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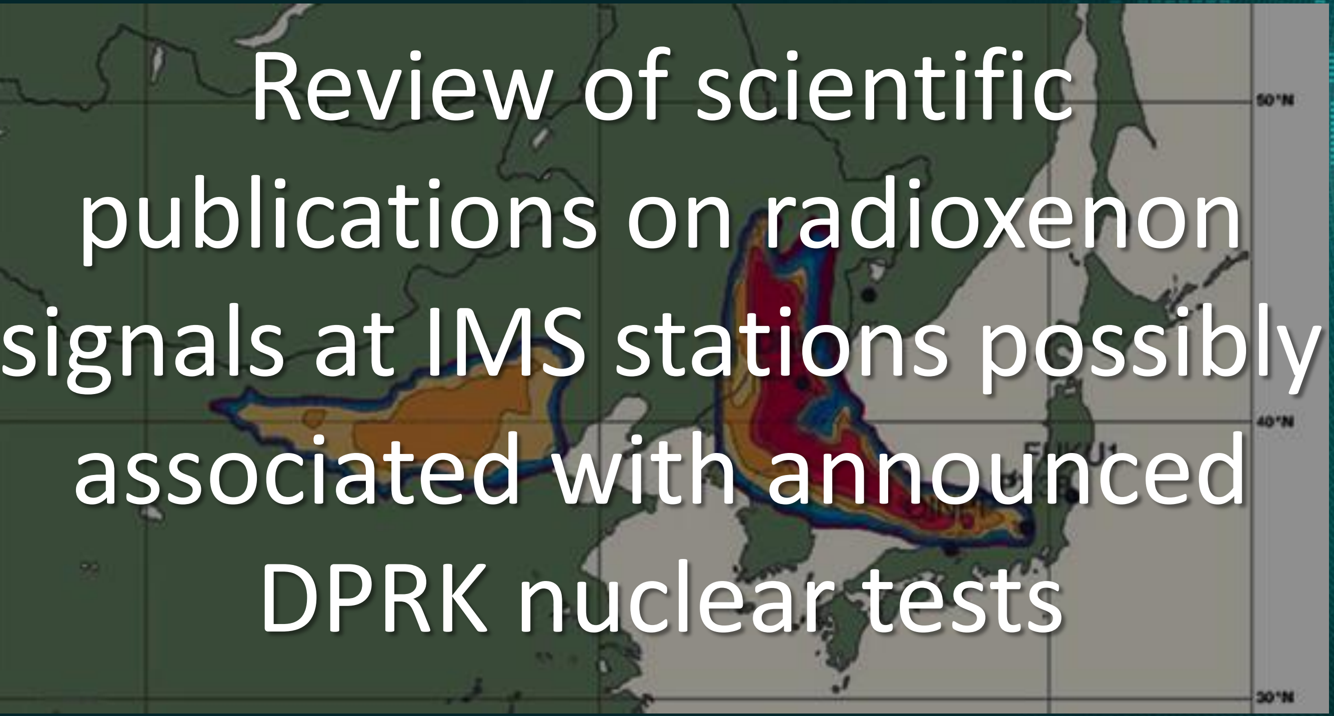

Review of scientific publications on radioxenon signals at IMS stations possibly associated with announced DPRK nuclear tests

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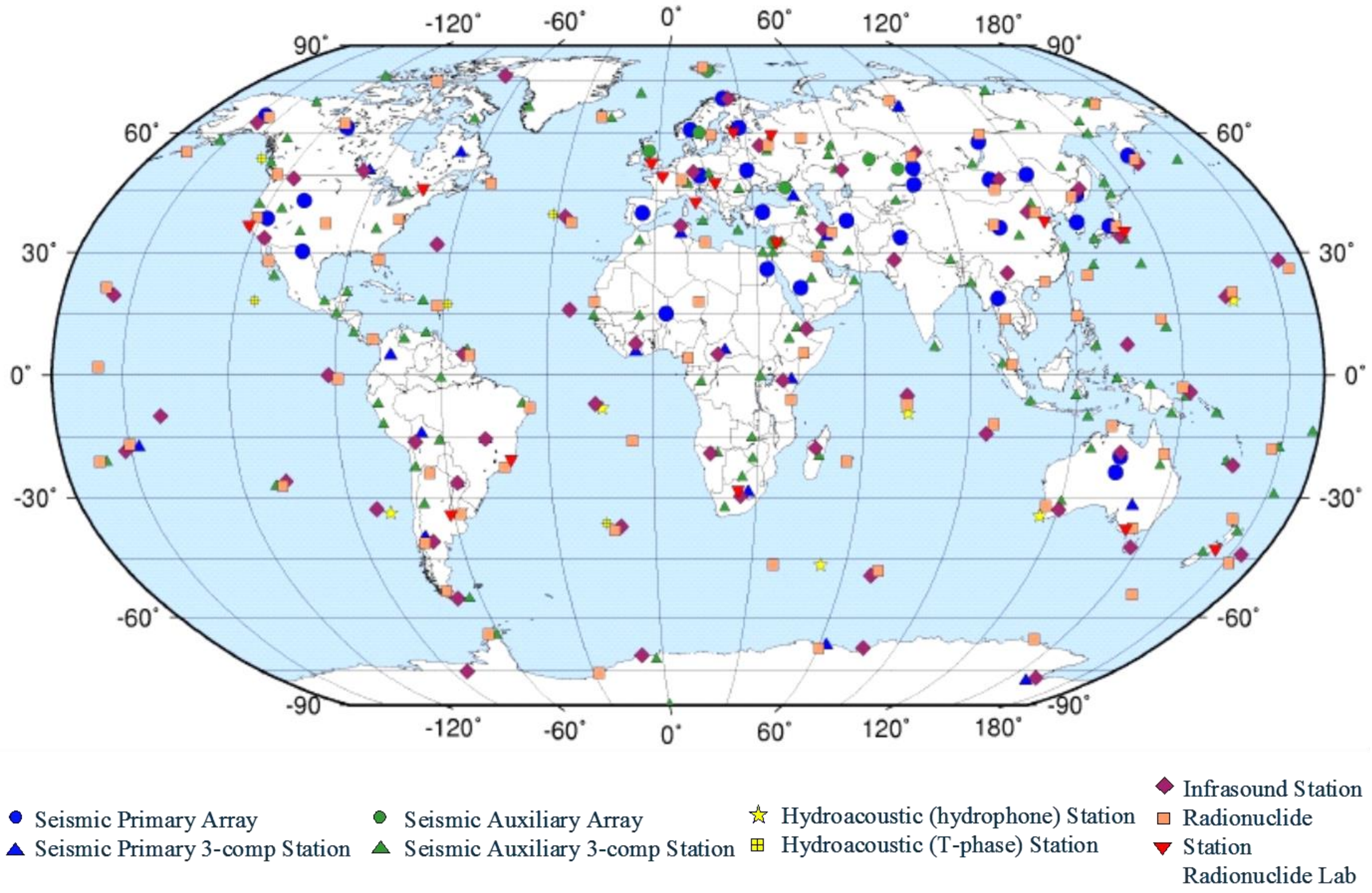
Introduction

The International Monitoring System (IMS) for the verification of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) includes 80 radionuclide stations, out of which 40 are initially equipped with noble gas systems to observe the four xenon isotopes ^{131m}Xe, ^{133}Xe, ^{133m}Xe and ^{135}Xe.

These four isotopes are serving as important indicators of nuclear explosions.



The purpose is to detect nuclear tests through radionuclide releases that are observed at IMS stations.

The geographic region of the source at assumed release times may be associated with a seismo-acoustic event.

Introduction

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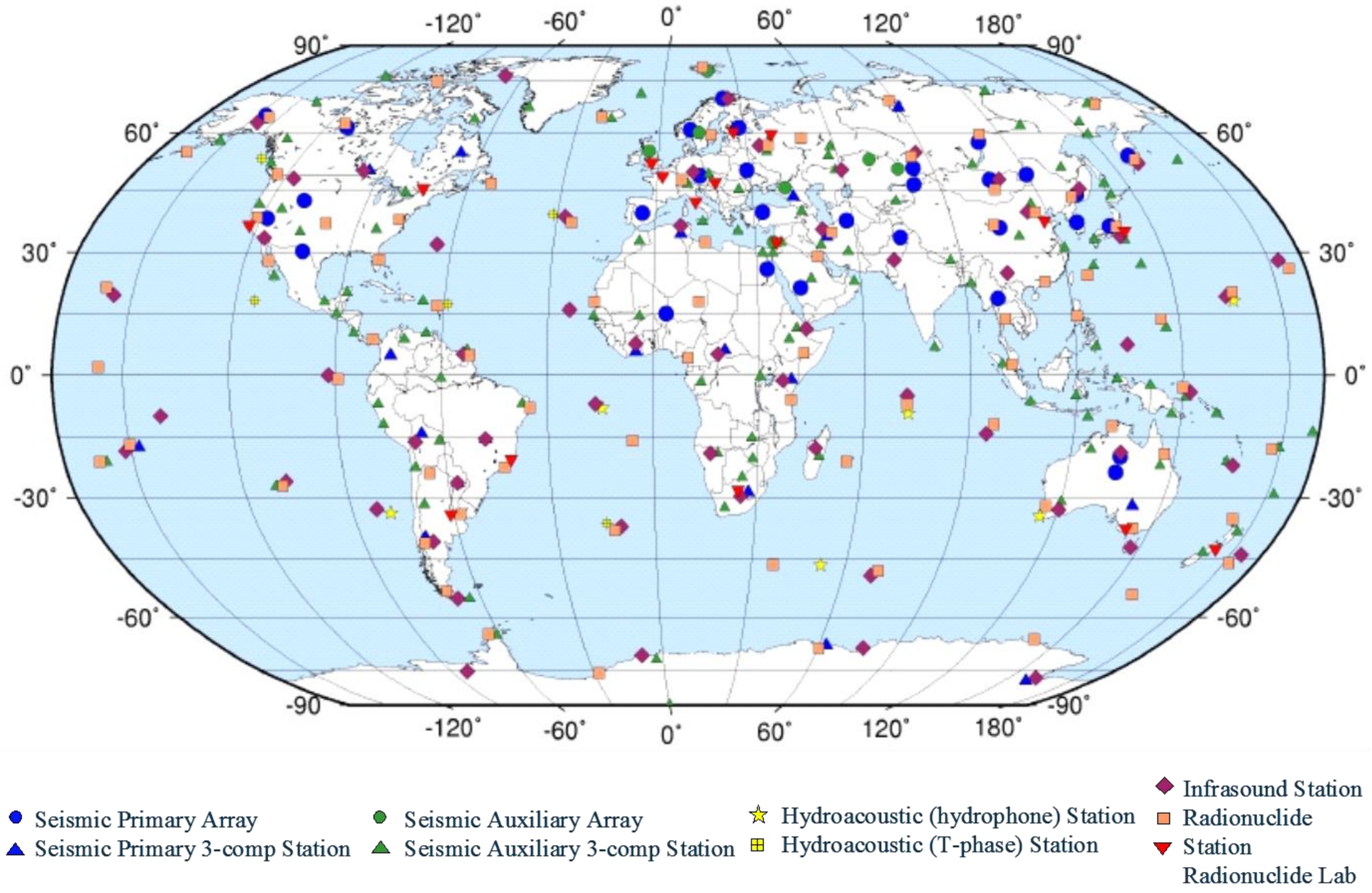


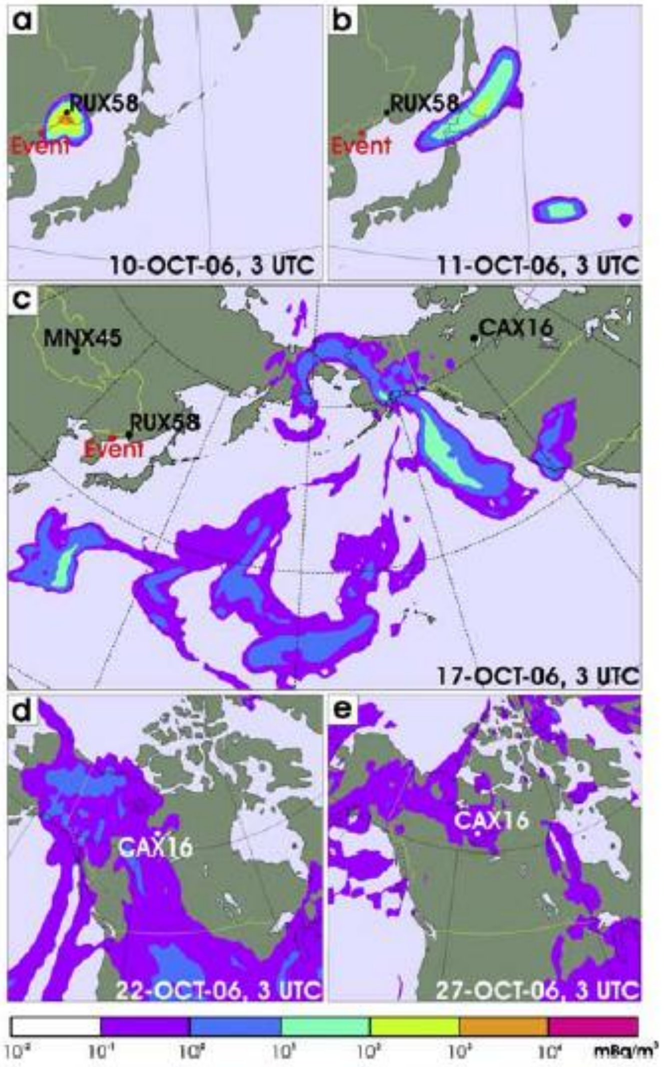
<u>A reality check</u>: The Democratic Peoples Republic of North Korea (DPRK) has announced 6 nuclear tests in 2006, 2009, 2013, January and September 2016 and 2017.

This presentations is about which detections of radioxenon can be associated with any of these nuclear tests.

- **This presentation uses the experience of radionuclide monitoring following all 6 announced DPRK tests.**
- **It builds on 11 peer-reviewed publications.**
- **Three questions are investigated here:**

1. **Which features of IMS observations were used?**
1. **Are there possibly releases of DPRK tests that are recorded in IMS data but have not yet been found?**
2. **What needs to be done to make full use of the IMS capabilities?**

RN evidence of announced DPRK test 2006



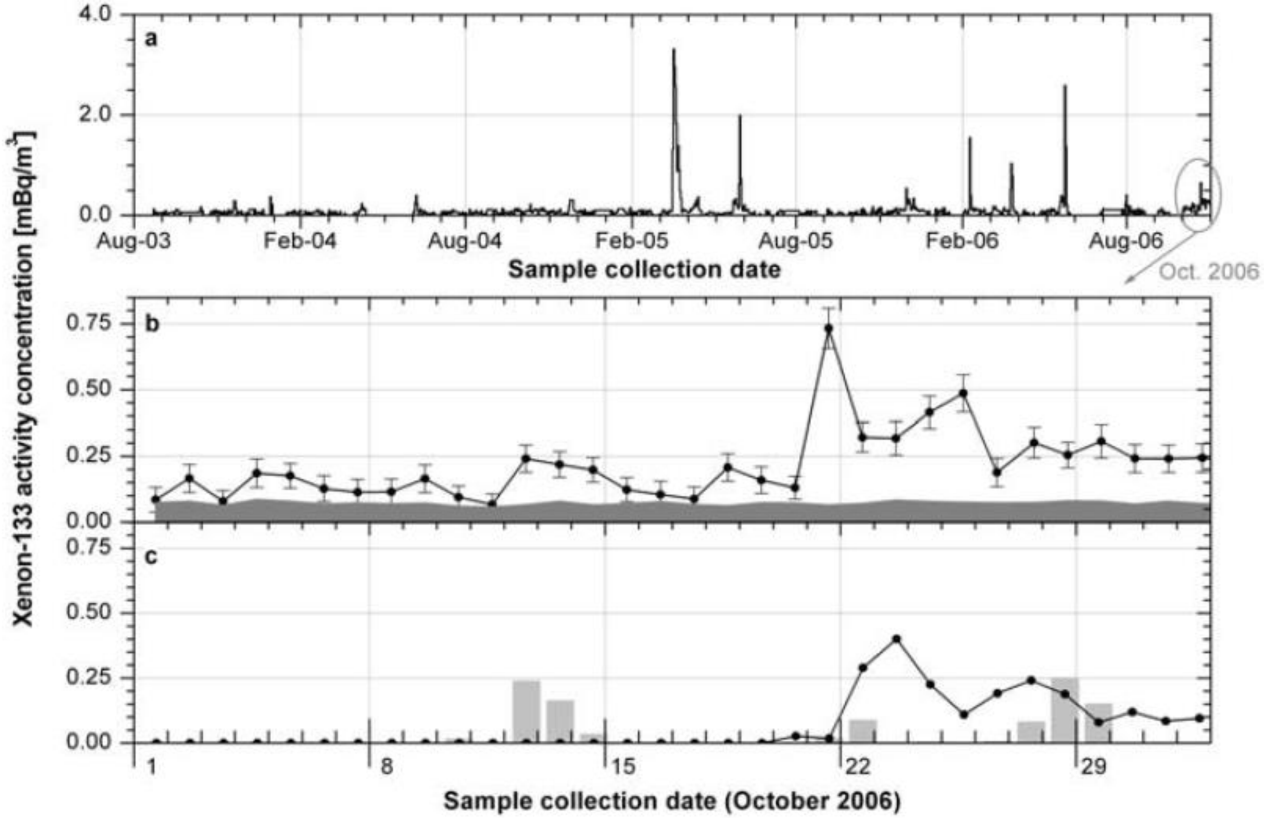


Figure 1. (a) The daily activity concentration of ^{133}Xe measured at Yellowknife, Canada, during three years from 15 August 2003 to 31 October 2006. (b) The observations of ^{133}Xe activity concentration at Yellowknife in October 2006 where the continuous grey pattern represents the minimum detectable concentration of ^{133}Xe. (c) The atmospheric transport modelling of the activity concentration of ^{133}Xe at the Yellowknife station, assuming the emission of 1 PBq of ^{133}Xe from the event on 9 October 2006. The small grey histogram in Figure 1c shows the contribution of the CRL facility when a maximum release rate is assumed for the whole month of October.

Saey, P.R.J., et al. (2007)

9 October 2006

RN evidence of announced DPRK test 2013

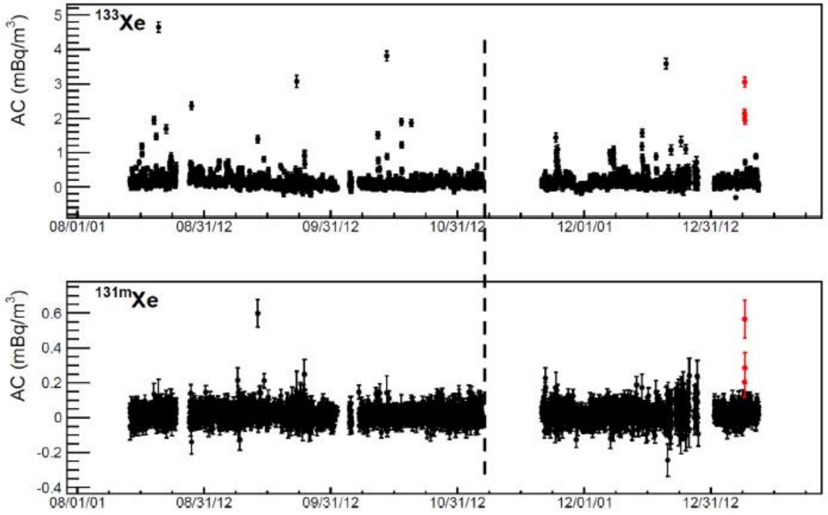


Fig. 5. ^{133}Xe and ^{131m}Xe activity concentration time series for station RN38 in Takasaki, Japan, measured between July 1, 2008 and May 18, 2013. Data between March 13 and August 31 2011, affected by the large xenon release from the Fukushima accident was removed for clarity. The time of the accident is indicated with the dashed vertical line. Results from the three RN38 samples discussed in this report are colored red.

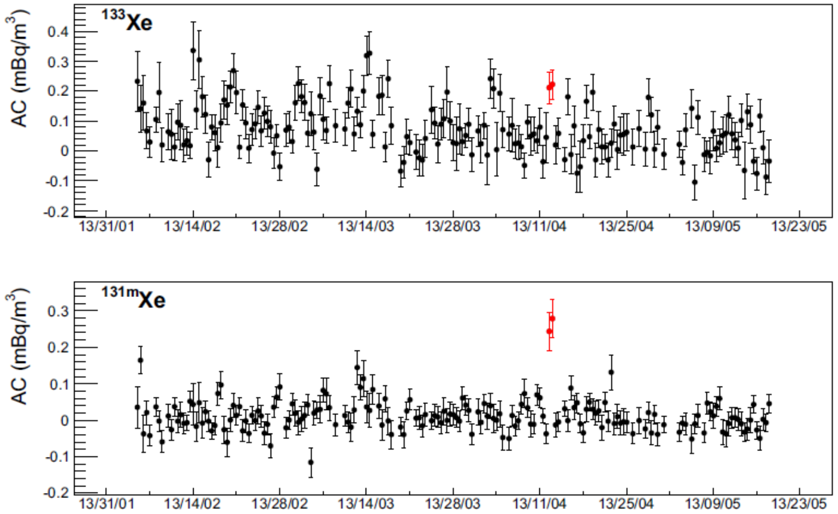


Fig. 6. ^{133}Xe and ^{131m}Xe activity concentration time series for station RN58 in Ussuriysk, Russia, measured between February 5 and May 18, 2013. The two RN58 samples discussed in this report are colored red.

Ringbom, A. et al. (2014)

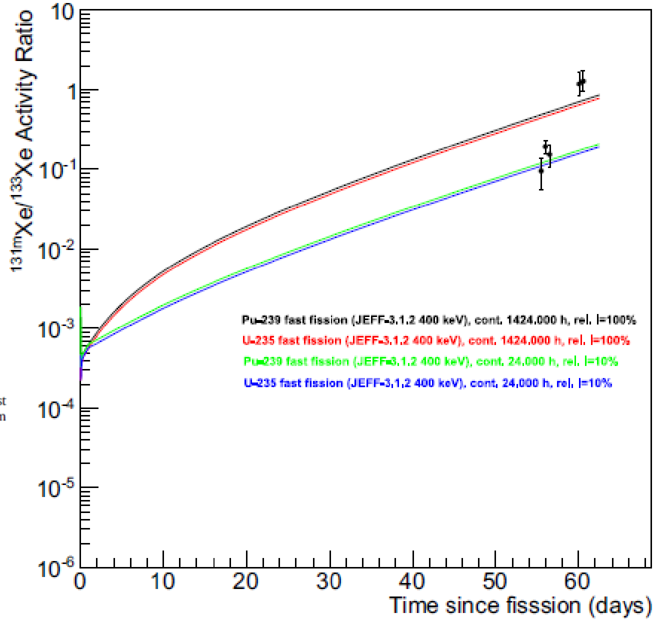


Fig. 17. Calculated ^{131m}Xe/^{133}Xe ratios as a function of time since fission for four different nuclear explosion scenarios (solid lines). The black markers are the observed ratios. Uncertainties are at the 1σ level. The two upper curves assumes full ingrowth of all precursors until release, and fits best to samples 4 and 5, while the two lower curves assumes separation of xenon and 10% of the iodine inventory after 24 h.

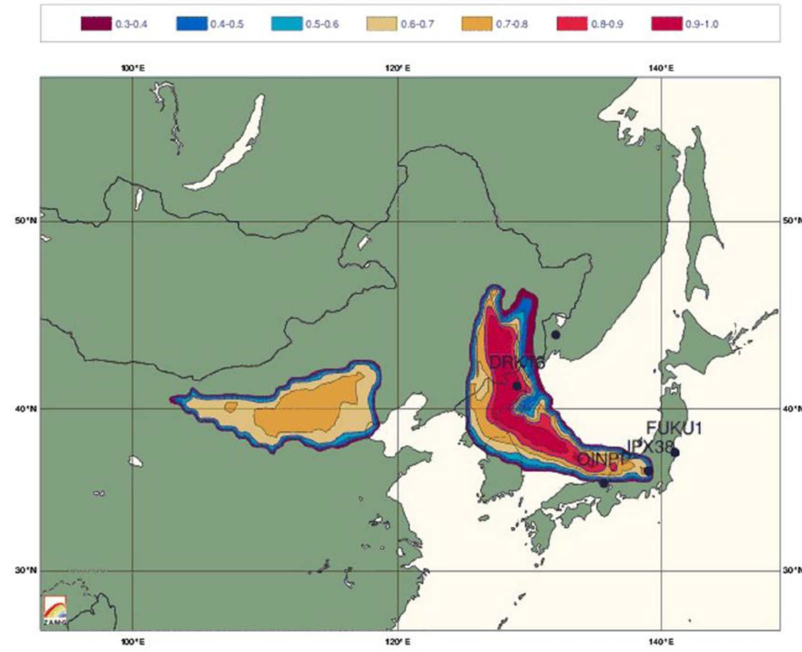


Fig. 13. Possible source regions (correlation maxima) calculated using the extended scenario described in Section 5.2,. The point "DPRK13" denotes the DPRK event location, "FUKU1" the location of the Fukushima Daiichi NPP, and "OINPP" the location of the NPP Ohi, the only NPP in operations in Japan during the time of the DPRK event in 2013.

12 February 2013

RN evidence of DPRK 2006 and 2013

For the first test (9 October 2006) and the third one (12 February 2013), radioxenon observations were immediately found being associated with the time and location of the relevant seismic events and therefore, consistent with the assumption that the observations are reflecting a radioxenon emission from the DPRK test site.

DPRK announced nuclear test	IMS station	Detection of prompt release	Detection of delayed release
9 October 2006	CAX16	21-25 Oct	
12 February 2013	JPX38		8-9 Apr
	RUX58		12-13 Apr

Additional emissions of DPRK 2013?

Further investigation with in-depth scientific analysis, partly applying new methodologies, show potentially more IMS samples than initially thought may contain traces from the same emissions that were already identified.

DPRK announced nuclear test	**IMS station**	**Detection of prompt release**	**Detection of delayed release**
9 October 2006	CAX16	5 samples (21-25 Oct)	
12 February 2013	JPX38		3 samples (8-9 Apr) + 6-7 April
	RUX58	+ 13-20 Feb	2 samples (12-13 Apr) + 3-4, 22 April
	CNX20, JPX38, MNX45, RUX58		57 samples (5-15 Apr)

Eslinger et al. (2015)
Werth et al. (2017)

Kurzeja et al. (2018)
De Meutter et al. (2018)

Also DPRK Jan2016 and 2017 detected?

Even additional potential emissions may have occurred and captured at IMS stations : Two papers claim that also the DPRK tests of 6 January 2016 and 3 September 2017 have released radioxenon that was detected at IMS stations.

DPRK announced nuclear test	IMS station	Detection of prompt release	Detection of delayed release
6 January 2016	JPX38, MNX45, USX77		50 samples (11-23 Feb)
3 September 2017	RUX58		5 samples (5, 19, and 26 October)

De Meutter et al. (2017)

Gaebler et al. (2019)

This would leave only two DPRK tests undetected at IMS stations.

25 May 2009			
9 September 2016			

Which IMS observations were used?

How effective are the standard indicators?

For the immediate detections:

Anomalous concentration (Level C):

- Xe-133 **10 out of 10 samples (100%)**
- Xe-131m **5 out of 10 samples**

Isotopic ratio flags:

- In nuclear explosion domain: **none out of 10 samples**

Which IMS observations were used?

How effective are the standard indicators?

For the later hypothetical detections:

Anomalous concentration (Level C):

- Xe-133 — 11 out of 132 samples (8.3%)*
- Xe-131m — not considered

Isotopic ratio flags:

- In nuclear explosion domain: — not considered

* One paper uses a sequence of 50 samples out of which 23 have no radioxenon detected (non-detections). The authors call them "pseudo-observations" or "pseudo-samples".

Which IMS observations were used?

How effective are expert technical analysis methods?

For the immediate detections:

Isotopic ratios:

▪ Anomaly:	1 out of 2 cases
▪ Indicated time of fission event coincides with seismic event:	1 out of 2 cases

Source-receptor relationship:

▪ Forward simulation consistency	both cases
▪ Possible source region	both cases
▪ Alternative sources	1 out of 2 cases

Which IMS observations were used?

How effective are expert technical analysis methods?

For the later hypothetical detections:

Isotopic ratios: not considered

- Anomaly
- Indicated time of fission event coincides with seismic event

Source-receptor relationship: diverse approaches

- Forward simulation consistency
- Possible Source Region (PSR)
- Enhanced version of PSR with ensemble modelling
- Alternative source areas, knowledge of civil sources
- Variable emission profile, identifying most likely emission time with cost function

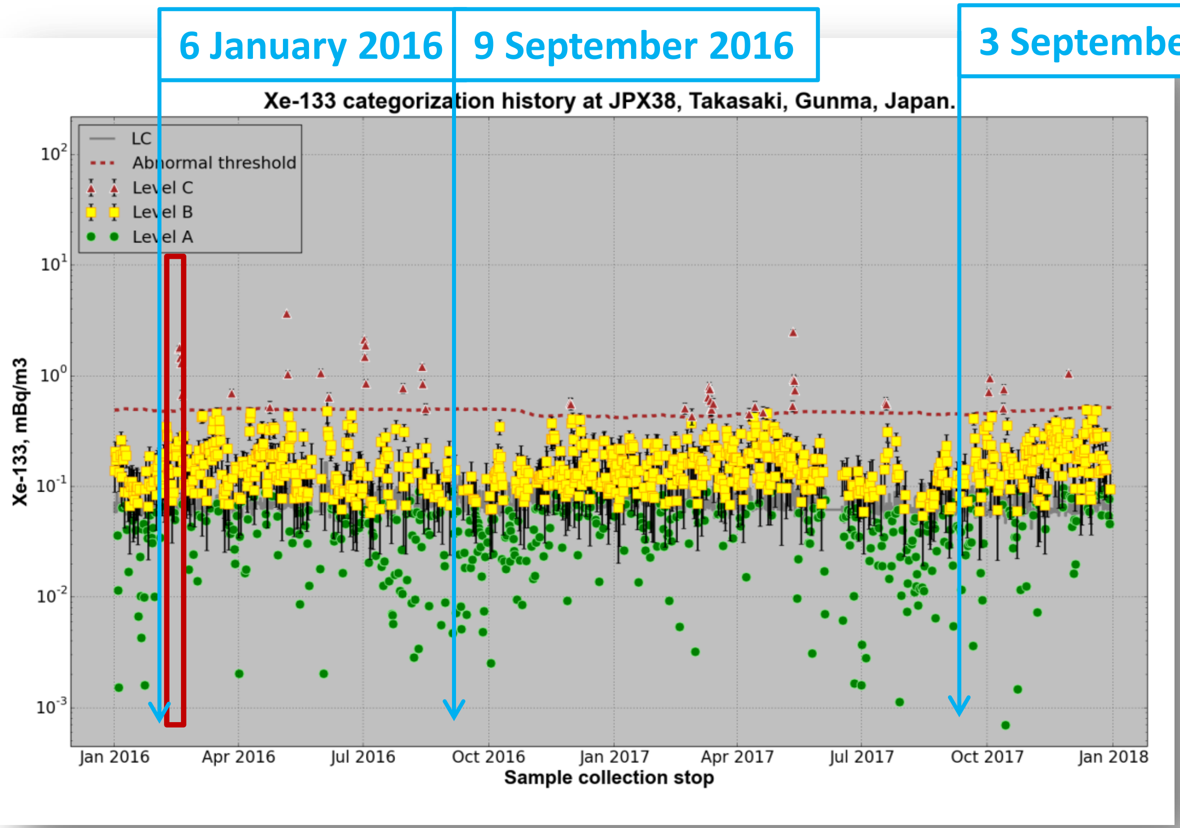
All 6 DPRK tests

A summary of all detections of interest is provided and the level of confidence of possible matches between a hypothetical release and IMS observations as reported in various scientific papers is assessed.

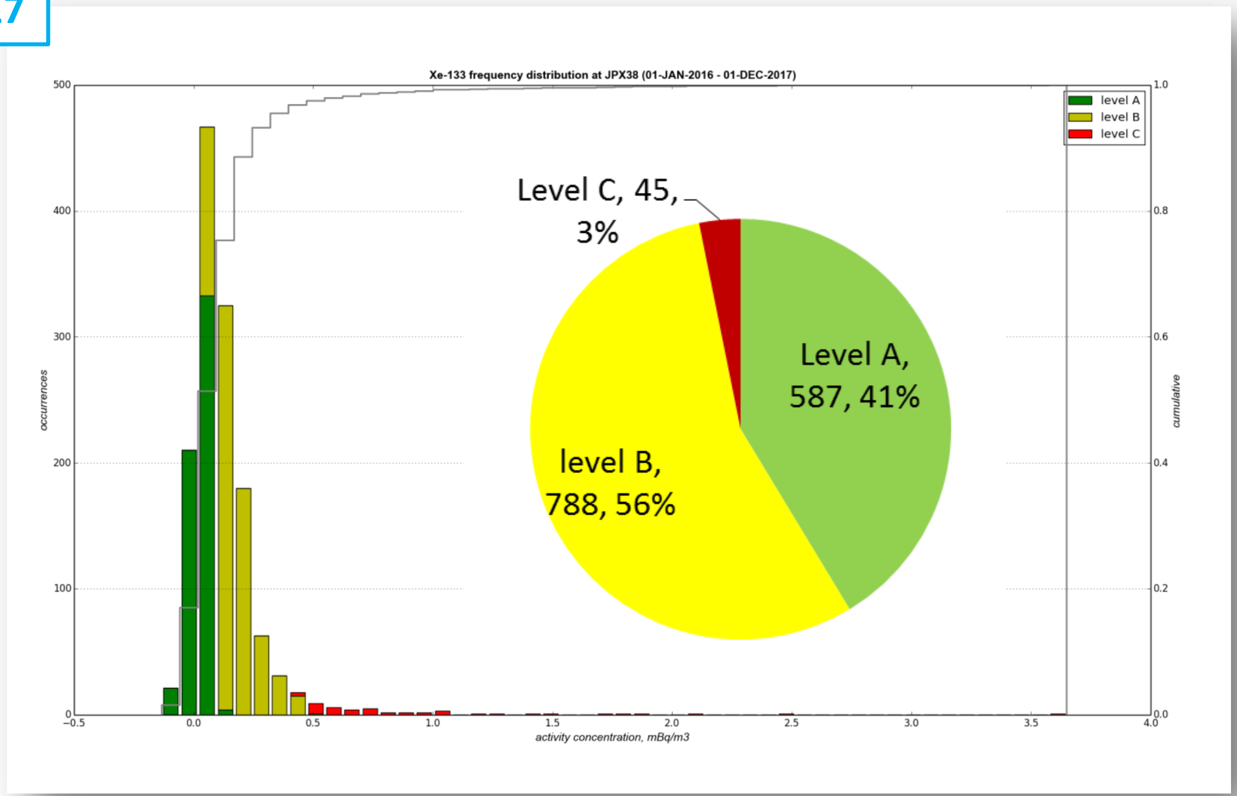
DPRK announced nuclear test	IMS stations	Type of samples	DPRK test site as source region	Seismic event time, isotopic ratios	Other potential sources	Conclusion	Confidence
9 October 2006	CAX16	5 Level C	Identified		Major source excluded	Clear association	**High**
25 May 2009							
12 February 2013	JPX38	3 Level C	Identified	Match	Not excluded	Clear associations	**Close to certain**, but two different release scenarios to be assumed
	RUX58	2 Level C	Identified	Match	Not excluded		
	CNX20, JPX38, MNX45, RUX58	57 samples	Possible, single most likely source region	7 weeks release delay plausible	Not excluded	Possible association, not conclusive	Medium
6 January 2016	JPX38, MNX45, USX77	50 samples	Possible	6 weeks release delay plausible	Single source excluded	Possible association	**High**
9 September 2016							
3 September 2017	RUX58	5 Level C	High probability	4-6 weeks release delay plausible	Low probability	Possible association, not conclusive	Medium

Which IMS data were not used?

Observations at JPX38 (Takasaki, Japan) from January 2016- December 2016



Xe-133 Categorization History



Xe-133 Frequency Distribution

De Meutter et al. (2017) used 50 samples (11-23 Feb 2016) of three IMS noble gas systems: JPX38, MNX45, USX77.

Long time series of IMS data

The example of De Meutter et al. (2017) related to the DPRK test of 6 January 2016.

DPRK announced nuclear test	IMS stations	DPRK test site as source region	Seismic event time, isotopic ratios	Other potential sources	Conclusion	Confidence
6 January 2016	JPX38, MNX45, USX77	Possible	6 weeks release delay plausible	Single source excluded	Possible association	**High**

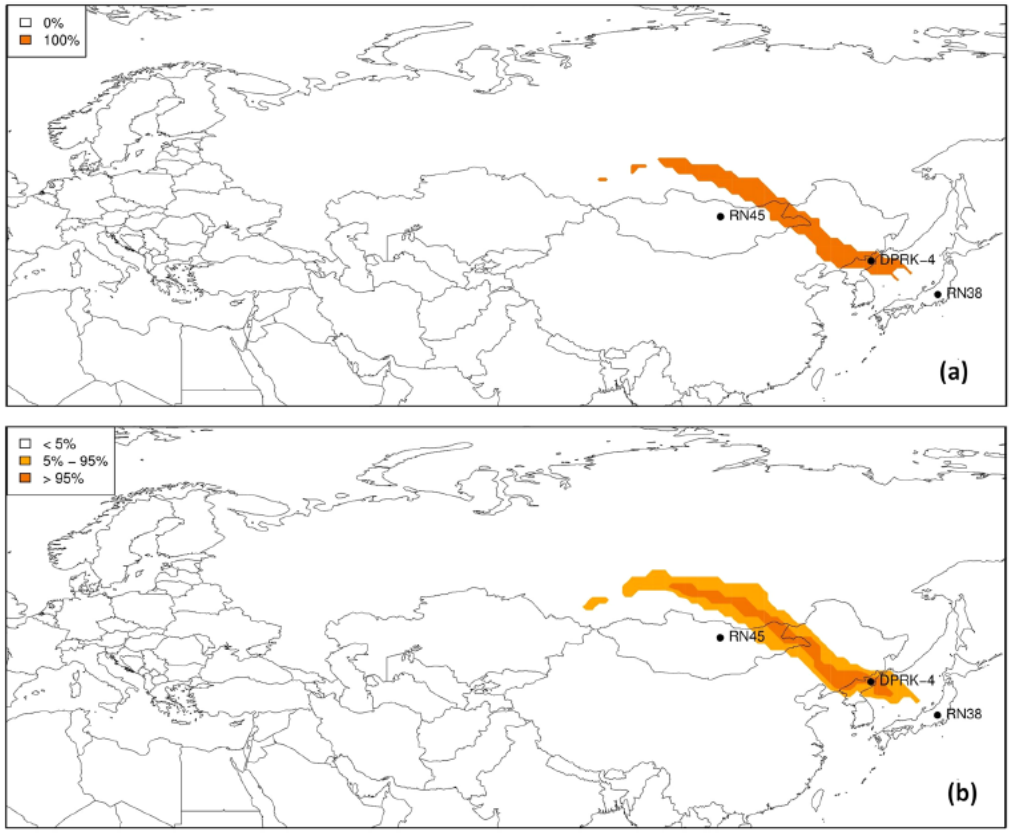


Figure 3. Pointwise probability that a certain grid point is a possible source for (**a**) the unperturbed simulation (thus fully deterministic) and (**b**) the full 51 member ensemble. Maps have been generated using ref. 48.

Conclusions

Further research and development needed on radionuclide monitoring of nuclear tests:

- Experience with DPRK tests: They were announced.

  How can nuclear test signatures be revealed without prior knowledge?

- Mainly anomalous concentration (Level C) indicated detections.
  - How can relevant samples be flagged that don't show standard anomalies?
  - How to make full use of all information contained in Level B observations?
  - How to integrate all data in automatic processing and IDC products?

  RN observations over long time and multiple stations, source-receptor-sensitivities, known sources.

- Scientific studies were published with a delay:

  Which methods of expert technical analysis to be applied?

References

Immediate detections

Becker, A. et al. (2010) Backtracking of Noble Gas Measurements Taken in the Aftermath of the Announced October 2006 Event in North Korea by Means of PTS Methods in Nuclear Source Estimation and Reconstruction. Pure Appl. Geophys. 167, 581–599.

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Saey, P.R.J., et al. (2007) A long distance measurement of radioxenon in Yellowknife, Canada, in late October 2006. Geophysical Research Letters, 34.

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Later publications

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De Meutter, P. et al. (2018) Source localisation and its uncertainty quantification after the third DPRK nuclear test. Scientific Reports 8:10155.

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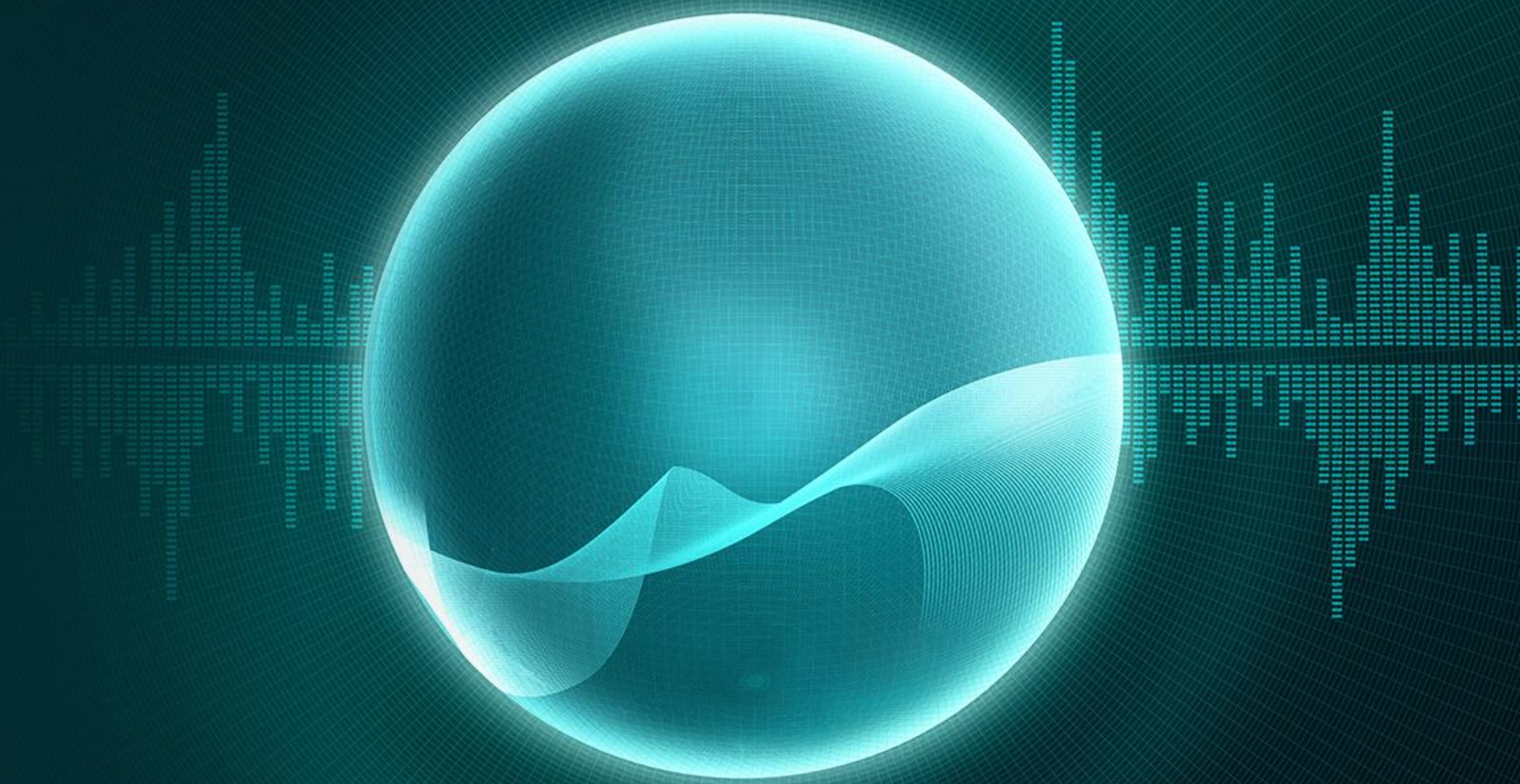

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