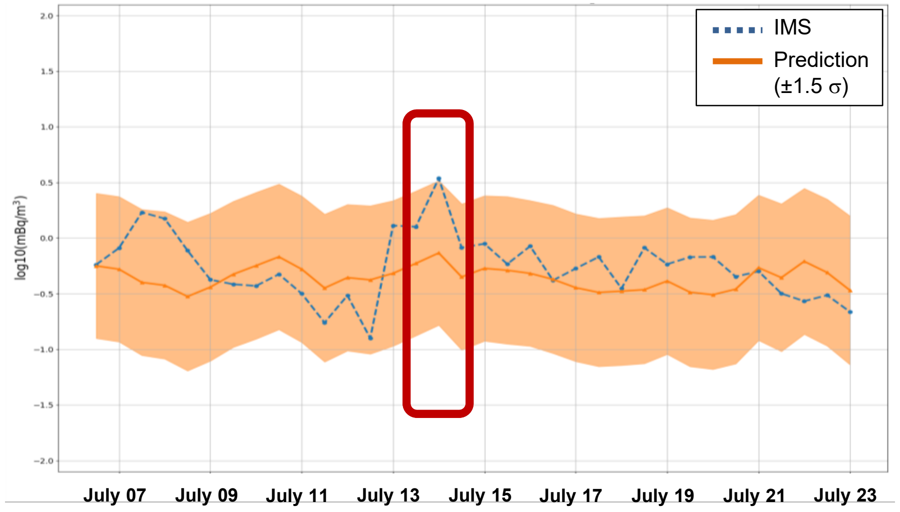
Injected signal on 19-21 July is detected as an anomaly.

Regression Inputs/Targets

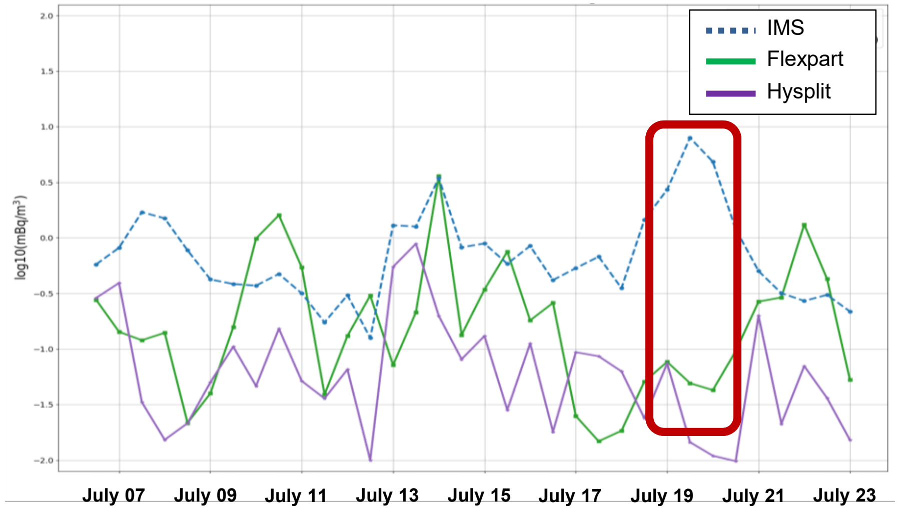
Regression Predictions

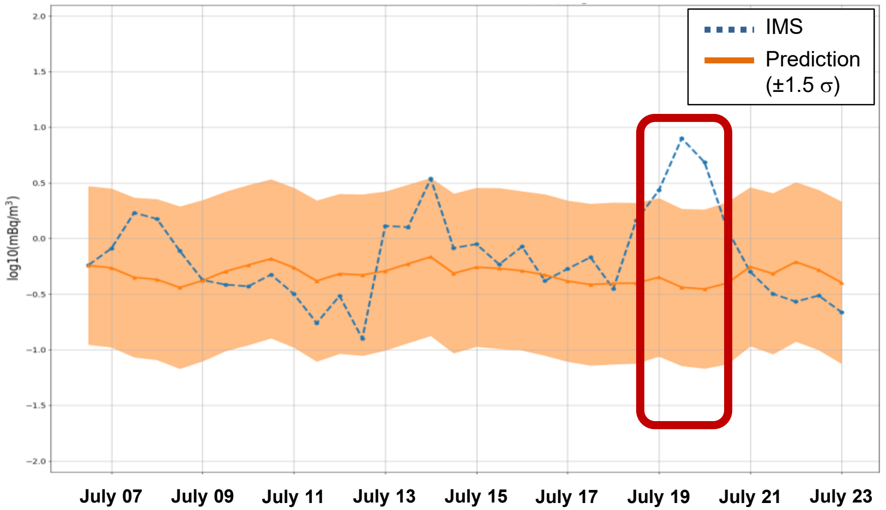
No Injection





With Injection





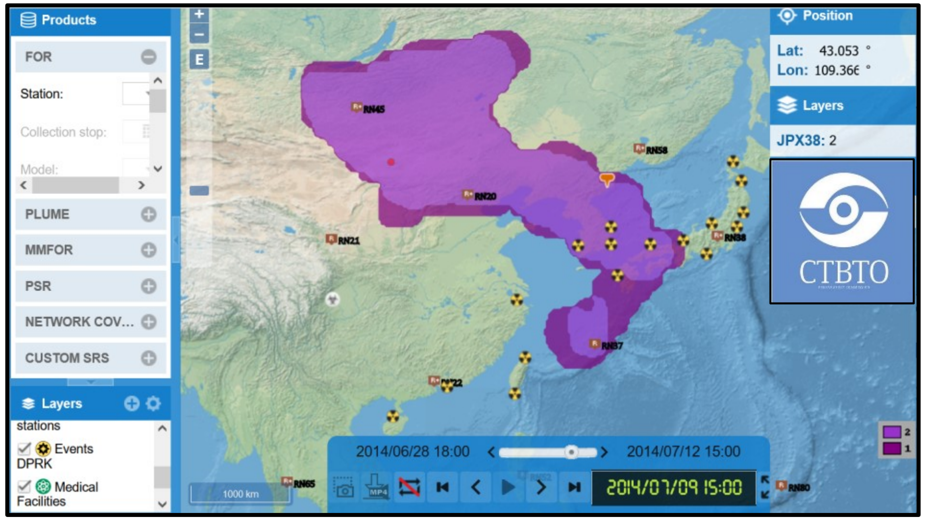
Identifying the Origin of Anomalies

Backwards Modeling

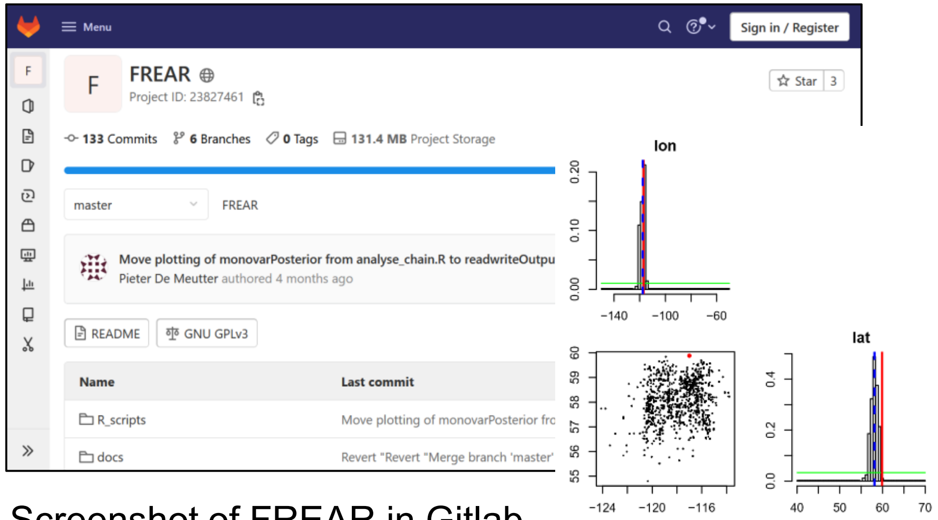
- Field of Regard (FOR)
- Possible Source Region (PSR)

Probabilistic Methods

- *Forensic Radionuclide Event Analysis and Reconstruction* Tool (FREAR)
- *Machine Learning Approach*
  - Forward model runs are used to create synthetic detections/non-detections for training data and testing.
  - Once trained, millions of alternate source locations can be quickly evaluated.
  - Previously presented at WOSMIP and INGE.



3-day multi-model field of regard for JPX38 for collection for sample ID 2862643 using Web-Grape



Screenshot of FREAR in Gitlab and test results.

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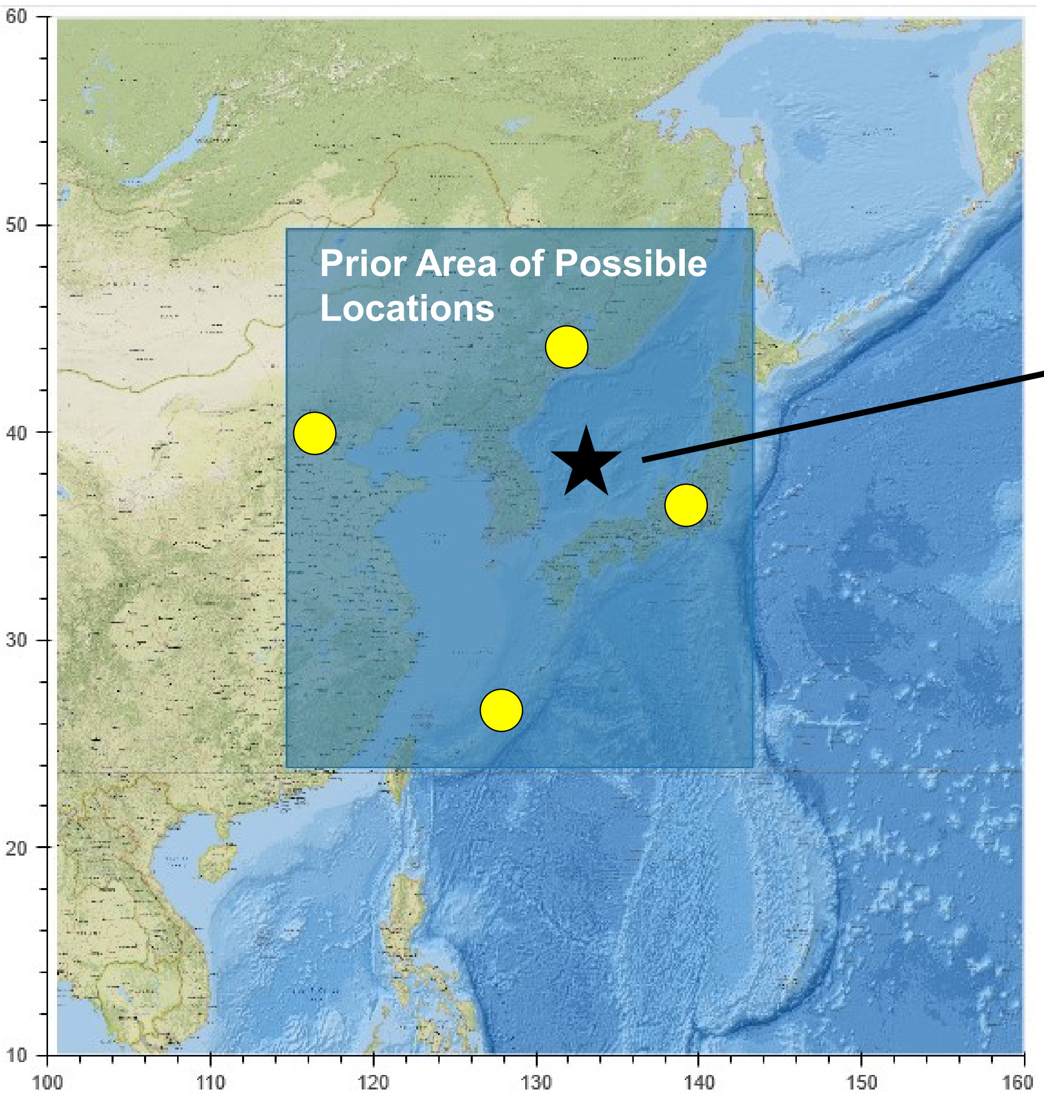
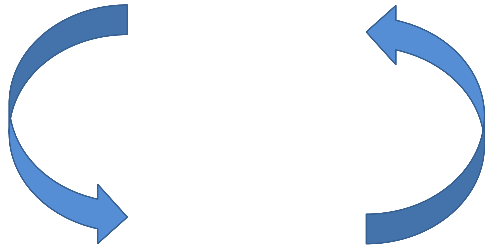
Identifying the Origin of Anomalies



Machine Learning Example

Values to Generate Synthetic Observations

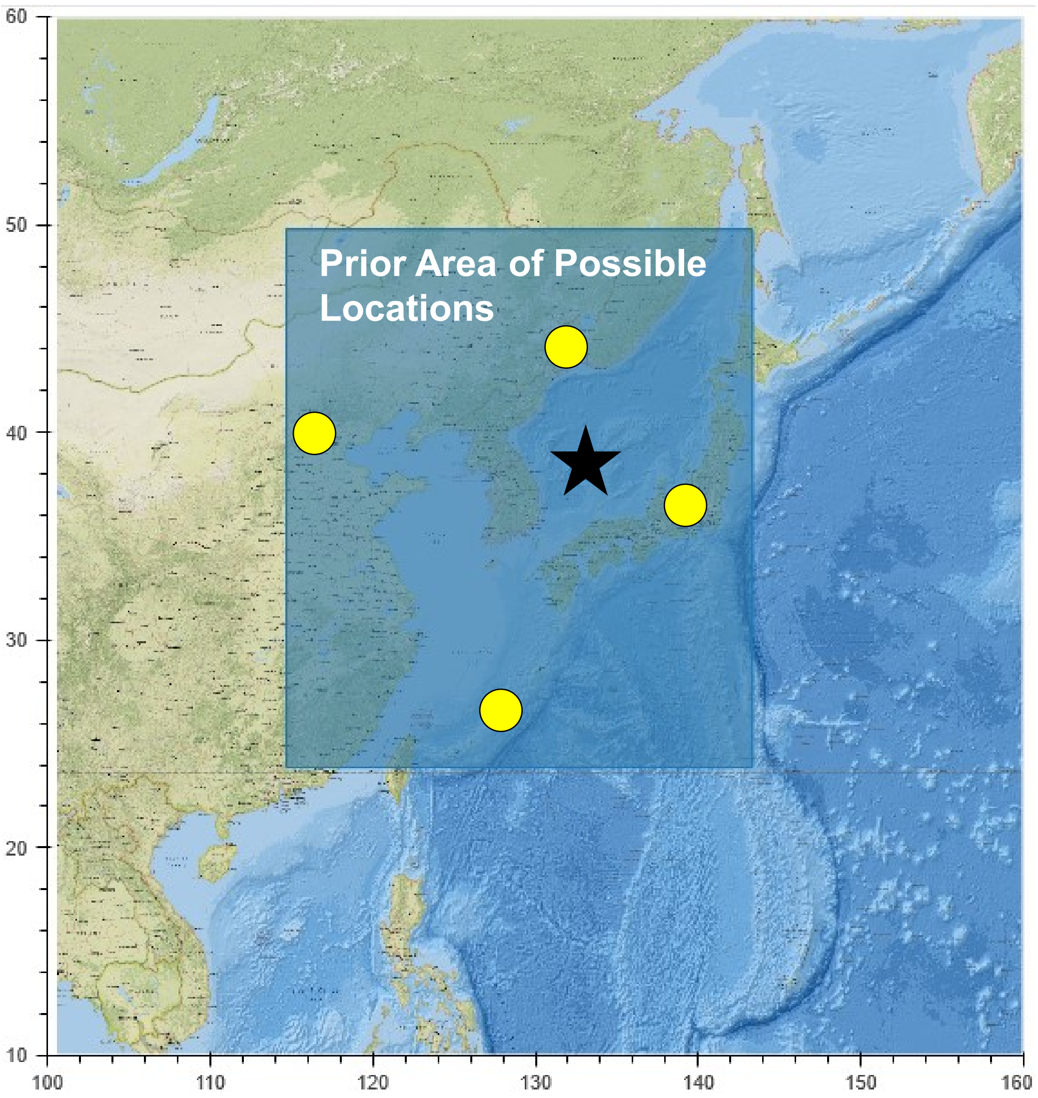
Latitude	Longitude	Start Hours	Duration Hours	Amount
38.1336	132.8962	65.4873	3.0234	896.9242



Site Name	Oct 09	Oct 10	Oct 11	Oct 12	Oct 13	Oct 14	Oct 15
RN20	0	0	0	0	0	0	0
RN37	0	0	0	0	0	0	1
RN38	0	0	0	0	1	1	1
RN58	0	0	0	0	0	0	0

= non-detect = detect

Identifying the Origin of Anomalies



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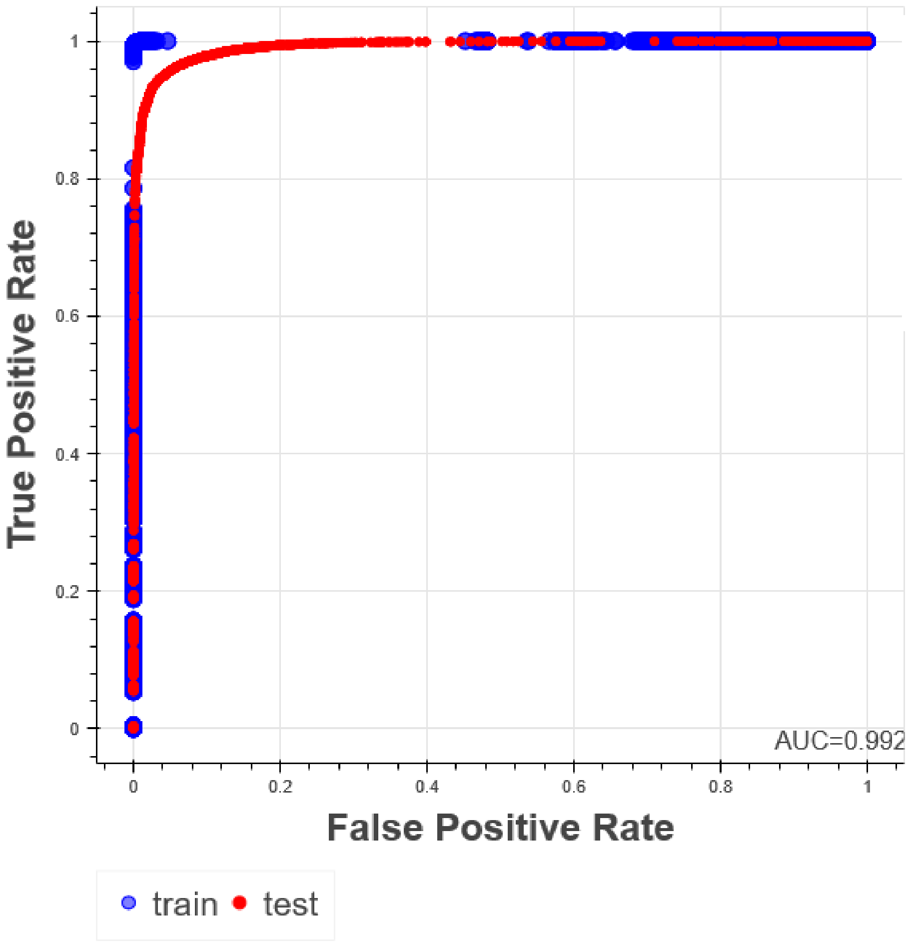

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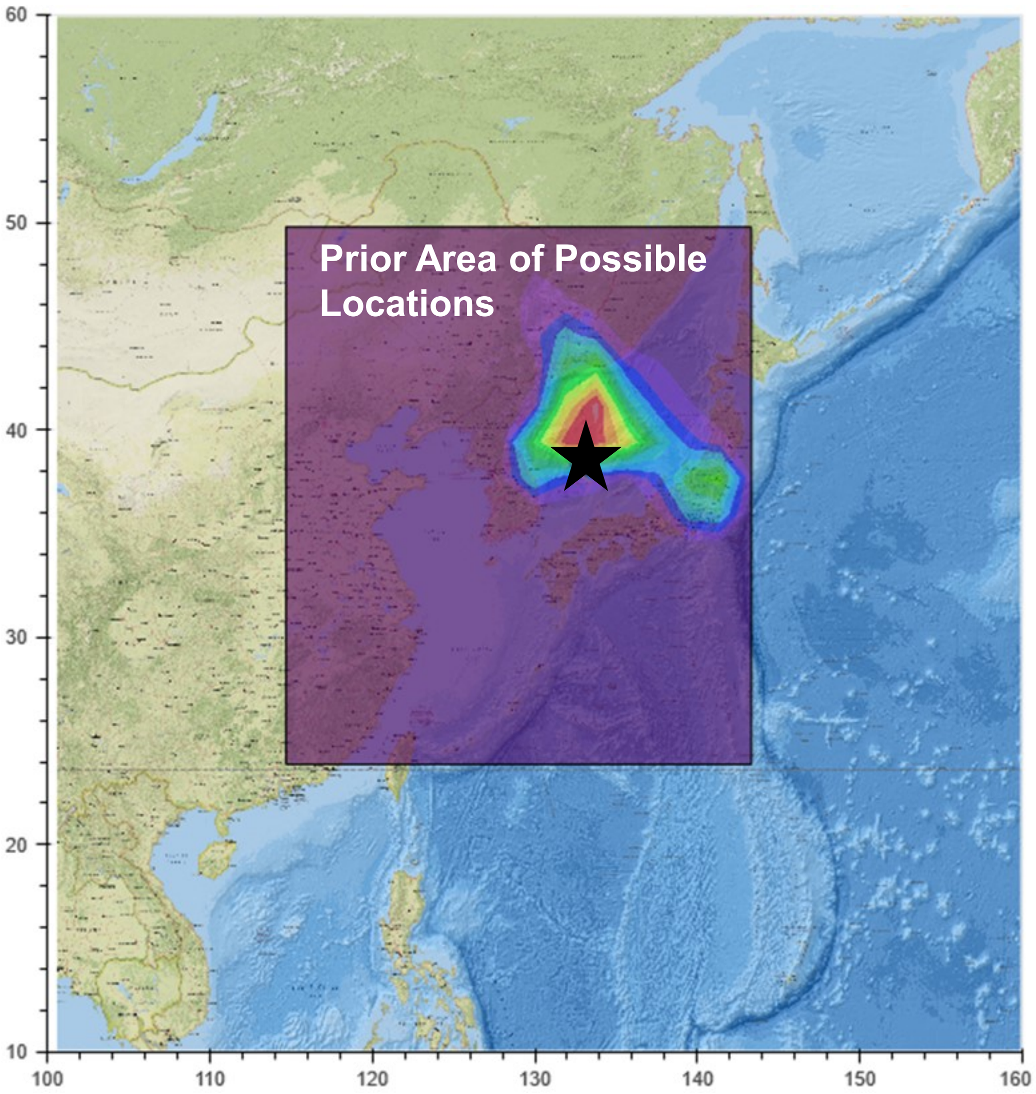

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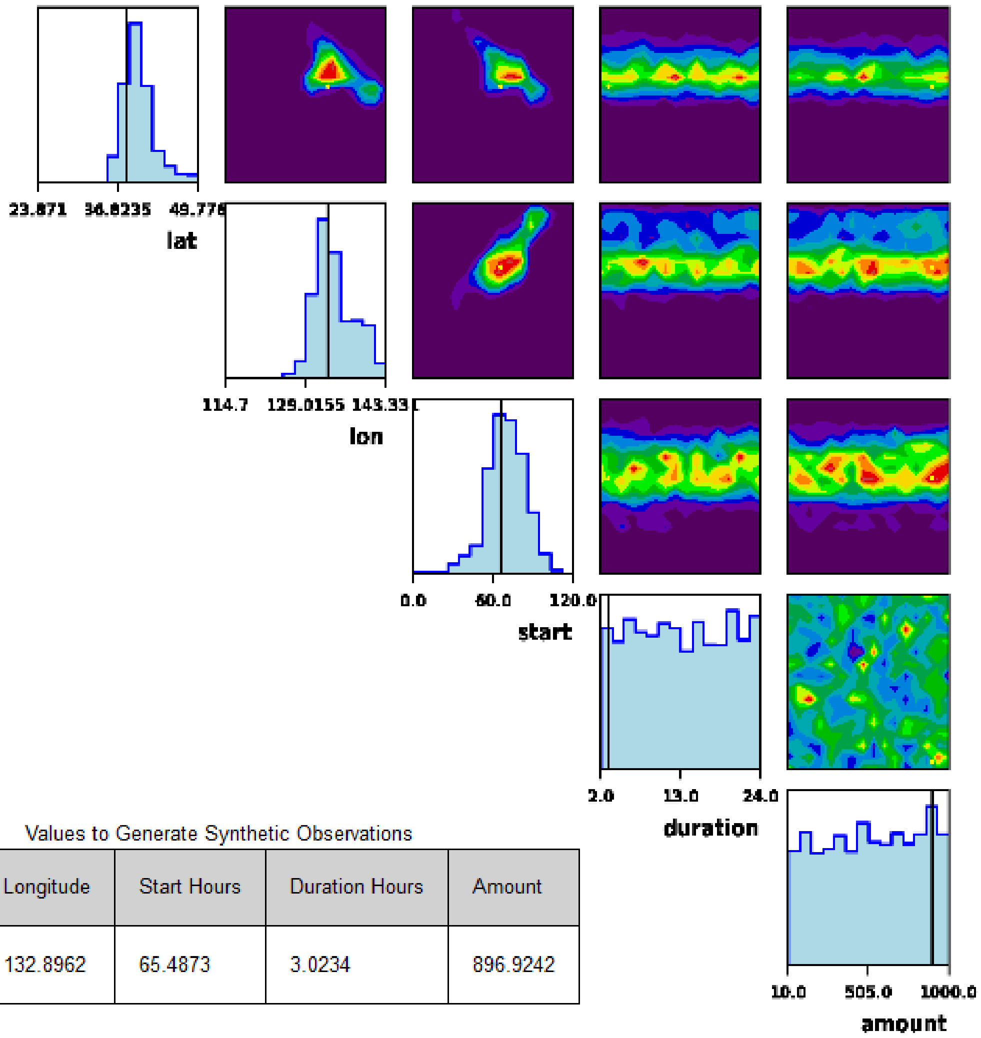

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Summary

- Xenon isotopes used for nuclear monitoring are highly variable in space and time due to
  - changes in weather.
  - the presence of many, widely distributed background industrial sources.

- Advanced methods using atmospheric modeling and statistical analysis are needed to
  - identify xenon anomalies of interest.
  - attribute the anomalies to background sources or nuclear testing.
  - determine the origin of detections.

- Through a collaborative effort, we
  - ran multiple atmospheric models to simulate xenon signals across the global IMS network in 2014.
  - developed and tested outlier and novelty detection methods using quantile approaches and unsupervised machine learning algorithms.
  - used supervised Bayesian regression algorithms to combine multi-model predictions and IMS collections for detecting anomalies with uncertainty.
  - applied probabilistic algorithms to locate the origin of suspected anomalies.

Extra Slides

Atmospheric Models Can Be Used to Estimate Background Xenon

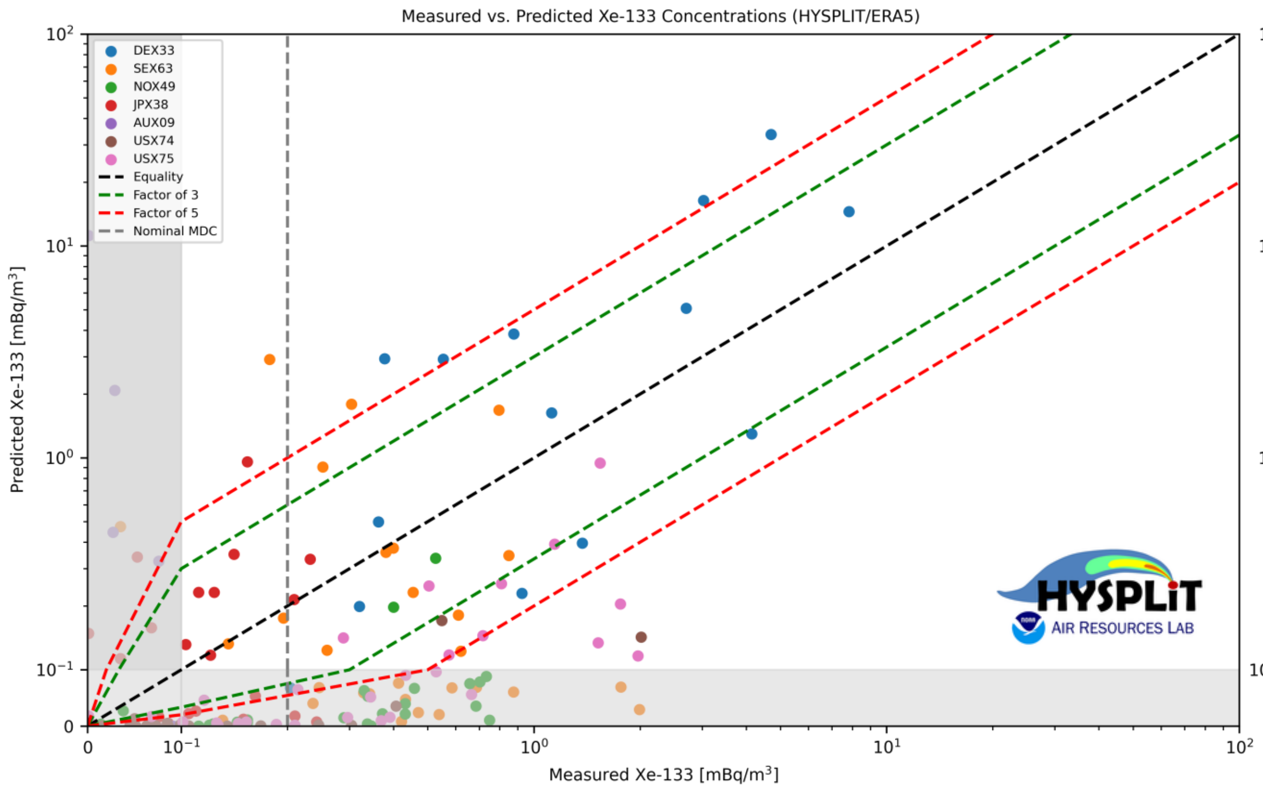
Atmospheric model performance statistics for January 2014

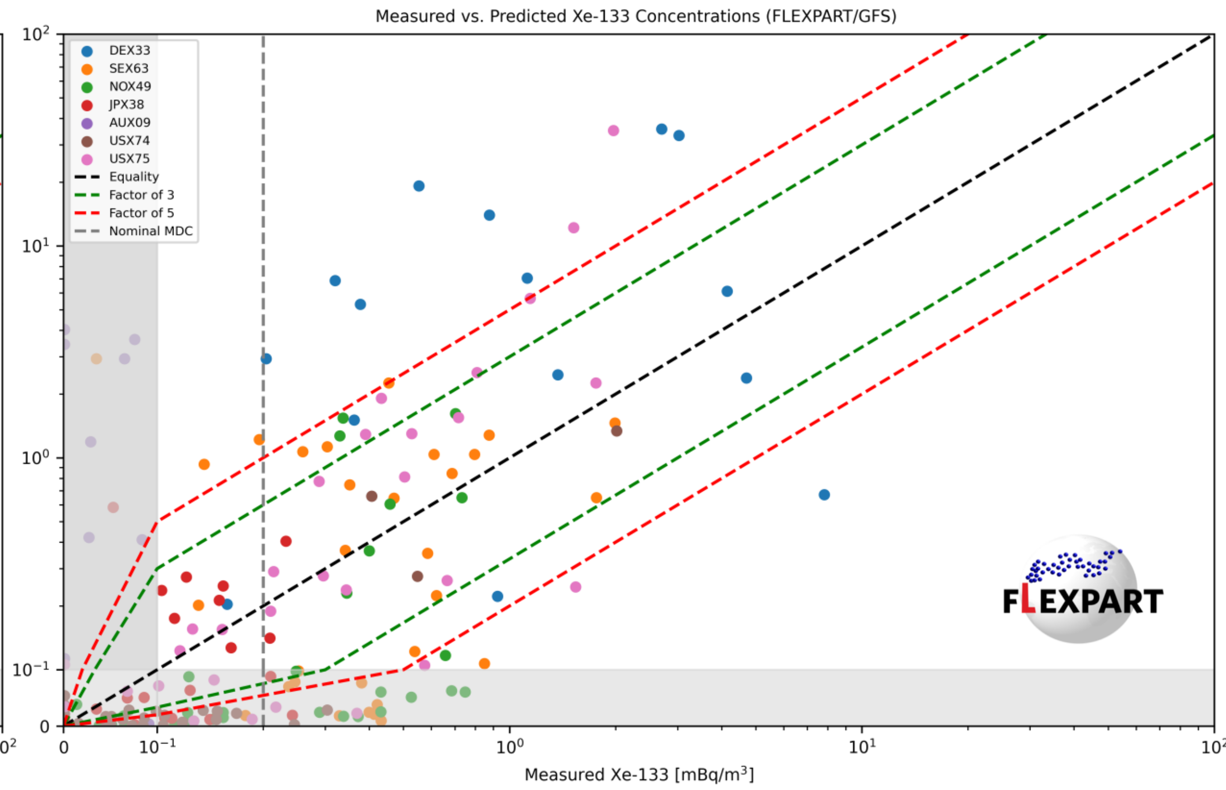
model	hysplit_era5			hysplit_gdas			flexpart_gfs		
	Factor 3x	Factor 5x	Corr	Factor 3x	Factor 5x	Corr	Factor 3x	Factor 5x	Corr
NOX49	0.1	0.133	0.45	0.033	0.1	0.208	0.267	0.367	0.389
DEX33	0.4	0.667	0.652	0.467	0.667	0.806	0.267	0.4	0.042
SEX63	0.267	0.367	-0.167	0.2	0.367	-0.097	0.433	0.667	0.109
JPX38	0.4	0.65	0.082	0.25	0.4	-0.448	0.65	0.65	0.12
AUX09	0.083	0.167	-0.257	0.167	0.25	-0.236	0	0.083	0.067
USX74	0	0.067	0.778	0	0.033	0.421	0.233	0.367	0.938
USX75	0.167	0.367	0.605	0.1	0.3	0.376	0.533	0.667	0.671
23 stations	**0.171**	**0.241**	**0.656**	**0.16**	**0.226**	**0.758**	**0.25**	**0.318**	**0.433**

Further data QC may be necessary (based on analysis of spectra)

Atmospheric Models Can Be Used to Estimate Background Xenon

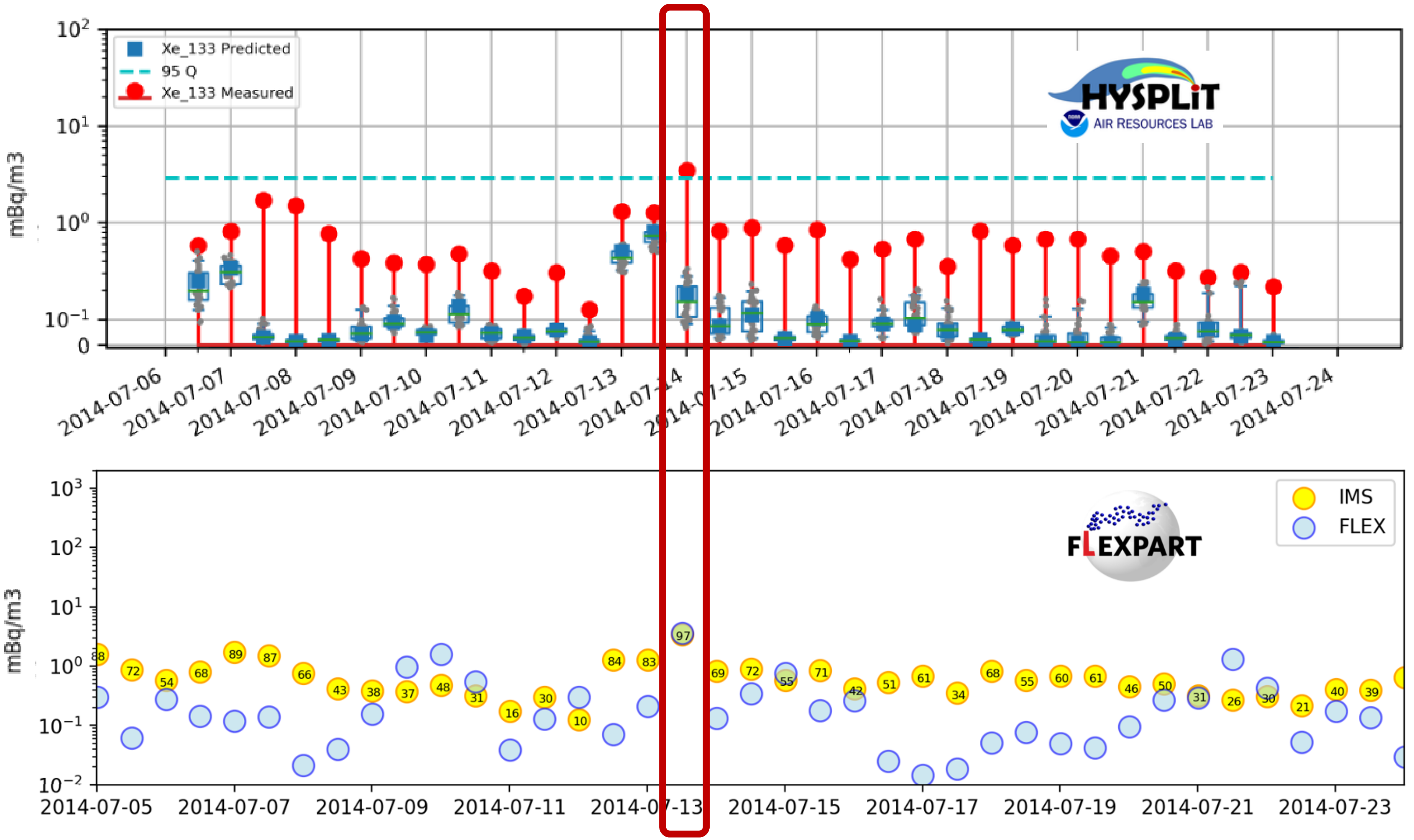
Atmospheric model performance for January 2014





Identifying Anomalies With Measurements & Atmospheric Models

Xe-133 at Stockholm RN63



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Identifying Anomalies With Measurements & Atmospheric Models

Bayesian ridge regression performs well at many IMS stations

Shown for July 2014 Xe-133 collections.

Performance evaluated by temporal correlation between predictions and independent collections.

Performance improves with increasing amounts of training data.

Some stations are more difficult to predict than others with atmospheric models.