The Fukushima releases: an inverse modeling approach to assess the source term by using gamma dose rate

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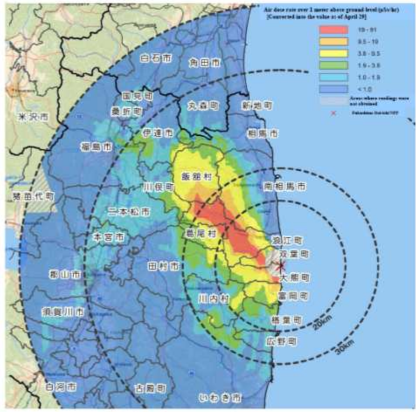
Faire avancer la sûreté nucléaire

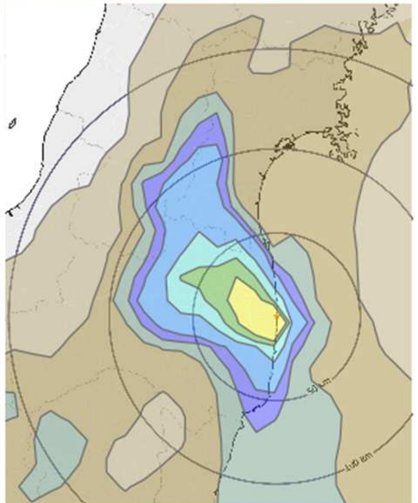
- **Chernobyl and Fukushima accidents proved that it can be tricky to estimate the releases in the atmosphere.**

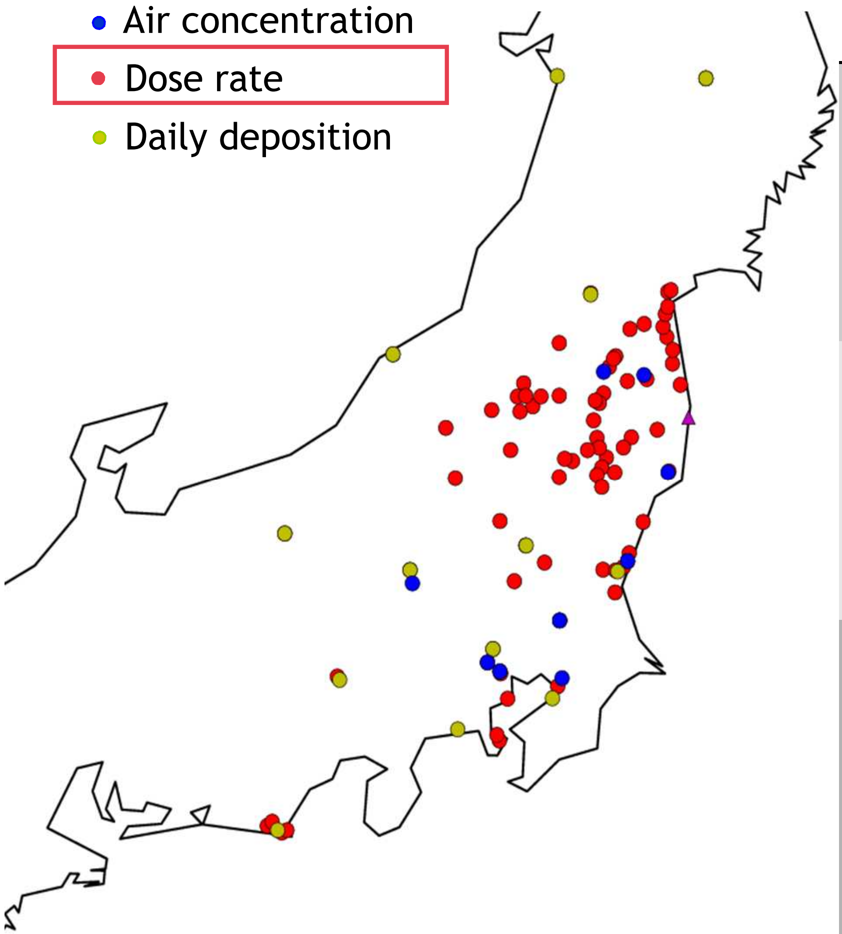
- **The strong uncertainties of the release prevent**
  - to have a complete understanding of the nuclear accident
  - to assess the actual impact on the population.

- **To assess the emissions: Inverse modeling approach by using observations in the environment.**

- Gamma dose rate observations
- Ingredients of the reconstruction
- Reconstruction of the Fukushima Daiichi source term
- Conclusions



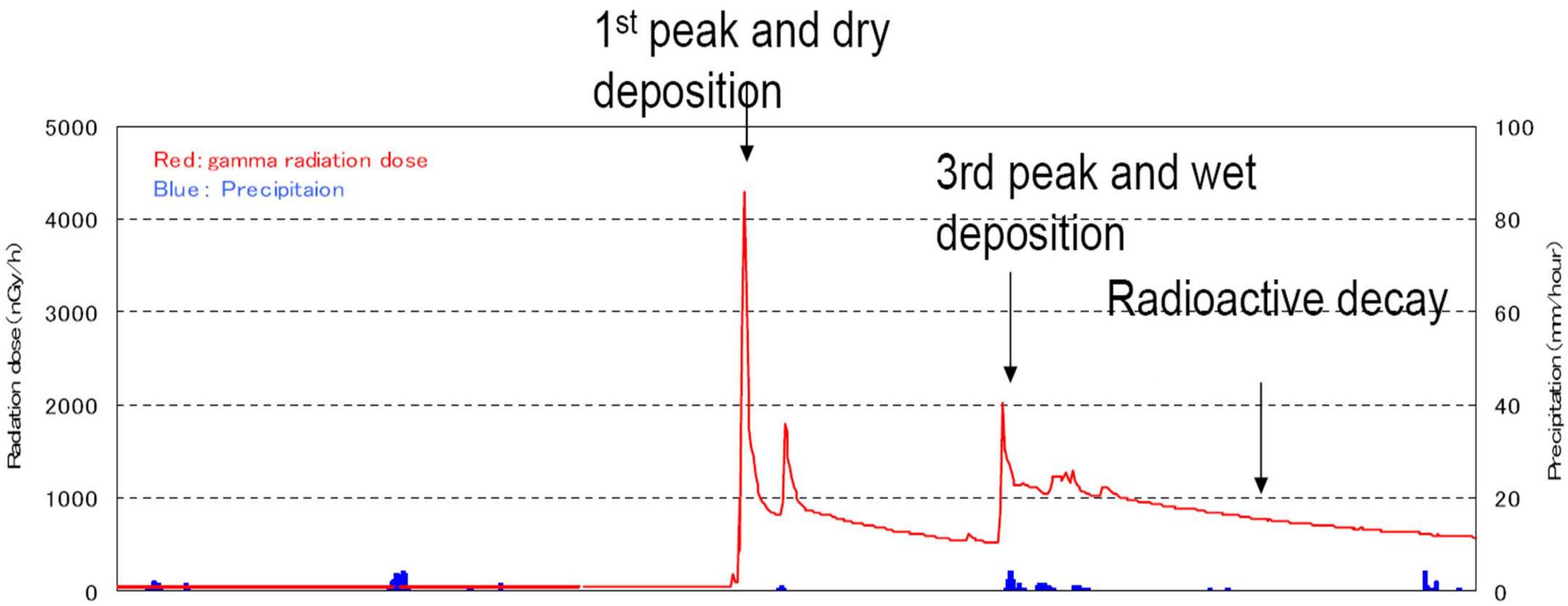




Observations	+	-
Air concentration	Easy to use (Model parameter & Isotopic composition)	Number & frequency (Very few data & Time averaged)
Deposition	Easy to use (Model parameter & Isotopic composition)	Number & frequency (Very few data during the release & Time integrated)
Dose rate	Number & Frequency	Difficult to use (Not a model parameter & Aggregate all the gamma radiations emitted by any radionuclides present on the ground and in the air)

- **Inverse modeling approach : the novelty of the method is the use of dose rate observations (70 stations and 381 time steps between 11st and 27th March).**

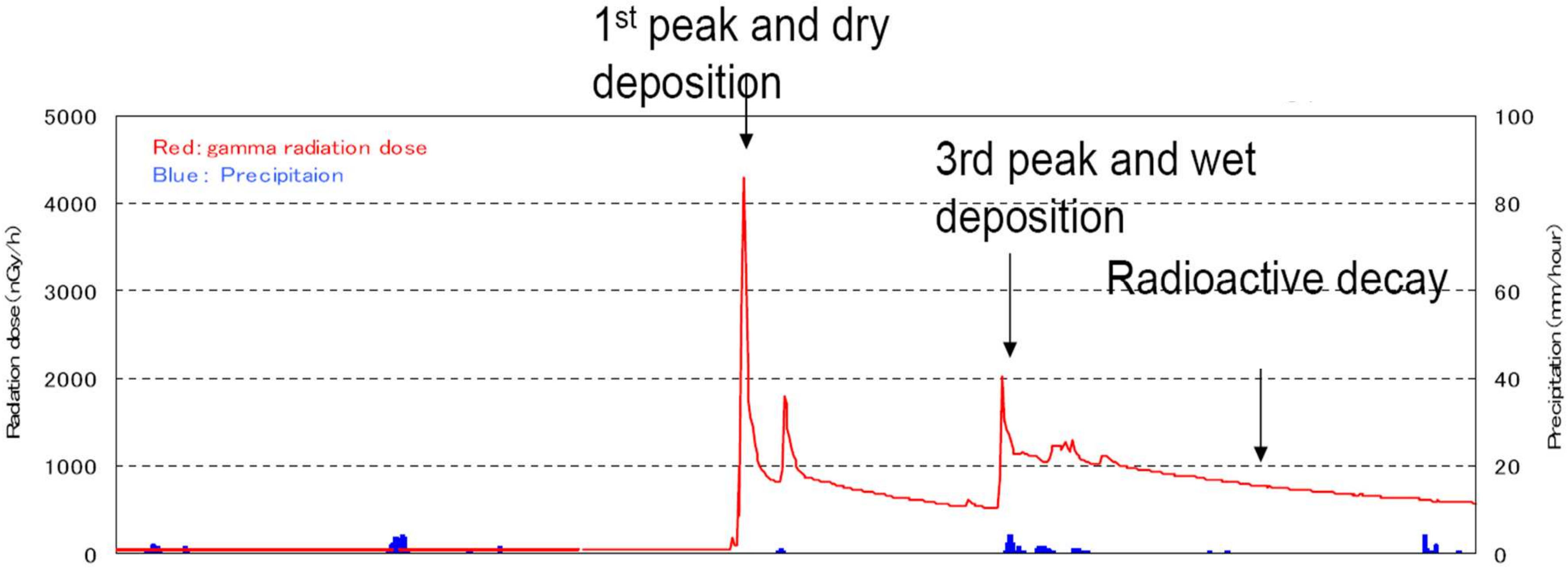
Gamma dose rate observations



How to use dose rate signal ?

- Plume detection when it blew over the station → timing of the release events.
- The slope due to the radioactive decay of the deposit → isotopic composition.
- The value of the observed dose rate → quantities released.

- **Gamma dose rate observations** to assess temporal evolution of the release rate + distribution between radionuclides



- NPP accident: the signal may be due to the contribution of more than a hundred radionuclides
  - Fukushima accident: signal mainly due to ~ 10 radionuclides (^{133}Xe ^{134}Cs ^{136}Cs ^{137}Cs ^{137m}Ba ^{132}Te ^{132}I ^{131}I ^{133}I ^{129}Te ^{99m}Tc) ;
  - The short life radionuclides cannot be discriminated from noble gases ;
  - Some radionuclides were in secular equilibrium (^{137}Cs/^{137m}Ba , ^{132}Te/^{132}I) ;
  - Others have a similar behaviour: constant isotopic ratio (^{134}Cs/^{137}Cs).

Objective: estimate the release rate of 5 radionuclides: ^{134}Cs, ^{136}Cs, ^{132}Te, ^{131}I and ^{133}Xe

The **inverse problem** to solve can be formalized by:

Source term *(ST): temporal evolution of the release rate + distribution between radionuclides*

$$\varepsilon = H\sigma - \mu$$

Vector of errors → ε

H ← Source receptor matrix computed with the forward atm. model (Abida et al. 2011)

σ ← Estimator of the ST

μ ← Vector of measurements

Dispersion model H + Observations μ → Inverse modeling → Estimation of the ST σ

- The objective is to assess the ST σ so that the error ε is minimized.

Cost function (minimized by using L-BFGS-B algorithm)

$$J(\sigma) = \frac{1}{2}(\mu - H\sigma)^T R^{-1}(\mu - H\sigma) + \frac{1}{2}(\sigma - \sigma_b)^T B^{-1}(\sigma - \sigma_b)$$

- **Hypothesis**
  - No prior knowledge of the ST ($\sigma_b = 0$)
  - Simple parameterizations (Winiarek et al., 2011): $R = B = I$

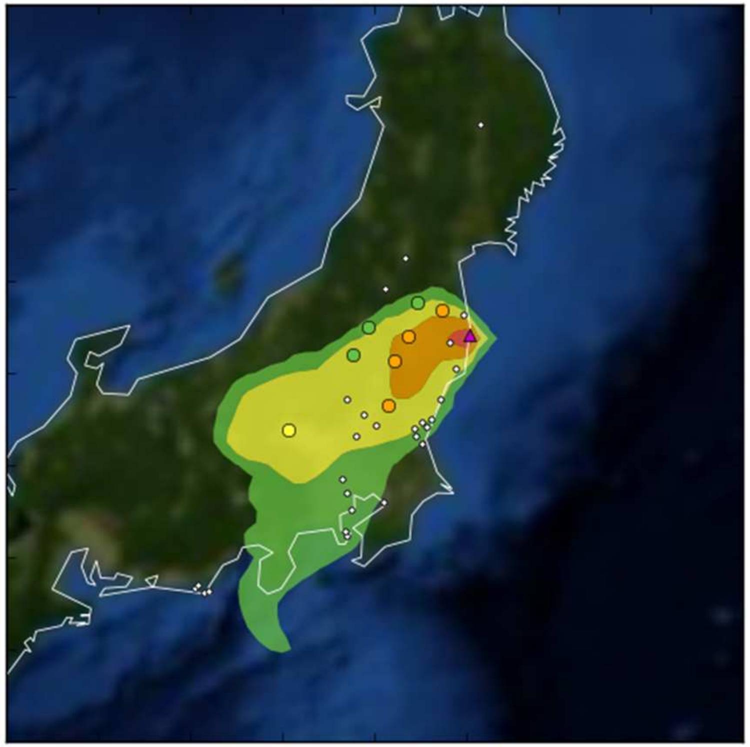
Eulerian dispersion model IdX from the operational C3X platform.

- Dry deposition: v_{dep} = 2 10^{-3} cm/s
- Wet deposition: $\Lambda s = a p_o^{\,b}$, with a = 5 10^{-5} and b = 1
- Vertical diffusion: Troen and Mahrt scheme
- Radioactive decay + filiation

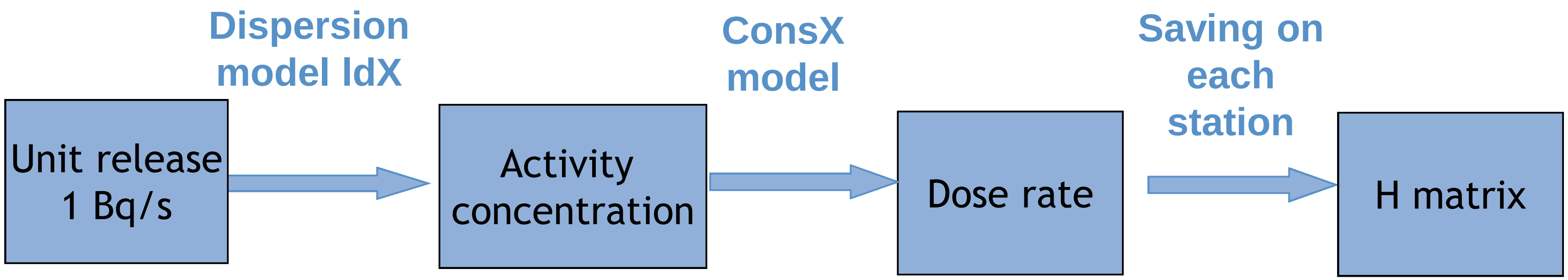
Met. data: ECMWF (0.125° - 3 h)

Spatial resolution: 0.125° x 0.125°

Time resolution: 1 hour



Consequences model : consX from C3X



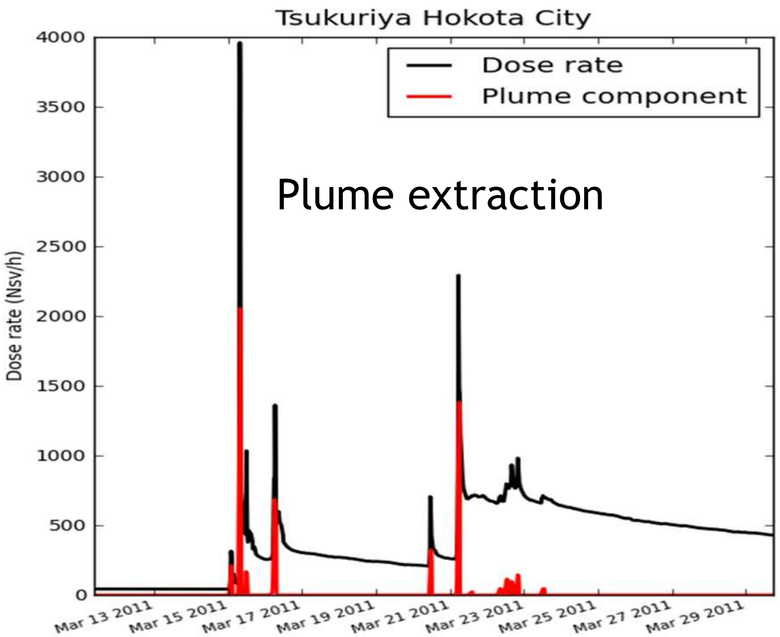
Inverse modeling method

Raw dose rate measurements cannot be used directly: inverse problem not sufficiently constrained

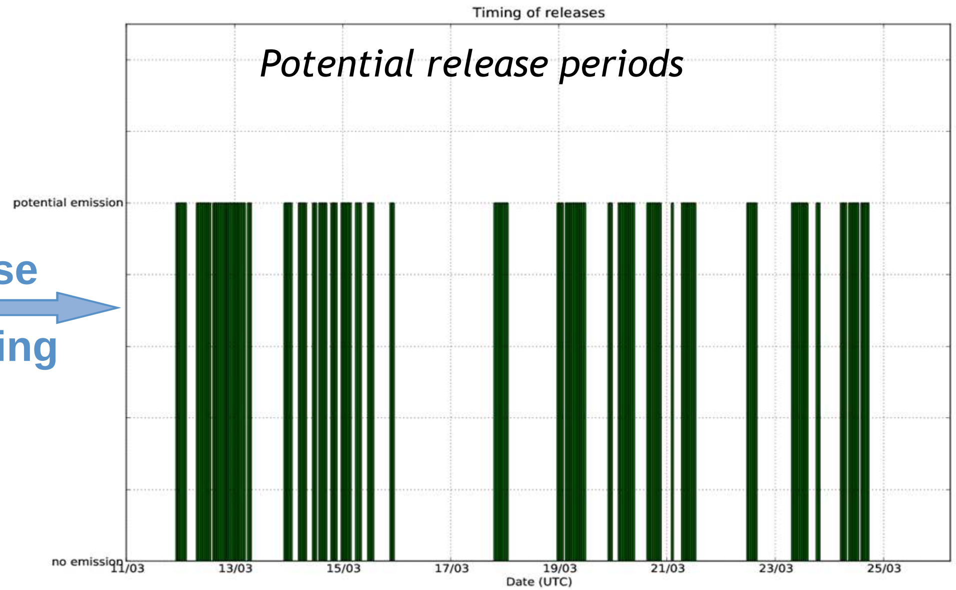
- **Solution to solve the inverse problem: reduce the number of parameters + limit the solution space**
  - **Isotopic composition of the ST: only 5 radionuclides**
  - **A two steps method**
    1. Identify the potential release periods
    2. Assess the release rates during periods identified in step 1
  - **Add isotopic constraints: radionuclides released in proportions that depends on their physicochemical properties + the core inventory**

Step 1: Inverse modeling to identify the potential release periods

Measurements: dose rate due to the plume component for 70 stations



Inverse modeling →

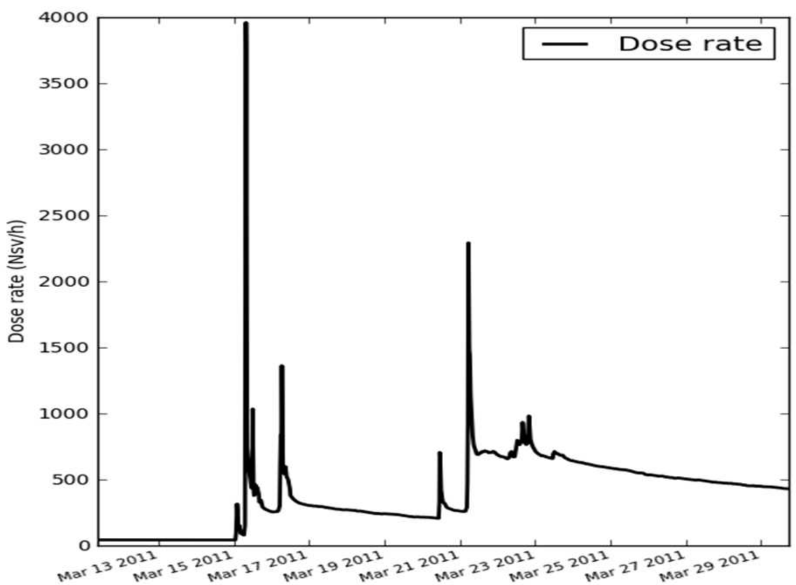


381 initial time steps → **Inverse modeling** → 120 potential release instants

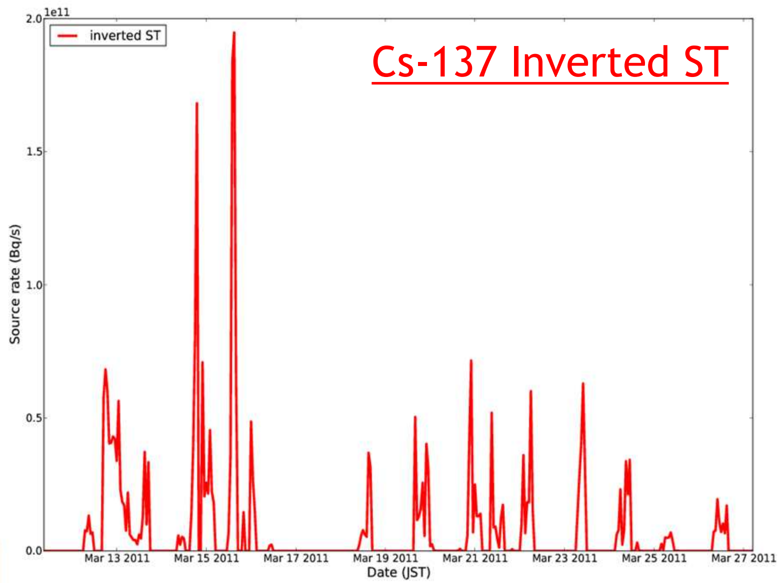
Step 2: Inverse modeling to assess the release rates during periods identified in step 1

- Measurements: the complete dose rate signal on 70 stations
- Soft constraints on isotopic ratio are imposed (based on analysis of core reactor and air concentrations measurements in Japan)

- The cost function to minimize uses a regularization function which contains information about isotopic ratios



Inverse modeling

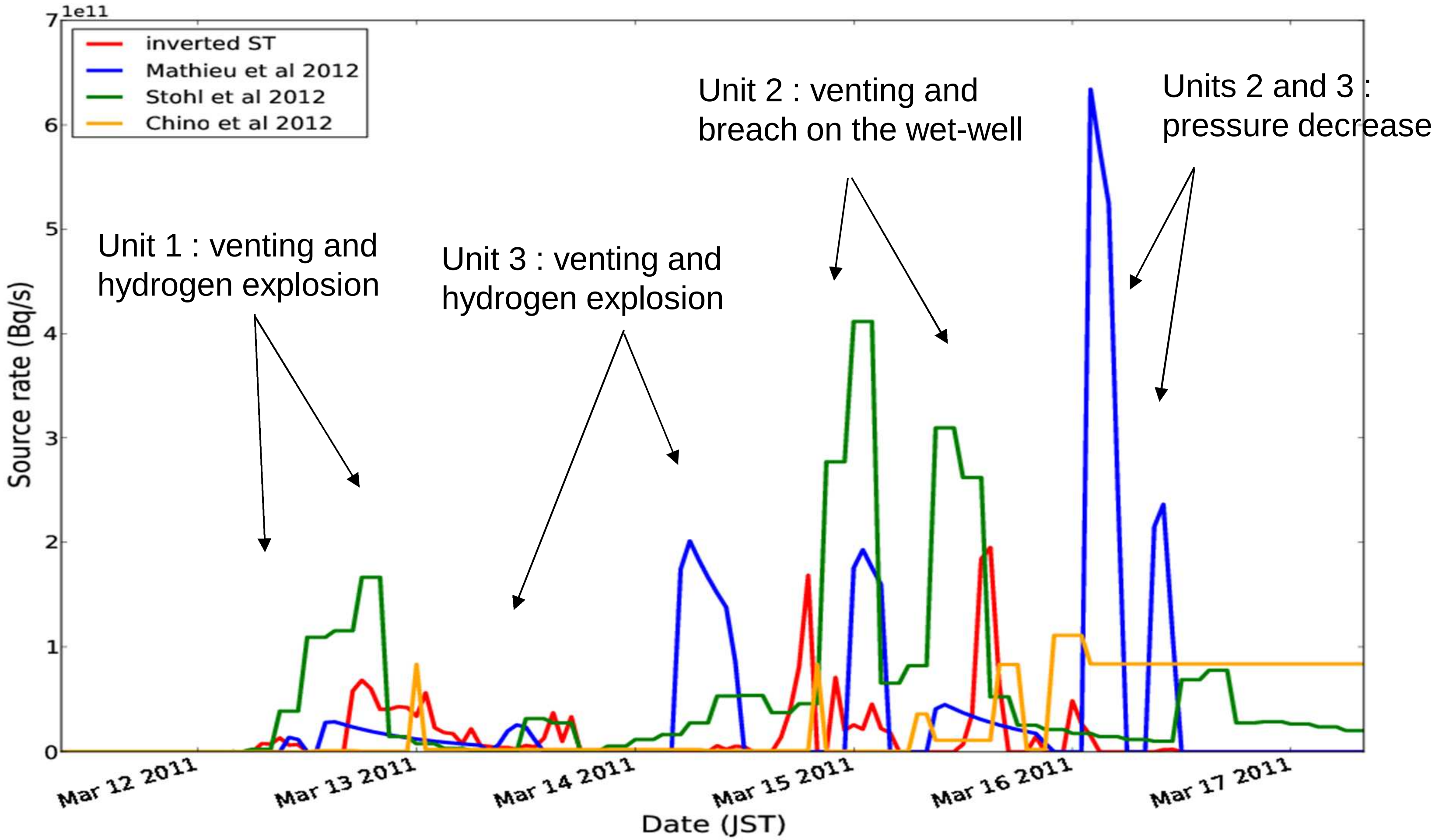


Comparisons with other ST

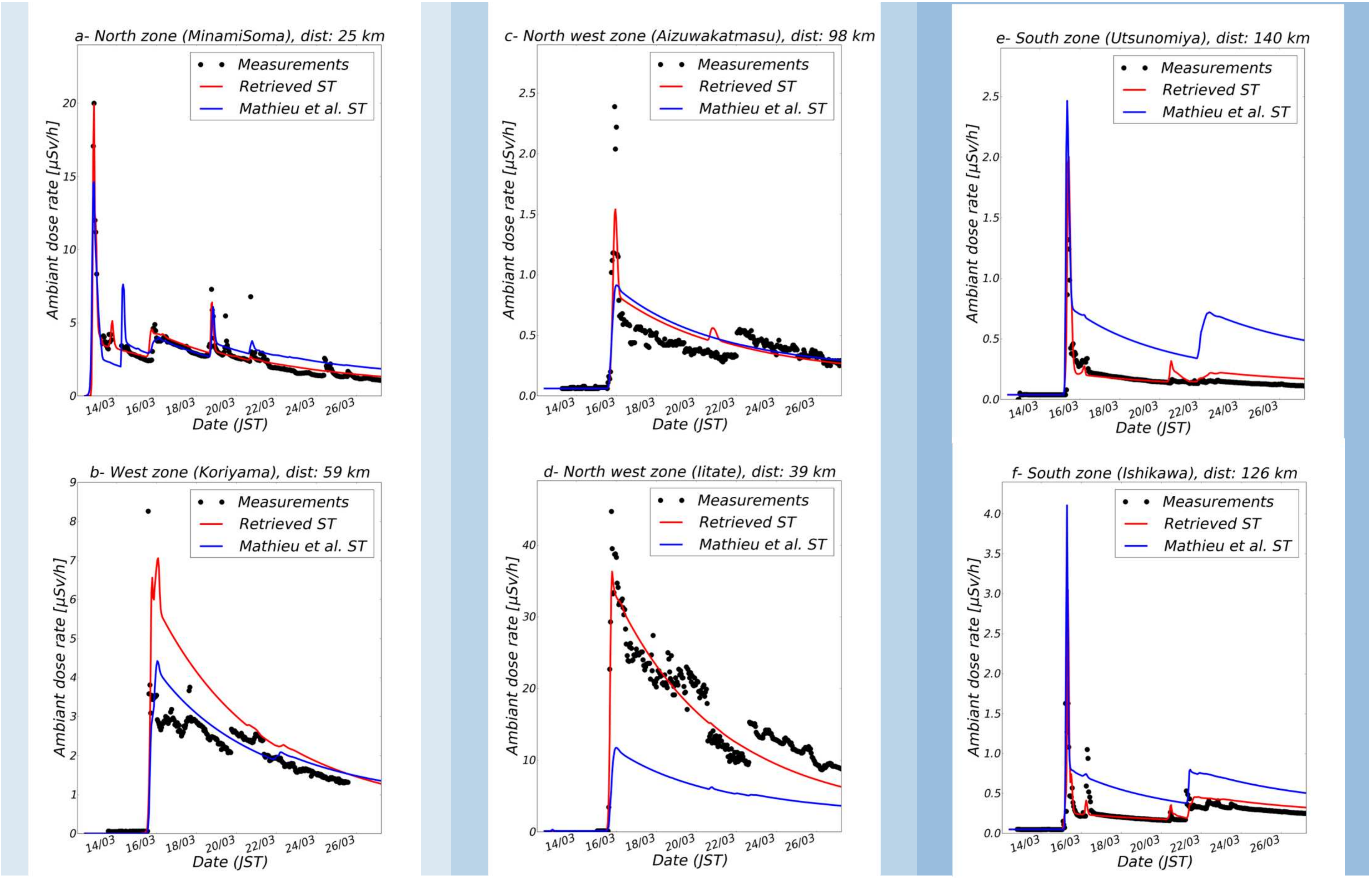
Source Term (PBq)	^{133}Xe	^{131}I	^{132}I	^{137}Cs	^{136}Cs
Inverted ST	12100	103	35.5	15.5	3.7
Mathieu et al. (2012)	5950	197	56.4	20.6	9.8
Winiarek et al. (2012)	-	190-380	-	12-19	-
Terada et al. (2012)	-	150		13	-
Stohl et al. (2012a)	13400-20000	-	-	23.3-50.1	-
TEPCO (2012)	500	500		10	

- Inverted quantities are **consistent with the other estimations.**
- Underestimation in iodine and cesium in comparison with Mathieu et al ST (several events are not identified by inversion).
- Amount of noble gases is similar to Stohl et al estimation: probably overestimated

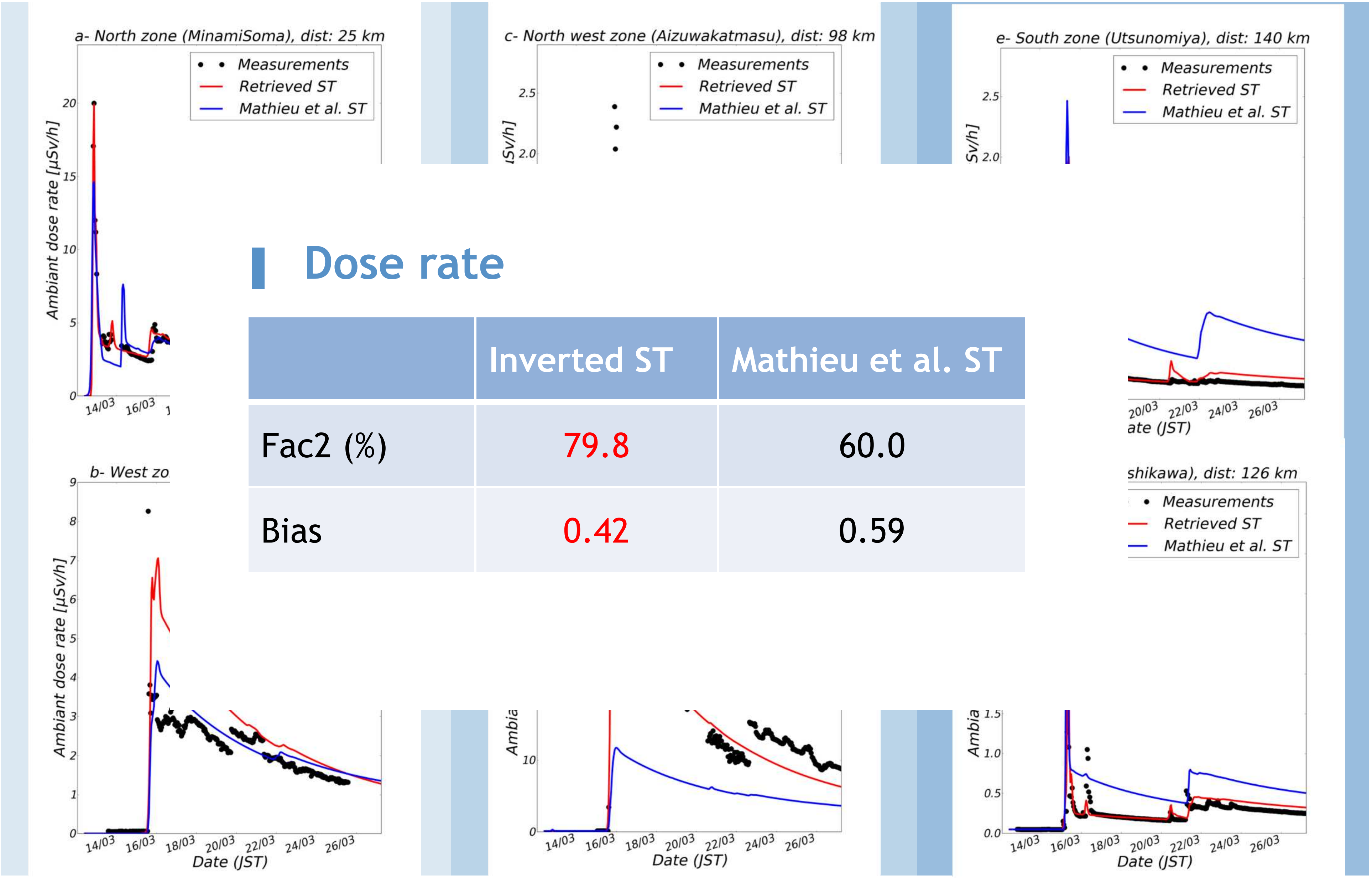
Comparisons with other ST



- **The main release events are well reproduced by the inverted ST.**
- Events occurred on the reactors 1 and 3 are uncertain (too few observations).
- **Amounts of radionuclides are quite different depending on the source term.**



- **Good agreement** between model and observations.
- **Additional releases are identified with the inverse modeling method.**
- Discrepancies are due mainly to inaccurate meteorological fields.



Dose rate

	Inverted ST	Mathieu et al. ST
Fac2 (%)	79.8	60.0
Bias	0.42	0.59

- **Good agreement** between model and observations.
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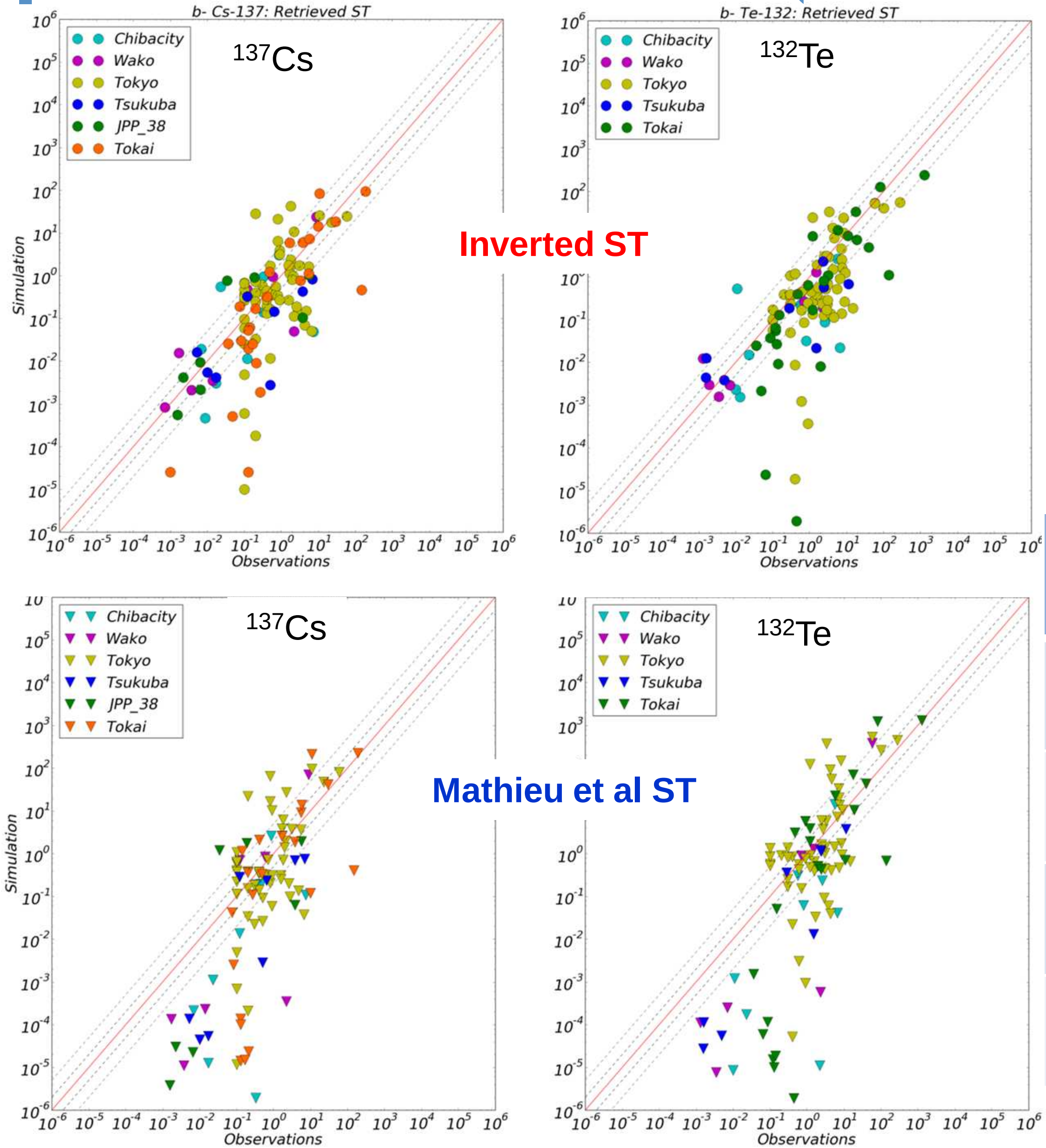
- Discrepancies are due mainly to inaccurate meteorological fields.

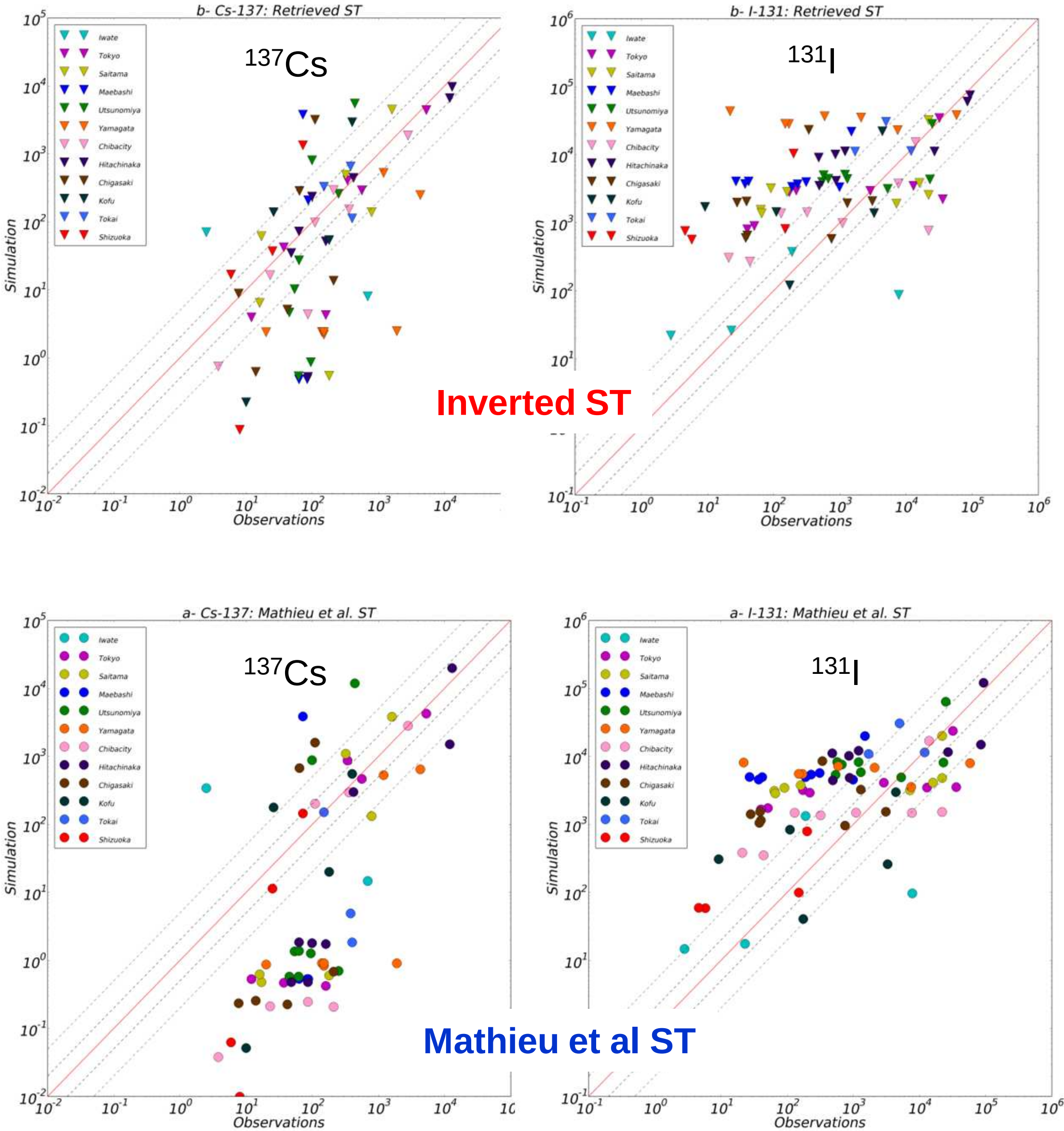
Air concentration measurements (not used in the inverse process)



- Good enough agreement between model (with inverted ST) and observations.
- Realistic isotopic composition.
- Underestimation of ^{132}Te: 72 % of the FAC5 data are underestimated (65 % for the Mathieu et al ST).

	Inverted Fac5 (%)	Mathieu Fac5 (%)
^{136}Cs	52,3	35,4
^{137}Cs	58,2	47,0
^{131}I	57,1	31,4
^{132}Te	53,7	40,1

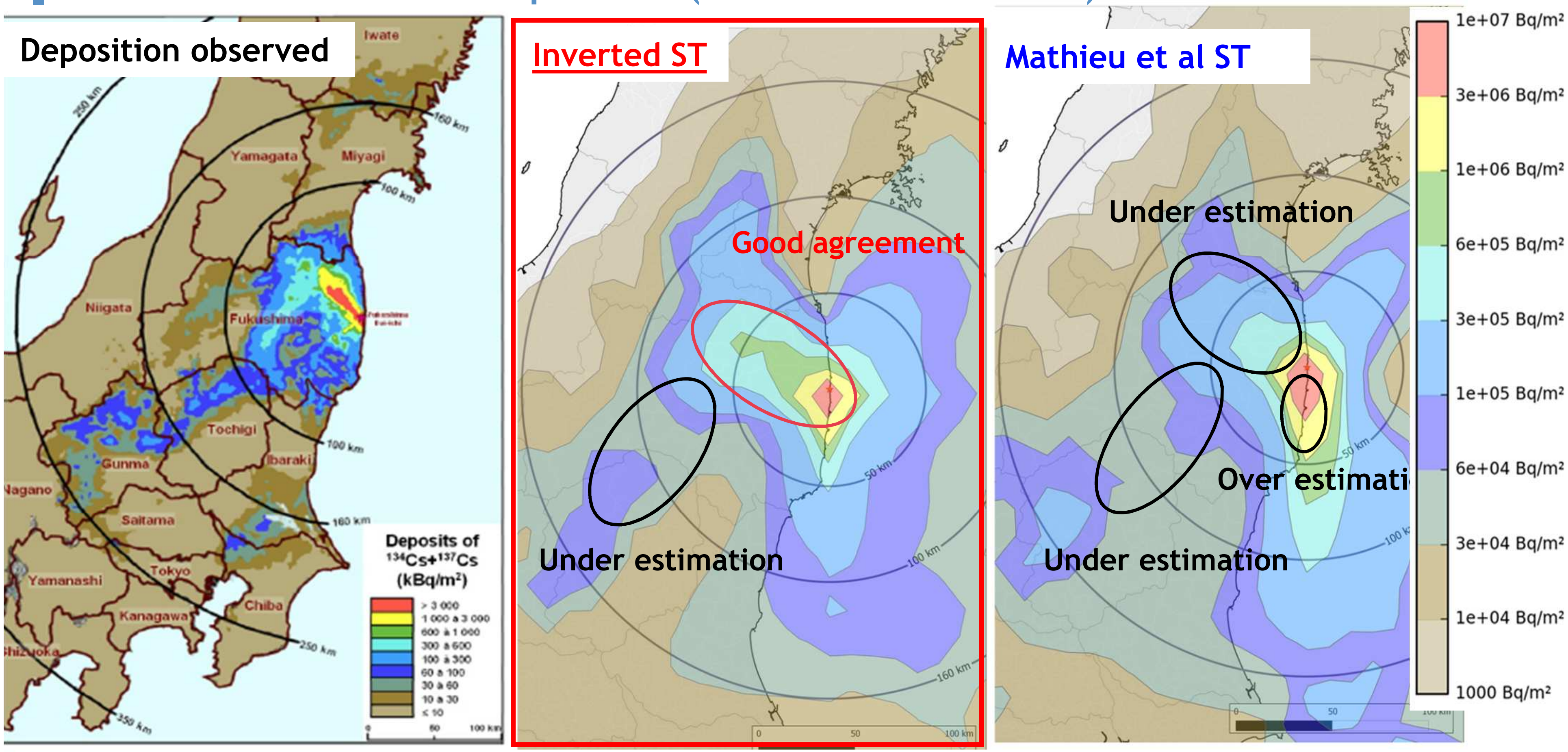
Deposition measurements (not used in the inverse process)



- Measurements mainly after March 18: the main events are not observed.
- Good enough agreement between model (with inverted ST) and observations.
- Realistic isotopic composition.

	Inverted Fac5 (%)	Mathieu Fac5 (%)
^{137}Cs	65,2	40,6
^{131}I	41,8	43,0

Total Cs-137+ Cs-134 deposition (not used in inversion)



- **In the north-west of the plant, good agreement between model (with inverted ST) and observations (not used to assess the ST).**
- The agreement is not perfect in some areas (Tochigi and west Fukushima prefectures).
- Differences are due mainly to inaccurate meteorological fields(precipitation, wind) and deposition scheme.

Reliable inversed modeling method to assess the source term by using dose rate measurements

Performances

- Good results achieved on the Fukushima accident.
- The quality of the meteorological forecast is a key point to retrieve a realistic source term.

Use

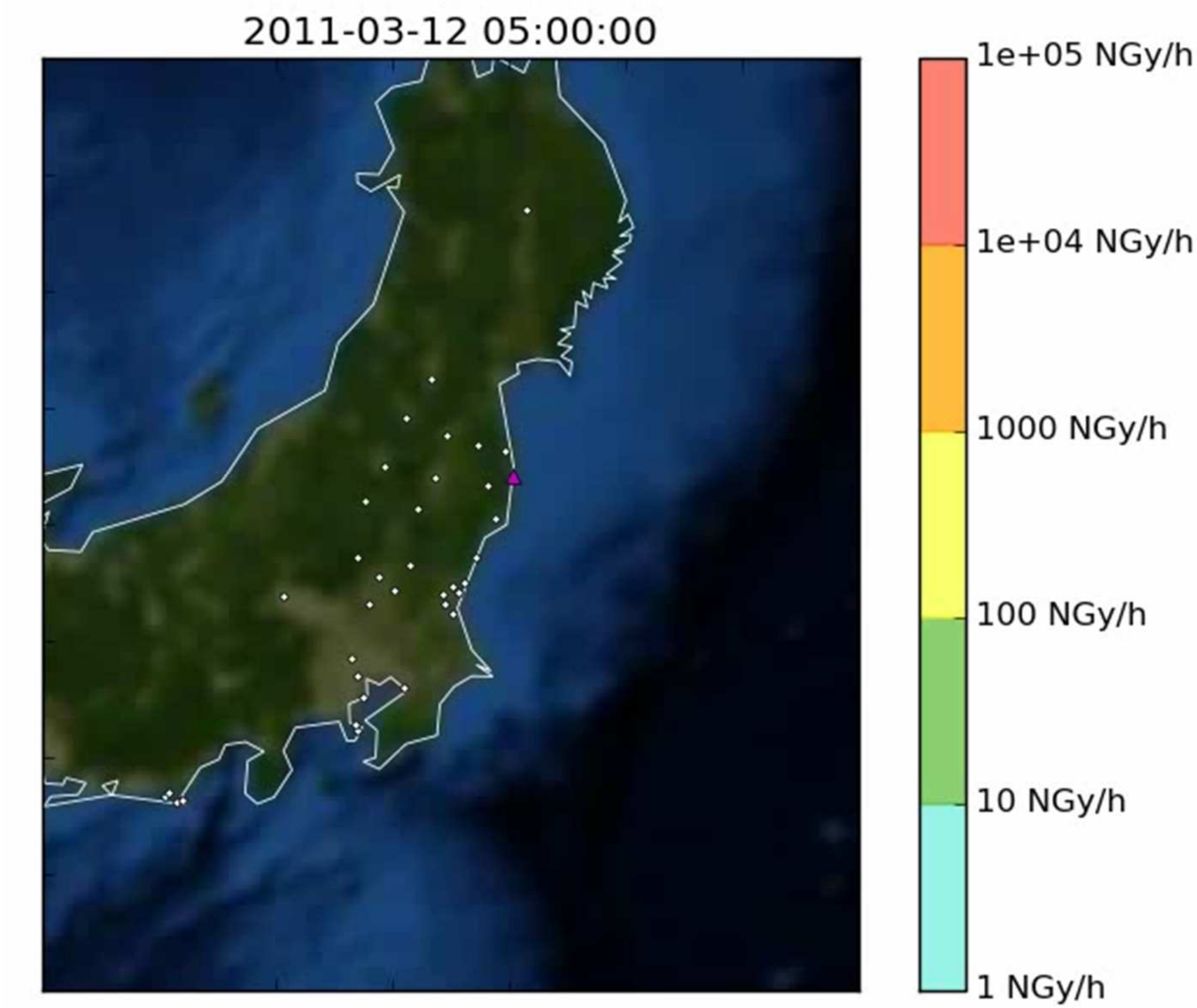
- Perfectly suited to crisis management.
- Efficient tool to improve the understanding of an accident.

Perspectives

- Improve the reconstruction of the isotopic composition (Iodine 132): air concentration, deposition and dose rate observations.
- Extend the method to all spatial scales.

➚ *Saunier et al., ACPD 2013 (submitted)*

Thank you for your attention



Model to data comparisons (dose rate - plume component)