

# Inverse atmospheric transport modelling: determining the source location, source term and its uncertainty quantification

Long-range

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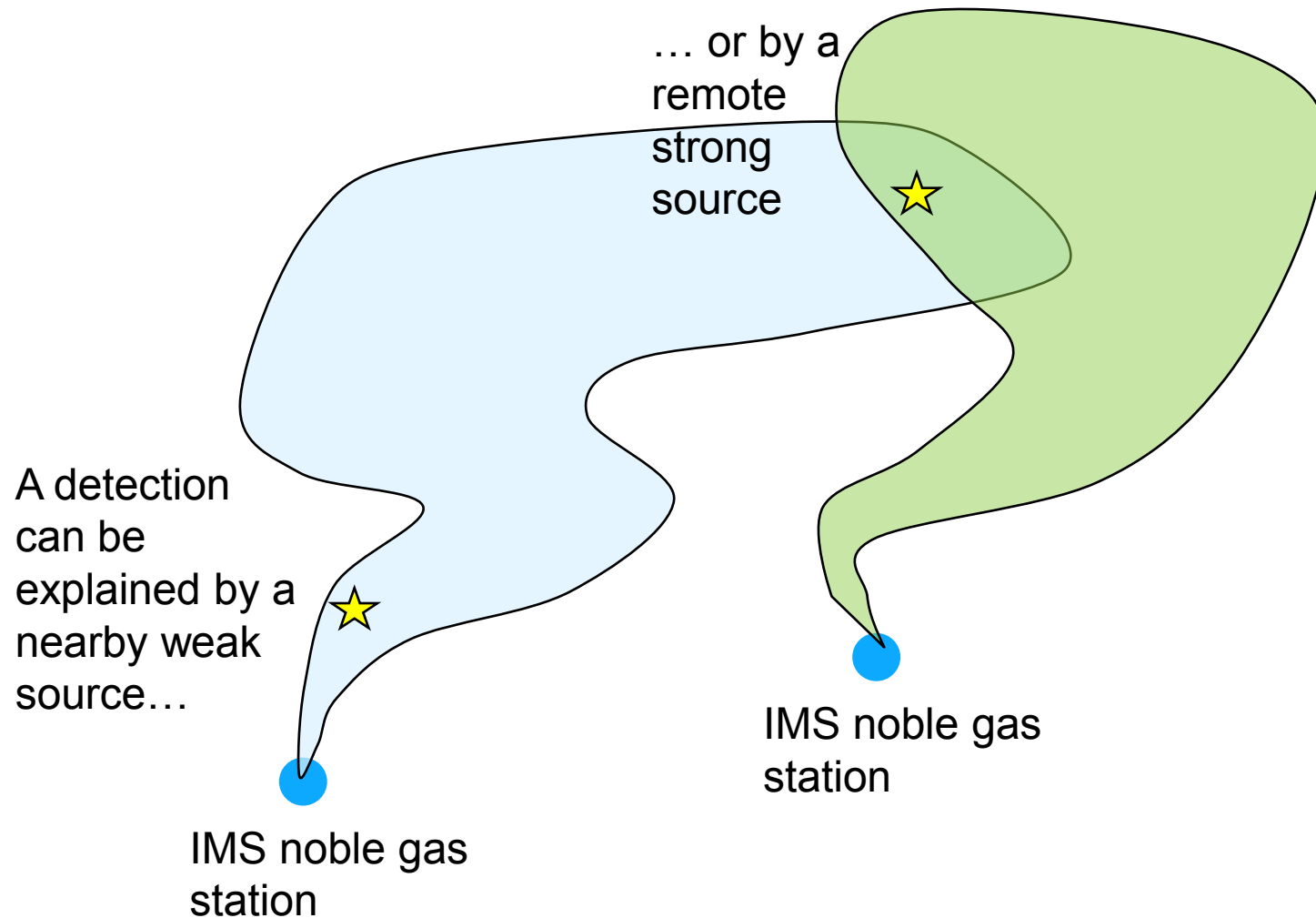
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1. Introduction to inverse atmospheric transport and dispersion modelling
2. Validation by reconstructing fictitious  $^{133}\text{Xe}$  sources
3. Application to the Takasaki  $^{133}\text{Xe}$  detections in February 2016
4. Uncertainty quantification of the source location

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# Inverse atmospheric transport and dispersion modelling



- The **IMS** will consist of at least **40 monitoring stations** equipped with noble gas detectors
- If a detection takes place, **ATM** can help to determine the **source** location and source parameters (time of release, amount, etc)
- Inverse modelling is generally **ill-posed**: there are many possible solutions
- By **combining multiple (non)detections**, part of this ambiguity can be removed (*e.g.*, *Issartel and Baverel, 2003*)

# Inverse atmospheric transport and dispersion modelling

1 sample

$$\begin{array}{c} \text{(measured)} \\ \boxed{AC(x, y, z, t_{start}, t_{end})} = \sum_{x', y', z', t'} \begin{array}{c} \text{(unknown)} \\ \boxed{Q(x', y', z', t')} \end{array} * \begin{array}{c} \text{(calculated by Flexpart)} \\ \boxed{SRS(x, y, z, t_{start}, t_{end}, x', y', z', t')} \end{array} \end{array}$$

- Flexpart in backward mode calculates source-receptor sensitivities  
(Seibert and Frank, 2004)
- A source term  $Q$  can be calculated by solving an optimisation problem
- A likelihood function or cost function can be defined depending on the problem, which allows to combine information from multiple (non)-detections:

$$\text{cost function} = \sum (AC_{obs} - AC_{sim})^2$$

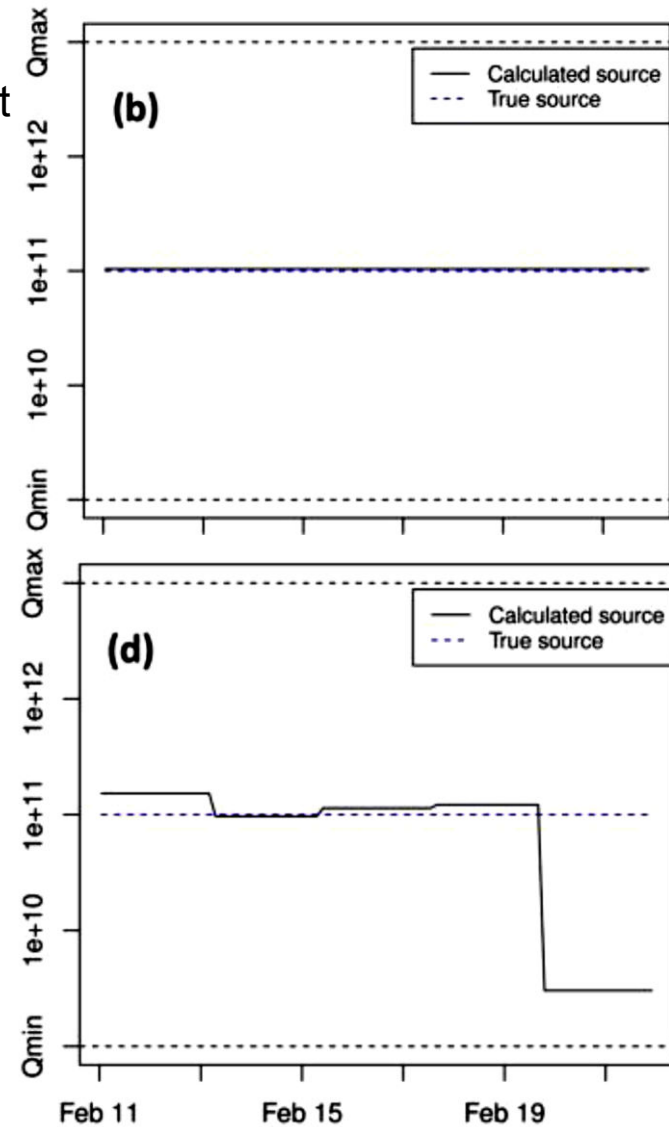
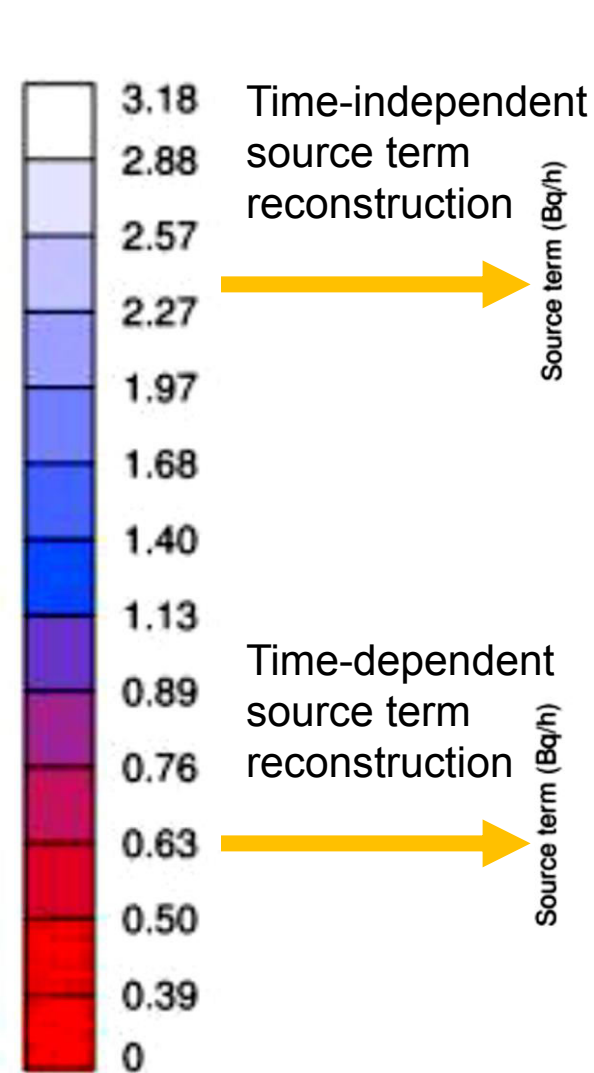
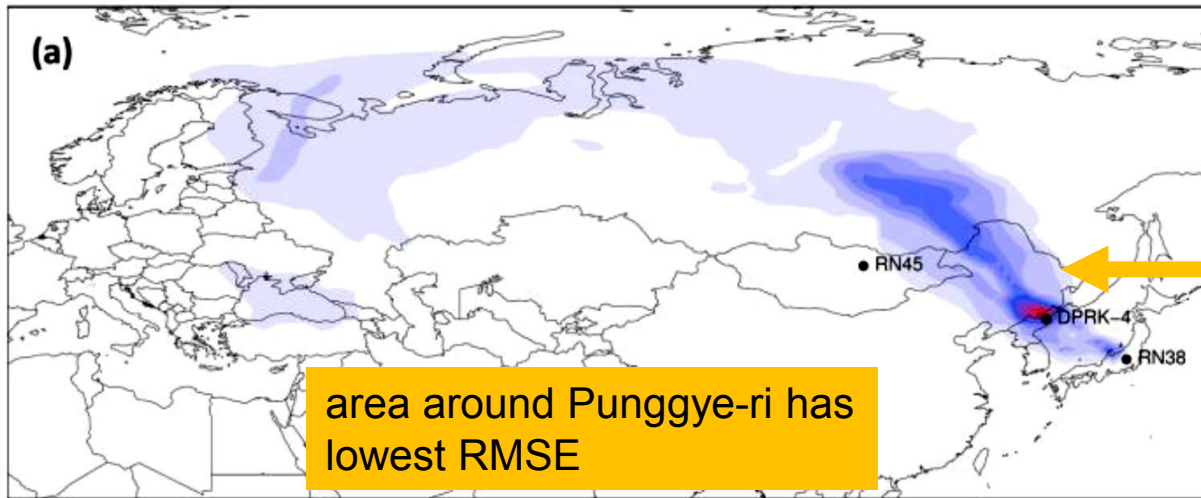
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## Setup for validating the method

1. Define a fictitious source
2. Calculate pseudo-observations as would be measured by IMS stations (loss of information due to 12 h or 24 h sampling time)
3. Perform a backward run for each pseudo-observation
4. Calculate the optimal source term for each grid box in the lowest model level by minimising the cost function (apply bounds  $Q_{\text{MIN}}$  and  $Q_{\text{MAX}}$ )
5. We obtain a map with minimum cost function values and corresponding sources (a low cost function corresponds to a likely source location)

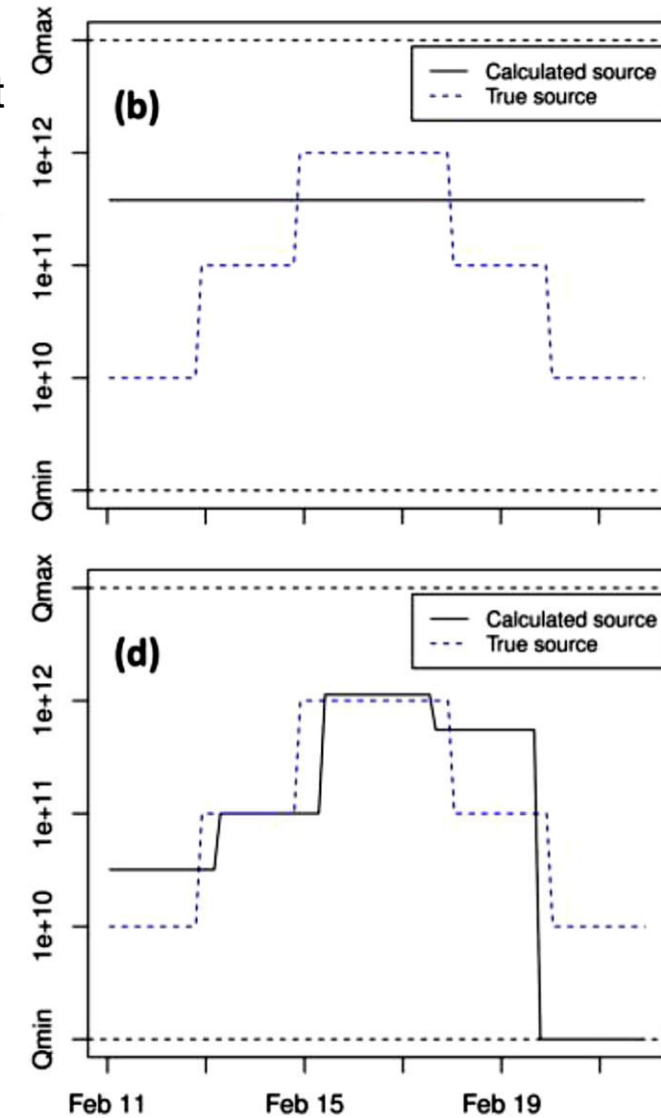
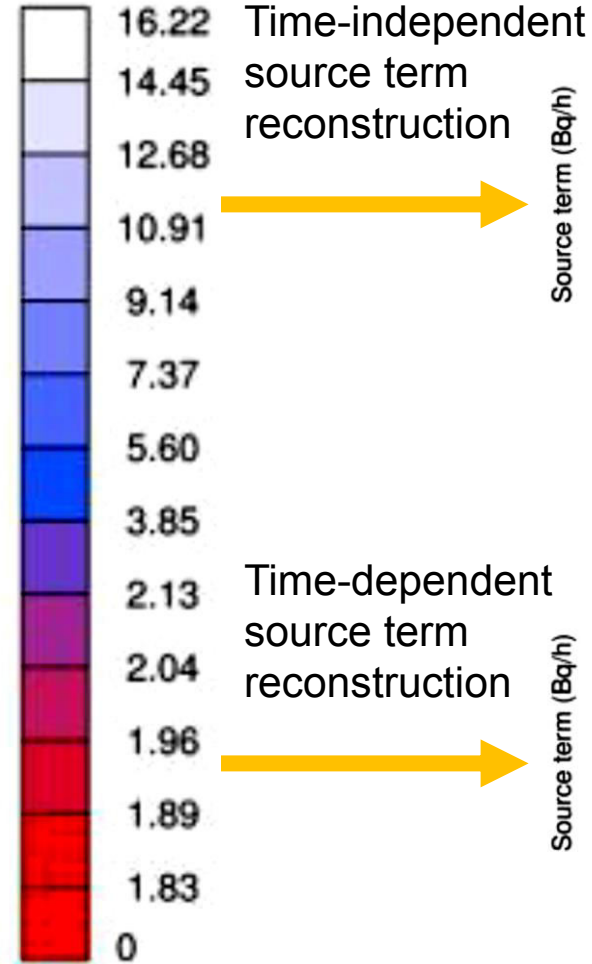
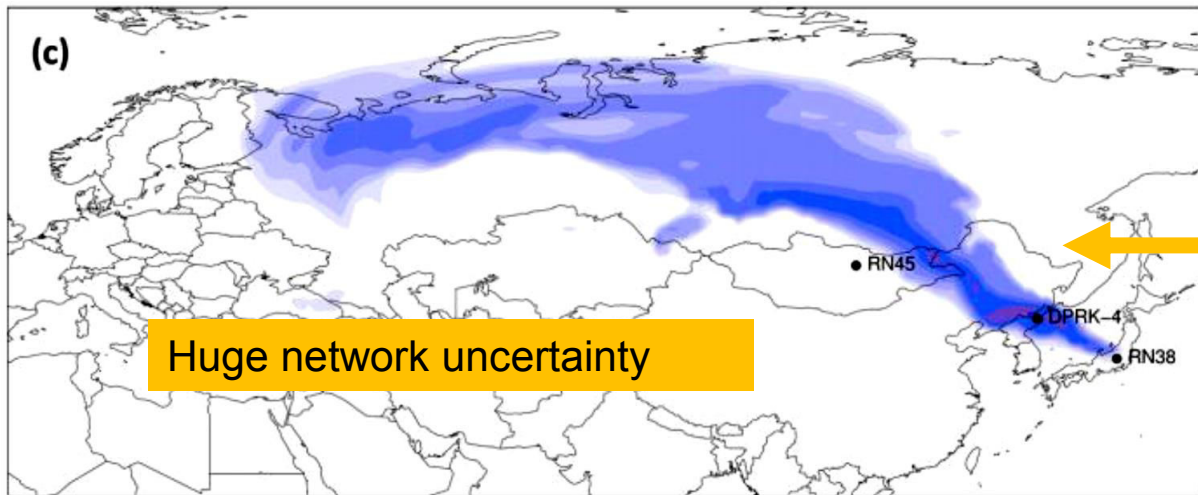
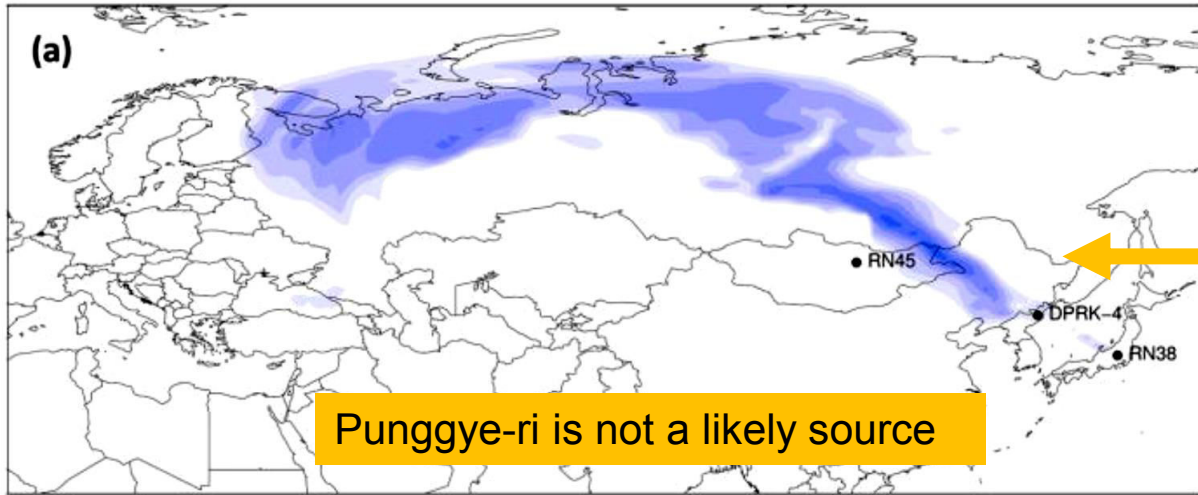
|              |  |
|--------------|--|
| ATM          | Flexpart (Stohl <i>et al.</i> , 2005) in backward mode |
|              | Output from 0-100 m                                    |
| Weather data | 3h data from ECMWF                                     |
|              | 0.5° horizontal grid spacings                          |
|              | 137 non-uniform levels                                 |
|              | 51-member EDA ensemble                                 |
| Domain       | Northern hemisphere                                    |
| Source       | Punggye-ri nuclear test site                           |
| Period       | February 2016  |

# Validation with fictitious sources: time-independent release at Punggye-ri



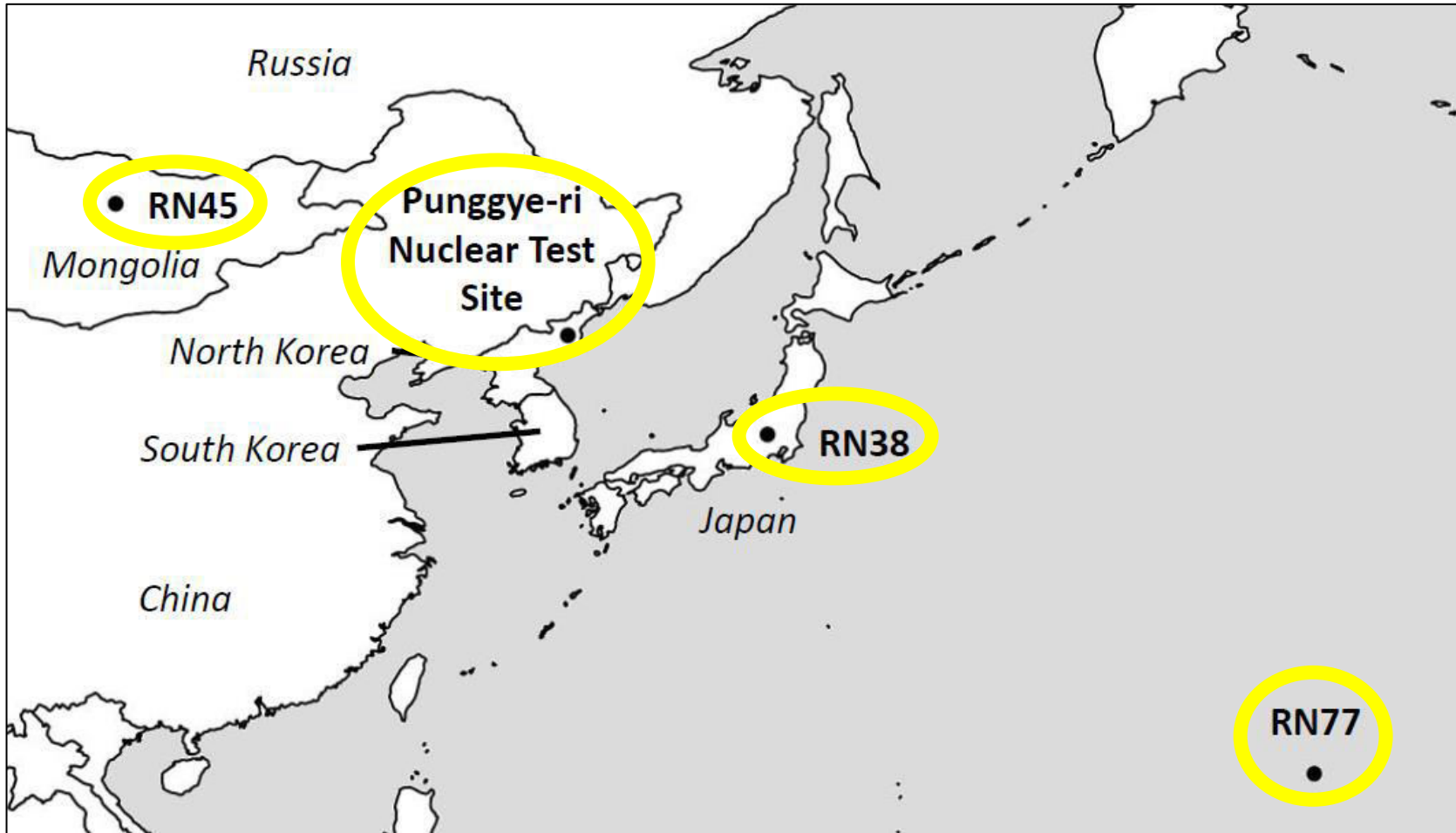
$$\sqrt{\text{cost function}} = \text{RMSE} = \sqrt{\sum (AC_{\text{obs}} - AC_{\text{sim}})^2}$$

# Validation with fictitious sources: time-dependent release at Punggye-ri



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# Elevated concentrations of $^{133}\text{Xe}$ were observed at RN38 in February 2016

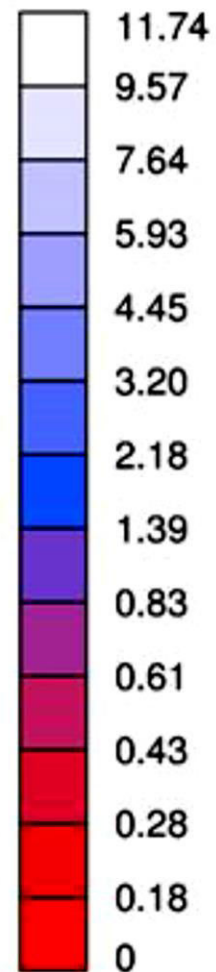
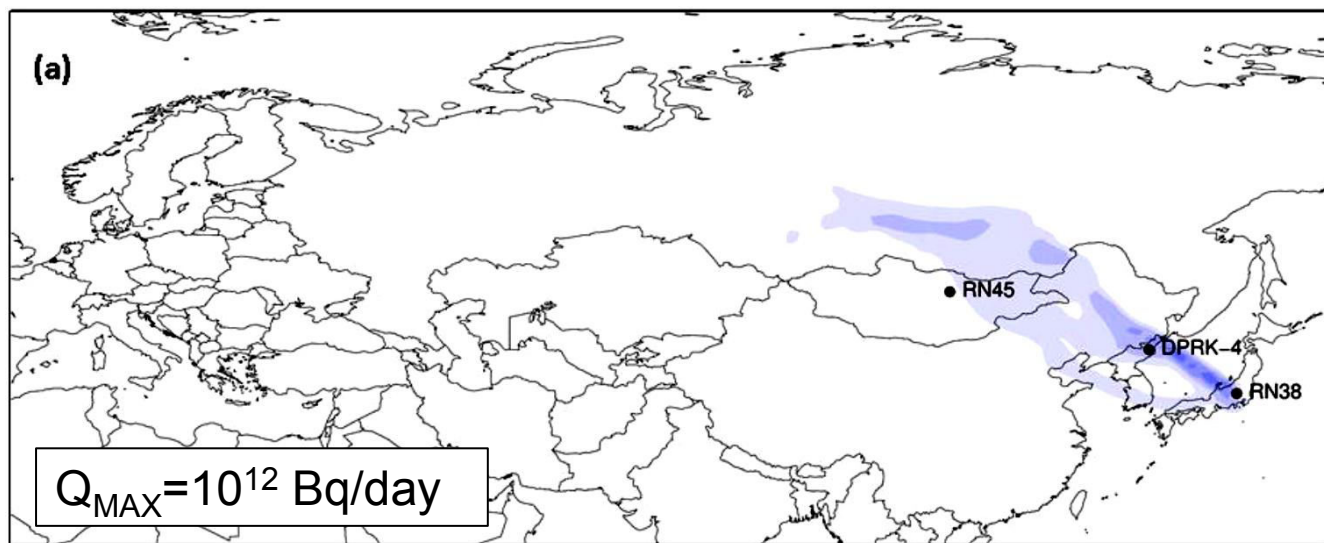


51 observations from RN38, RN45 and RN77

| Stat | Date                | AC (mBq/m <sup>3</sup> ) |
|------|---------------------|--------------------------|
| RN38 | 2016-02-17<br>08:35 | 1.76                     |
| RN38 | 2016-02-17<br>20:35 | 1.79                     |
| RN38 | 2016-02-18<br>08:35 | 1.44                     |
| RN38 | 2016-02-18<br>20:35 | 1.30                     |
| RN38 | 2016-02-19<br>08:35 | 0.67                     |

De Meutter et al, "Assessment of the announced North Korean nuclear test using long-range atmospheric transport and dispersion modelling", Scientific Reports, *in press*

# (Known) civil sources in normal conditions can be excluded

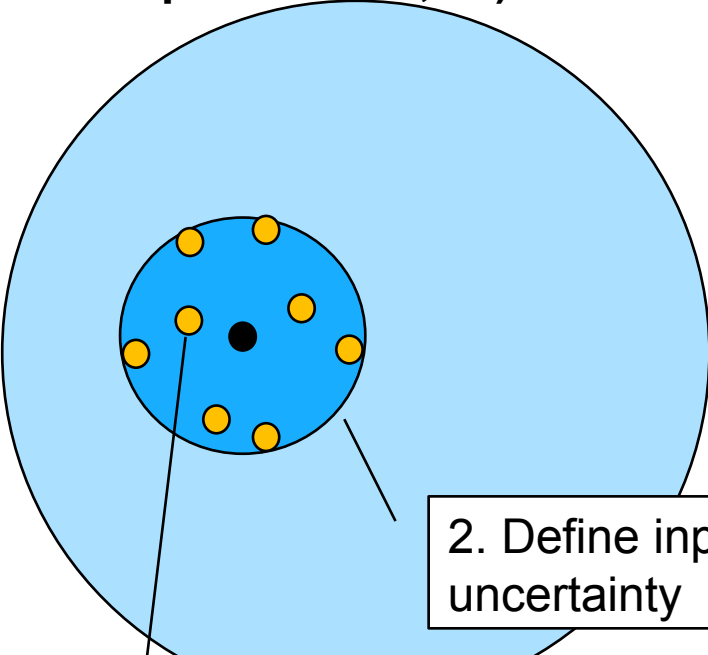


$$\begin{aligned}\sqrt{\text{cost function}} &= \text{RMSE} \\ &= \sqrt{\sum (AC_{obs} - AC_{sim})^2}\end{aligned}$$

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# The ensemble method allows uncertainty quantification

Input phase space (meteorology, source parameters, ...)

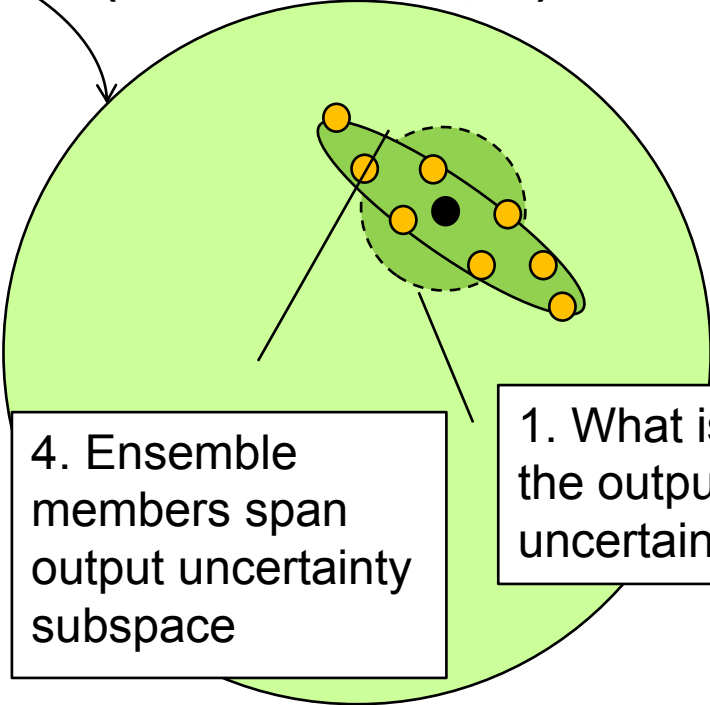


2. Define input uncertainty

3. Take samples from input uncertainty

Atmospheric transport and dispersion model

Output phase space (concentrations, ...)



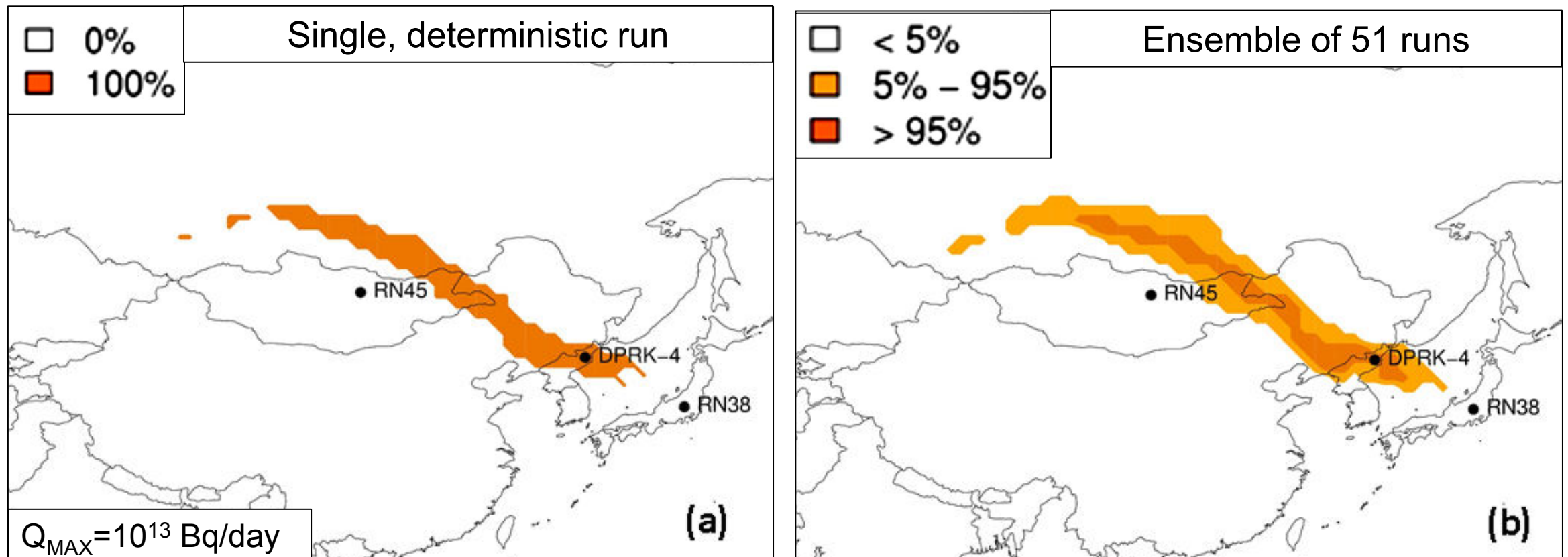
4. Ensemble members span output uncertainty subspace

1. What is the output uncertainty?

**The construction of a good ensemble requires good sampling of the input uncertainties**

# Release from the Punggye-ri nuclear test site is compatible with observations (grid pointwise probability maps)

$$RMSE\ threshold = \sqrt{\sum(\alpha * AC_{obs} + \beta)^2} \text{ with } \alpha = 0.2, \beta = 0.2\ mBq/m^3$$



## Summary and conclusions

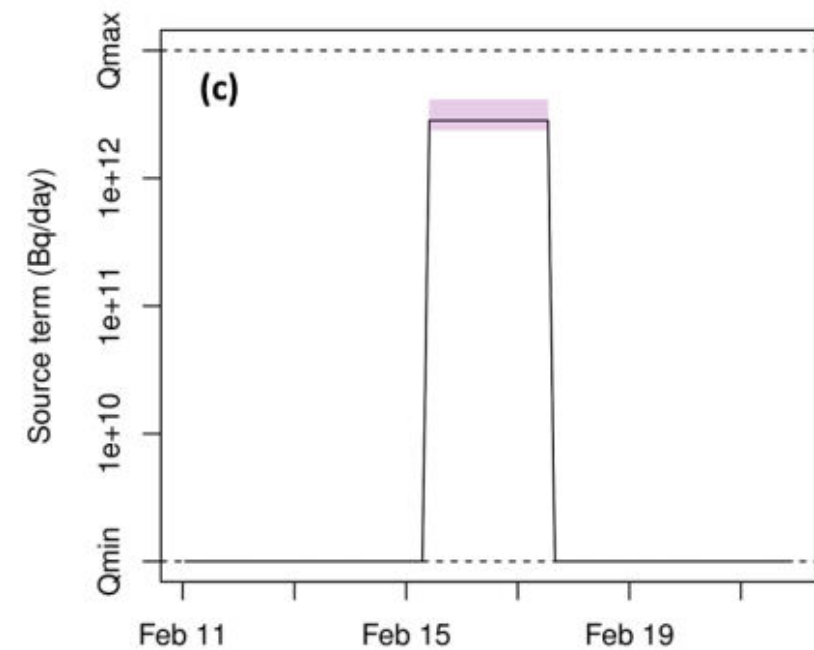
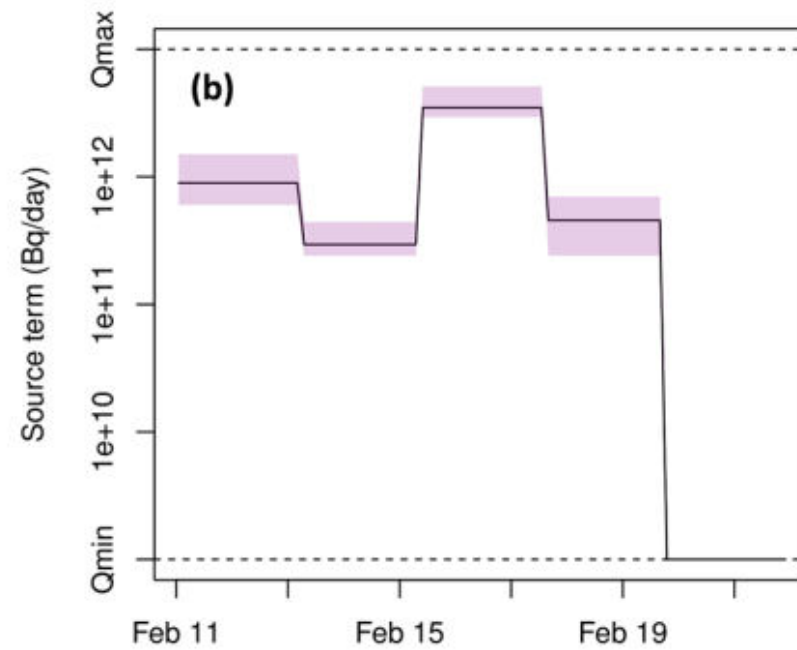
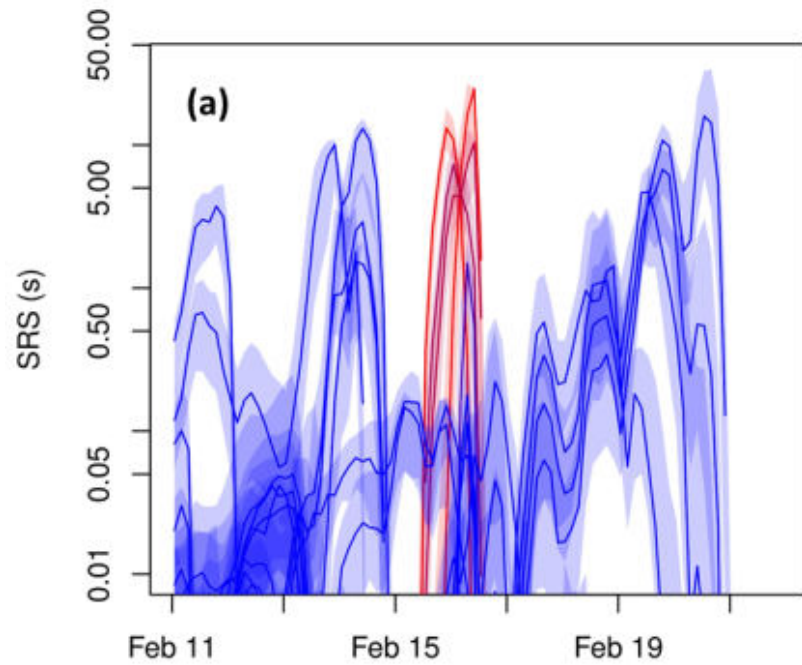
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1. **Inverse modelling is ill-posed**: detected  $^{133}\text{Xe}$  could originate from a nearby weak source or a remote strong source
2. Combining **multiple (non-)detections** allows to narrow down possible source locations
3. The resulting number of possible sources depends on the meteorological conditions and the network: more observations in time/space result in less ambiguity
4. Inverse modelling should account for **time-dependent sources**
5. Observations in February 2016 **cannot be explained by known civil sources** operating in normal mode
6. Observations in February 2016 are **compatible with** a delayed release from the **Punggye-ri nuclear test site**
7. **Ensembles allow to quantify uncertainty** of atmospheric transport modelling, for instance, by constructing pointwise probability maps

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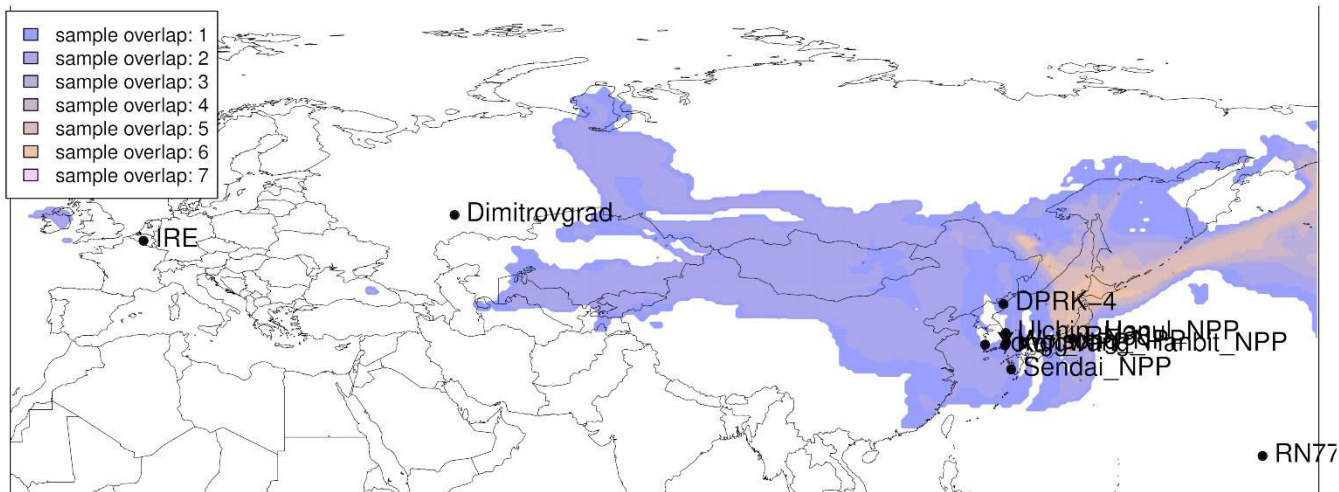
Thank you for your attention

# Source term at Punggye-ri nuclear test site



# $^{133}\text{Xe}$ detections at RN38 in 2015

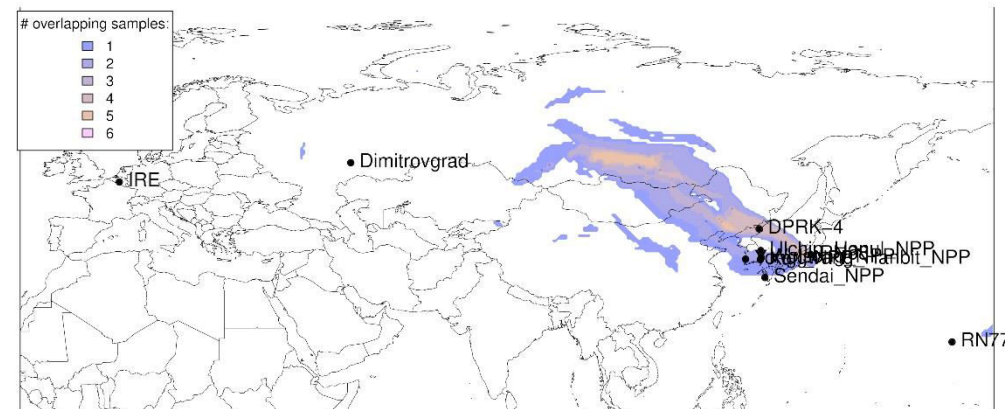
2015\_sample1 – CF source term below  $1.00\text{e}+13$  Bq/day



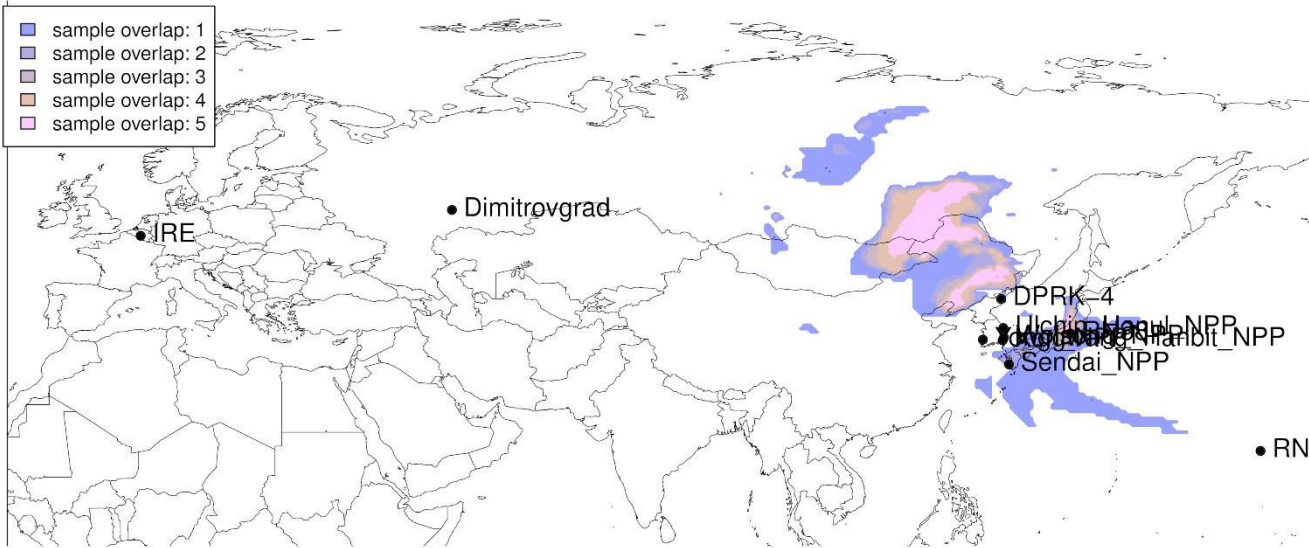
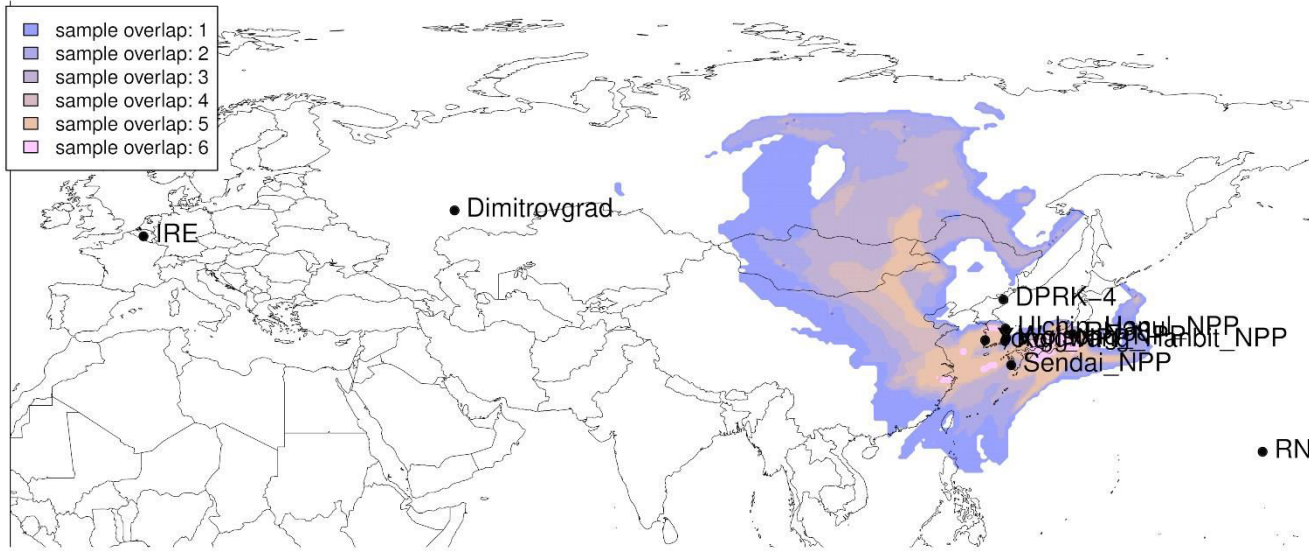
2015\_sample2 – CF source term below  $1.00\text{e}+13$  Bq/day



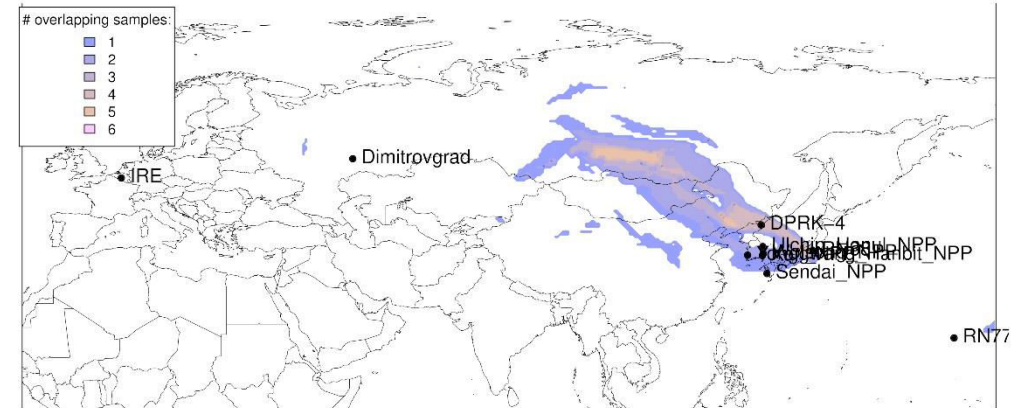
DPRK4\_Eurasia – CF source term below  $1.00\text{e}+13$  Bq/day



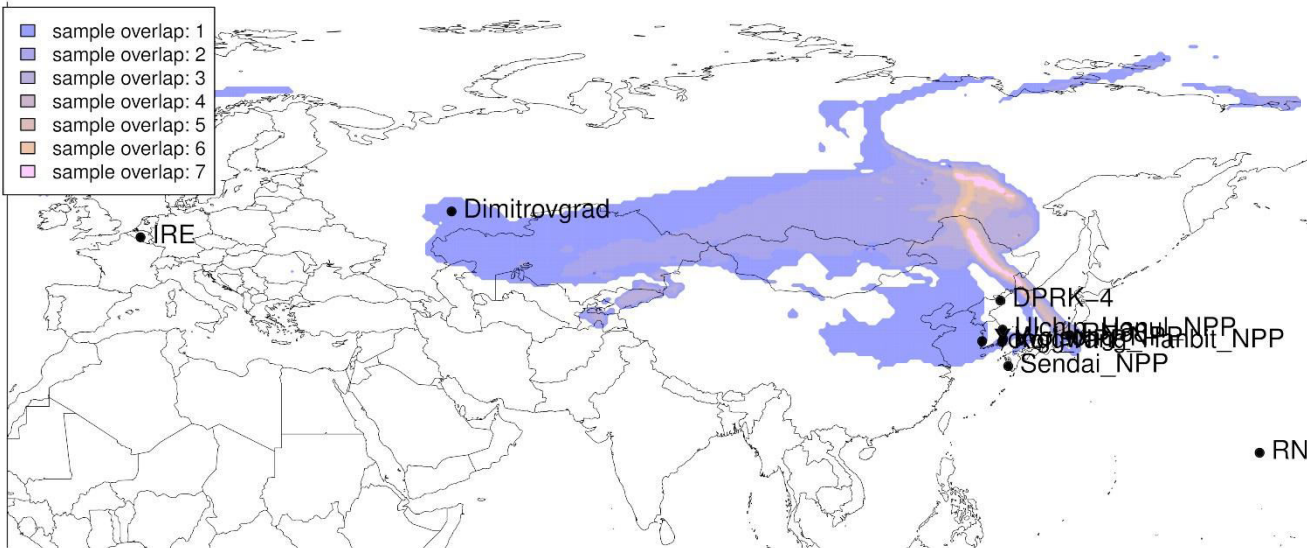
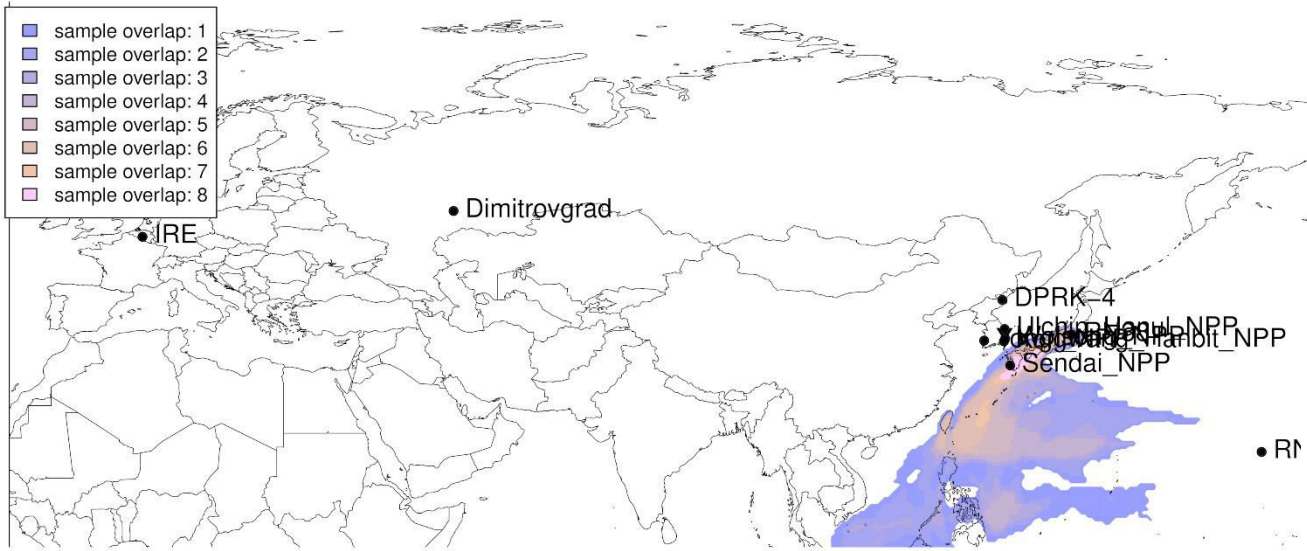
2015\_sample3 – CF source term below 1.00e+13 Bq/day



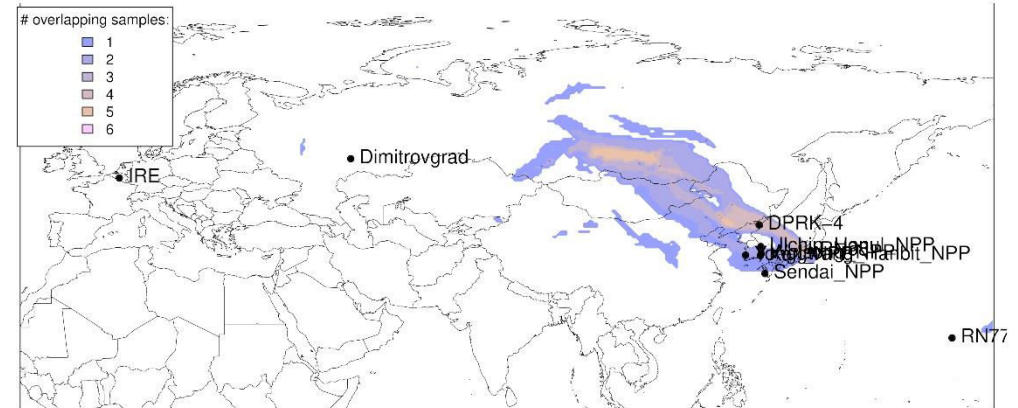
DPRK4\_Eurasia – CF source term below 1.00e+13 Bq/day



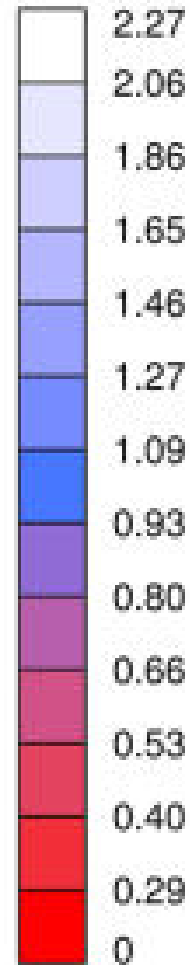
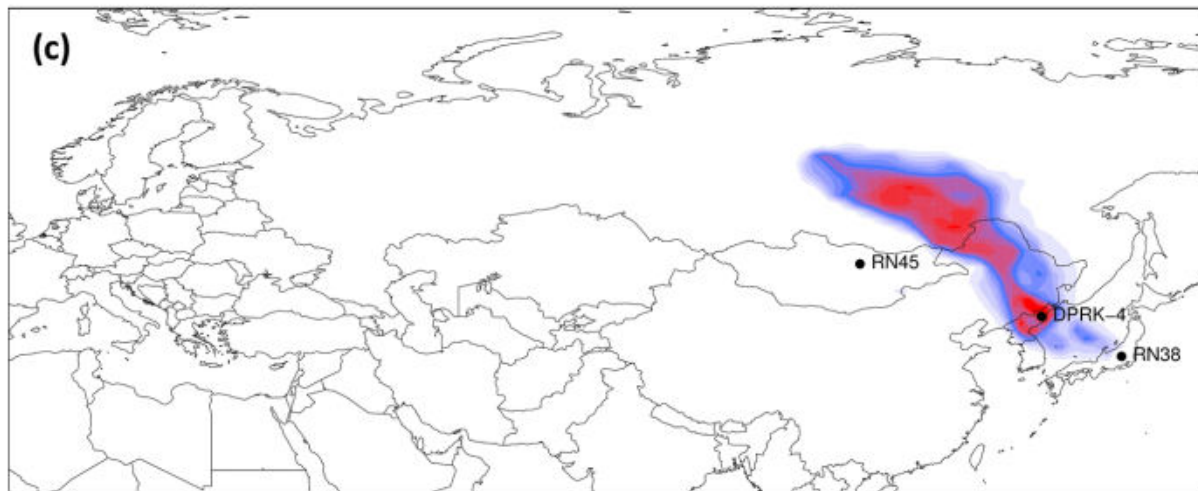
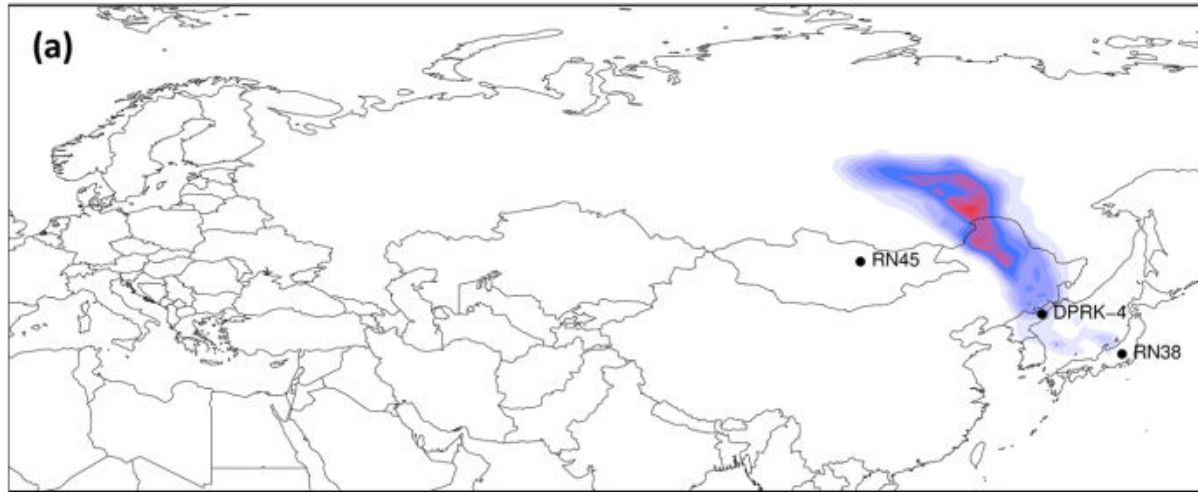
2015\_sample5 – CF source term below 1.00e+13 Bq/day



DPRK4\_Eurasia – CF source term below 1.00e+13 Bq/day

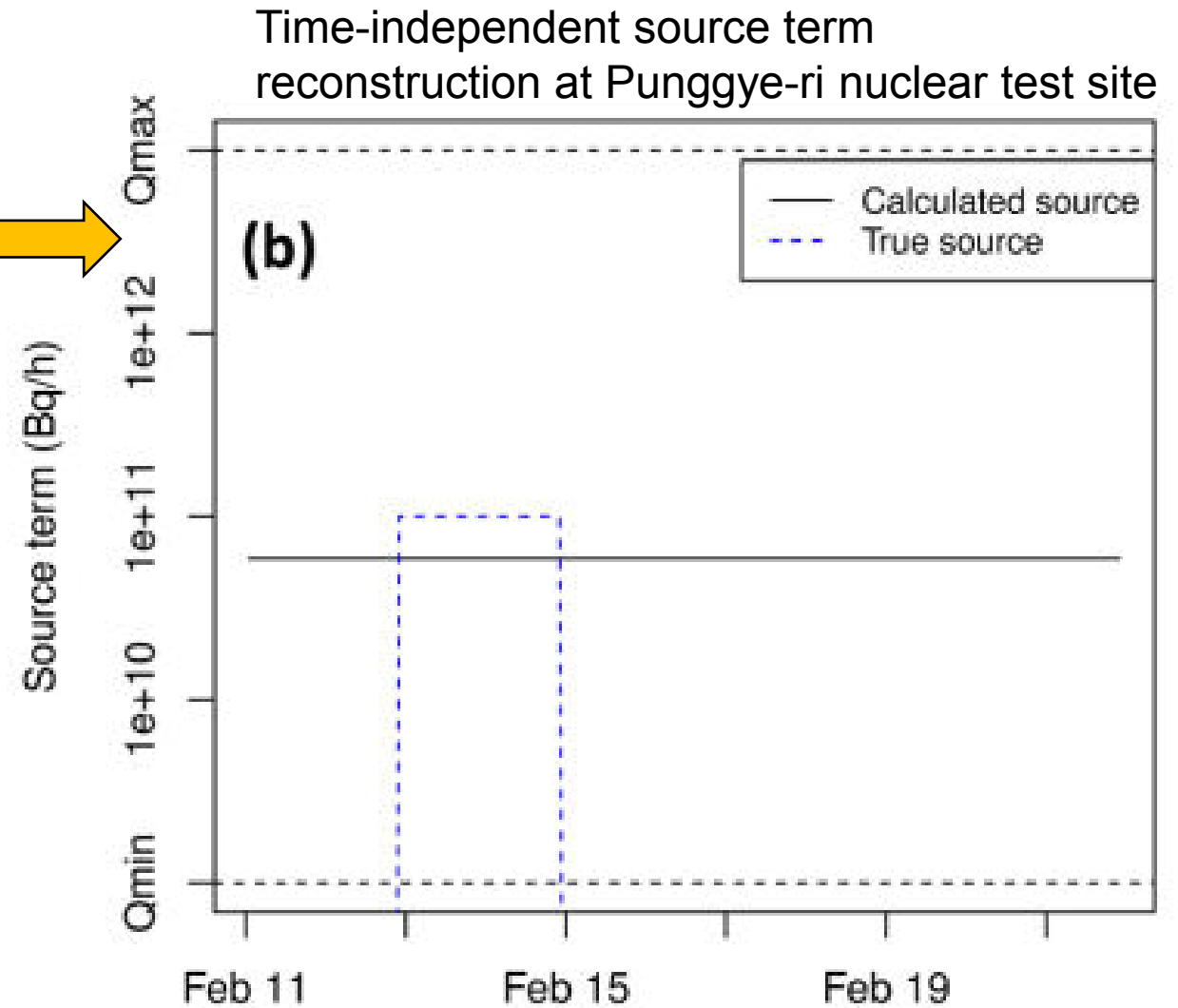
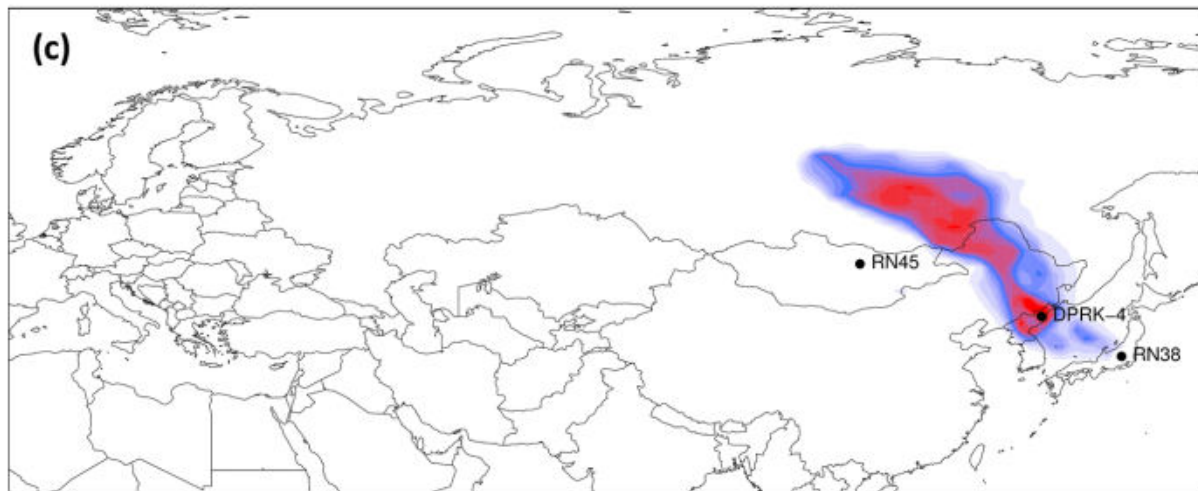
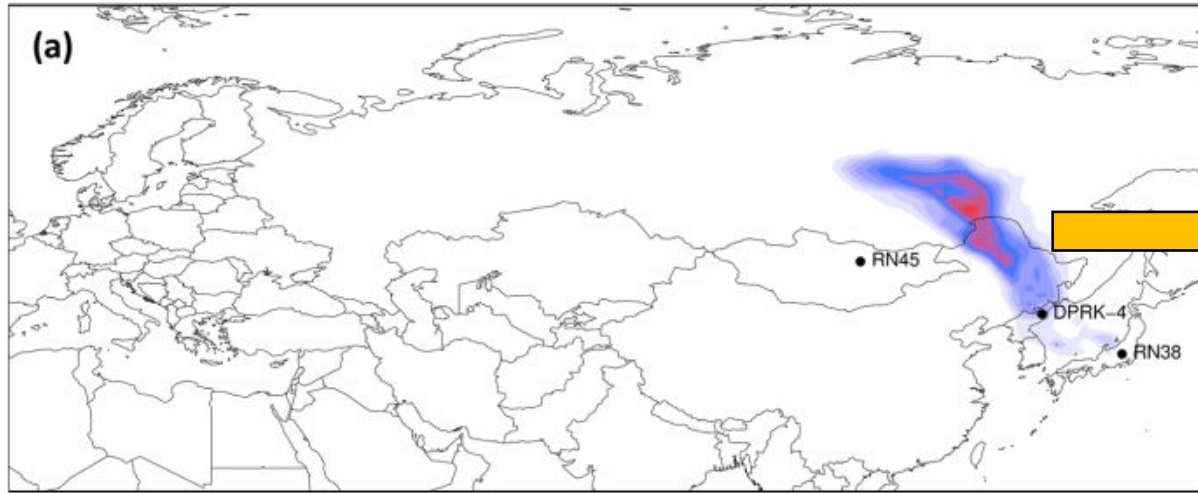


# Validation with fictitious sources: time-dependent release at Punggie-ri

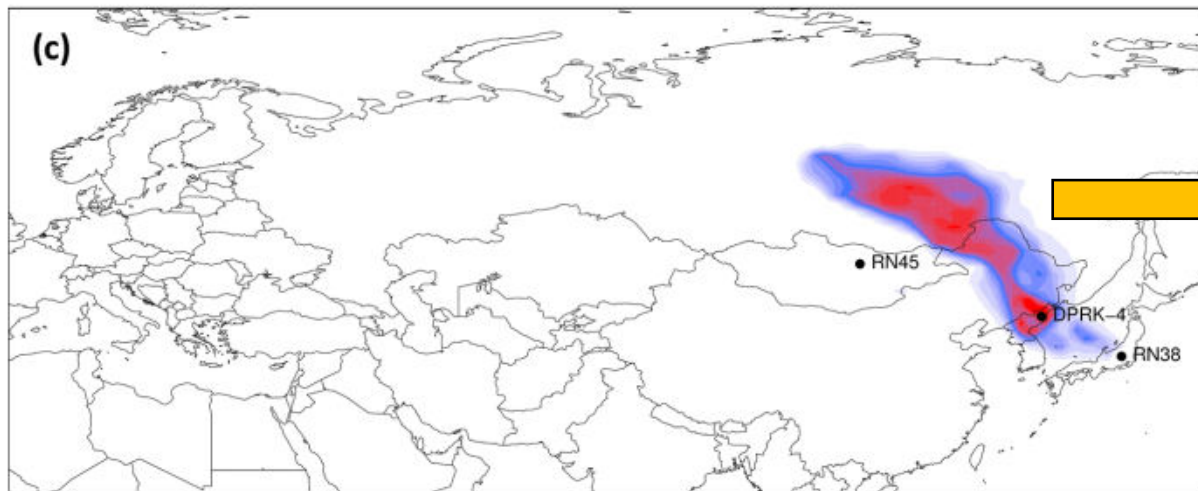
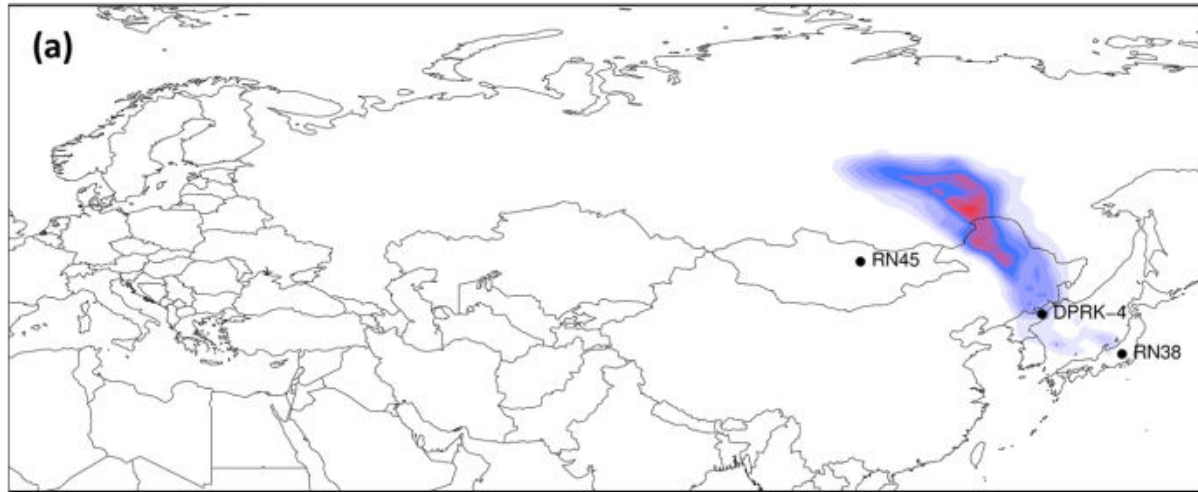


$$\sqrt{\text{cost function}} = \text{"RMSE"} = \sqrt{\sum (AC_{obs} - AC_{sim})^2}$$

# Validation with fictitious sources: time-dependent release at Punggye-ri



# Validation with fictitious sources: time-dependent release at Punggye-ri



Source term (Bq/h)

Time-dependent source term reconstruction at Punggye-ri nuclear test site

