Radioactive nuclei emission analysis from Fukushima Daiichi nuclear power plant by inverse model

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1-1. Background

A large amount of radioactive nuclei has been released from the Fukushima Daiichi nuclear power plant in March 2011.

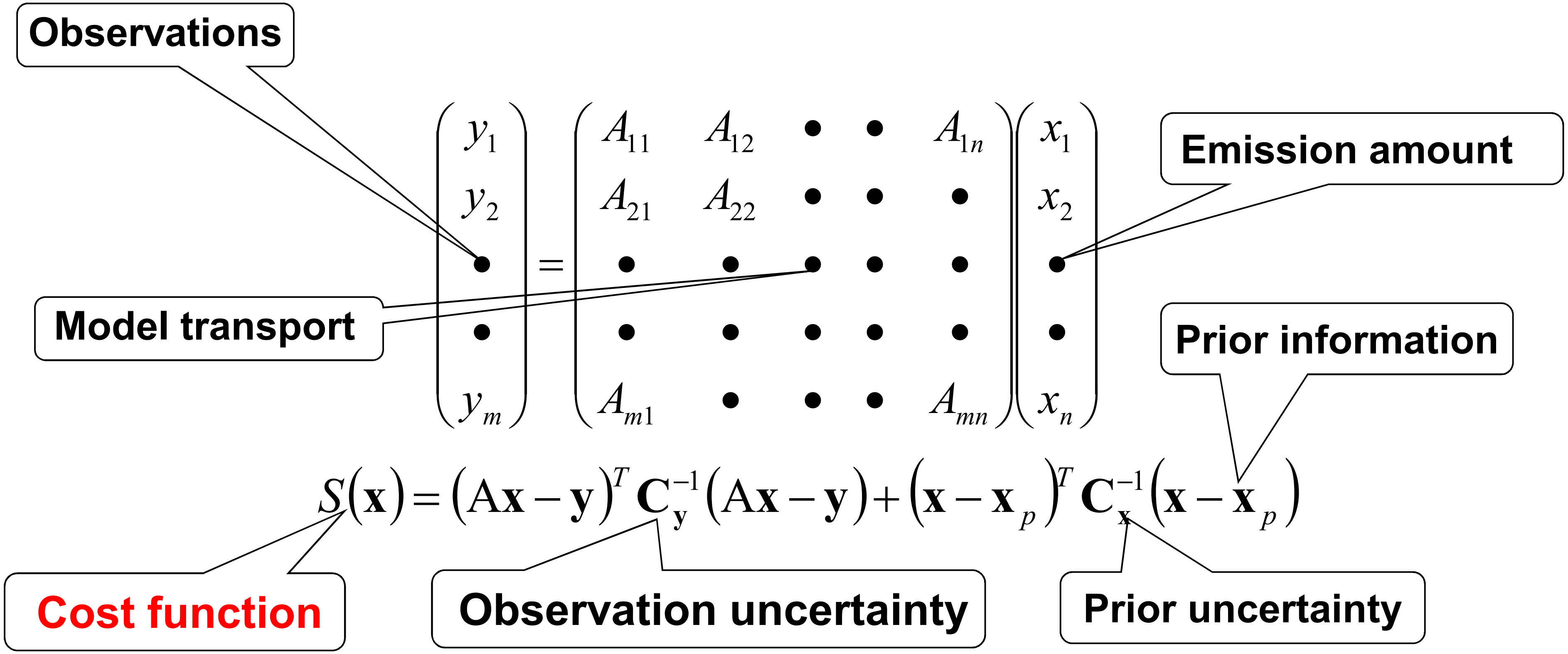
Although many institutions in Japan and abroad provided radioactive nuclei prediction information. However, such information could not be used effectively for evacuate.

Fukushima Daiichi nuclear power plant（TEPCO HP）

It is forced to be one reason that as the amount of radioactive nuclei emission is unknown. Therefore, the prediction accuracy is limited.

One important feature of this accident is that the position of the emitting source is known. Therefore, we consider it possible to estimate the emission time series by combining a transport model, observed data and an inverse model. Such time series of emission amount is significantly important for model hind cast experiment, evaluation of deposition and so on.

1-2. Bayesian Synthesis Inversion



Observations

Emission amount

Model transport

Prior information

$$\begin{pmatrix} y_1 \\ y_2 \\ \bullet \\ \bullet \\ y_m \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & \bullet & \bullet & A_{1n} \\ A_{21} & A_{22} & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet \\ A_{m1} & \bullet & \bullet & \bullet & A_{mn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \bullet \\ \bullet \\ x_n \end{pmatrix}$$

$$S(\mathbf{x}) = (\mathrm{A}\mathbf{x} - \mathbf{y})^T \mathbf{C}_{\mathbf{y}}^{-1} (\mathrm{A}\mathbf{x} - \mathbf{y}) + (\mathbf{x} - \mathbf{x}_p)^T \mathbf{C}_{\mathbf{x}}^{-1} (\mathbf{x} - \mathbf{x}_p)$$

Cost function

Observation uncertainty

Prior uncertainty

$(\mathrm{A}\mathbf{x} - \mathbf{y})^T \mathbf{C}_{\mathbf{y}}^{-1} (\mathrm{A}\mathbf{x} - \mathbf{y})$ Shows mismatch between observation and model

$(\mathbf{x} - \mathbf{x}_p)^T \mathbf{C}_{\mathbf{x}}^{-1} (\mathbf{x} - \mathbf{x}_p)$ Shows mismatch between prior and posterior emission

↓

We determine emission x which minimize cost function $S(\mathrm{x})$.

2-1. Features of our analysis

	Chino et al.	**Stohl et al.**	**This study**
Number of Obs.	17（17）	43（5）	50(2)
Transport model	WSPEEDI	FLEXPART	MASINGAR mk-2
Model type	Off-line Lagrange	Off-line Lagrange	On-line Euler
Meteorology	JMA GSM （0.25×0.2°）	ECMWF（0.18°） #GFS（0.5°）	JCDAS（1. 25°）
Estimation method	Peak comparison	Inversion	Inversion
Time resolution	Daily	3 hourly	Daily

Meteorological data used in Japan area

An important features of our analysis is that we adopt On-line Eulerian global chemistry transport model (MASINGAR-mk2). We could treat detailed physical process (cumulus convection, turbulent diffusion and deposition processes) in radioactive nuclei transport.

2-2. Our Global Inversion System

Observation data (^{137}Cs) About 50 sites (CTBT, Ro5, Hoffmann, Berkeley, Taiwan), daily mean.

Transport model

MASINGAR-mk2 (TL319) by Tanaka et al.,

Prior flux information[1]

Chino posterior and Stohl prior

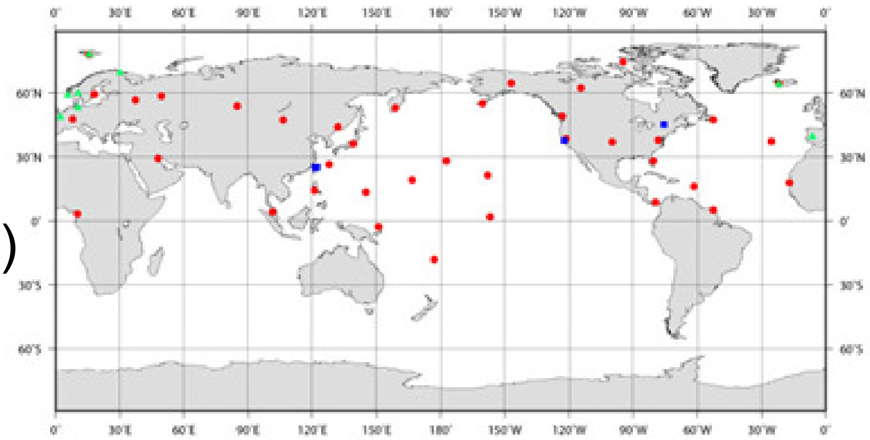
Observation uncertainty[2]

20% (Obs. error and representative error)

Prior flux uncertainty

Valuable[3]

Obsevation Point of Cs137 ;Fukushimar–Daiichi nuclear disaster.



[1] Prior information

We adopted prior flux (not posterior) by Stohl et al., in order to avoid double use of observation data. Chino posterior uses only Japanese sites.

[2] Observation data uncertainty

We gave a large observation uncertainty when data in periods of no observation.

[3] Prior flux uncertainty

The difference between Chino posterior (9PBq) and Stohl prior (29PBq) is too large. Results of the inverse analysis is highly dependent on the a priori information. Therefore, we changed prior flux uncertainties to obtain suitable prior flux uncertainty.

2-3. On-line Global Model (MASINGAR-mk2)

- Included radionuclides: 6 species
  - I-131, Cs-137, Cs-134, Te-132, I-132, Xe-133
  - Xe-133 is treated as non-reacting gas with no dry and wet depositions.
  - Other species are assumed to be attached to aerosols (Lognormal size distribution with r_n=0.07μm, σ=2.0, and hydrophilic)

- Model resolution: Horizontal TL319 (0.56°, approx.60km), vertical 40 layers (ground– 0.4hPa)

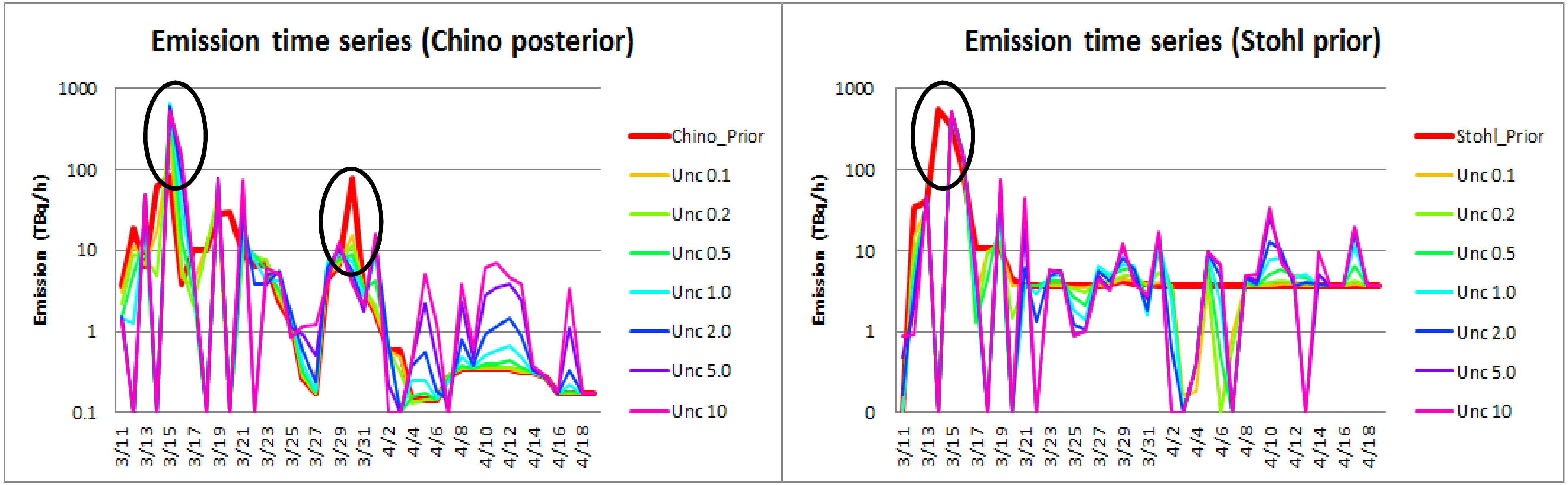
- Atmospheric dynamical model: JMA/MRI unified general circulation model (MRI-AGCM3)

- Horizontal wind components are nudged using JMA global analysis (GANAL).

- We released an unit radionuclides at lowest model layer (about 100m) in tagged tracer transport experiments.

- MASINGAR is operationally used in JMA (aeolian dust information)

3-1. Estimated ^{137}Cs emission time series



Using both prior flux time series, estimated results tends to similar when we use larger prior flux uncertainties.

The maximum radioactive nuclei emission happened at 15th March.

There are some emission events at 15th – 16th March, 19th - 21th March, 29-30th March, 1st April, 10th April and 17th April.

The estimated emission amount at 15th March are larger than Chino prior emission.

The estimated emission amount at 30th March is smaller than Chino prior emission.

3-2. Estimated ^{137}Cs emission amount and statistics

$$\sum_{n=1}^{N} \mathbf{x}_n$$

Table 1: Total radionucleide emission amount from 11th March to 19th April (PBq)

Prior Flux uncertainty	0.1	0.2	0.5	1.0	2.0	5.0	10.0	20.0
Chino prior (9PBq)	9.3	13.3	17.4	18.5	18.8	19.5	20.2	20.7
Stohl posterior (28PBq)	18.2	18.7	19.2	19.5	19.9	20.4	21.1	22.0

$$\sum_{n=1}^{N} \left(\mathbf{x}_n - \mathbf{x}_p\right)^2$$

Table 2: Square of the difference between prior and posterior emission (TBq/h)

Prior Flux uncertainty	0.1	0.2	0.5	1.0	2.0	5.0	10.0	20.0
Chino prior	26.8	56.5	87.0	91.8	87.0	80.4	78.9	78.5
Stohl posterior	93.5	87.5	99.2	102.5	100.8	98.3	97.9	97.8

$$\sum_{n=1}^{N} \left(\frac{\mathbf{x}_n - \mathbf{x}_p}{\mathbf{C}_{\mathbf{x}_n}}\right)^2$$

Table 3: Normalized square of the difference between prior and posterior emission

Prior Flux uncertainty	0.1	0.2	0.5	1.0	2.0	5.0	10.0	20.0
Chino prior	0.4	0.8	1.3	2.0	3.7	6.9	10.4	16.0
Stohl posterior	0.4	0.5	0.8	1.5	2.2	2.8	3.5	4.3

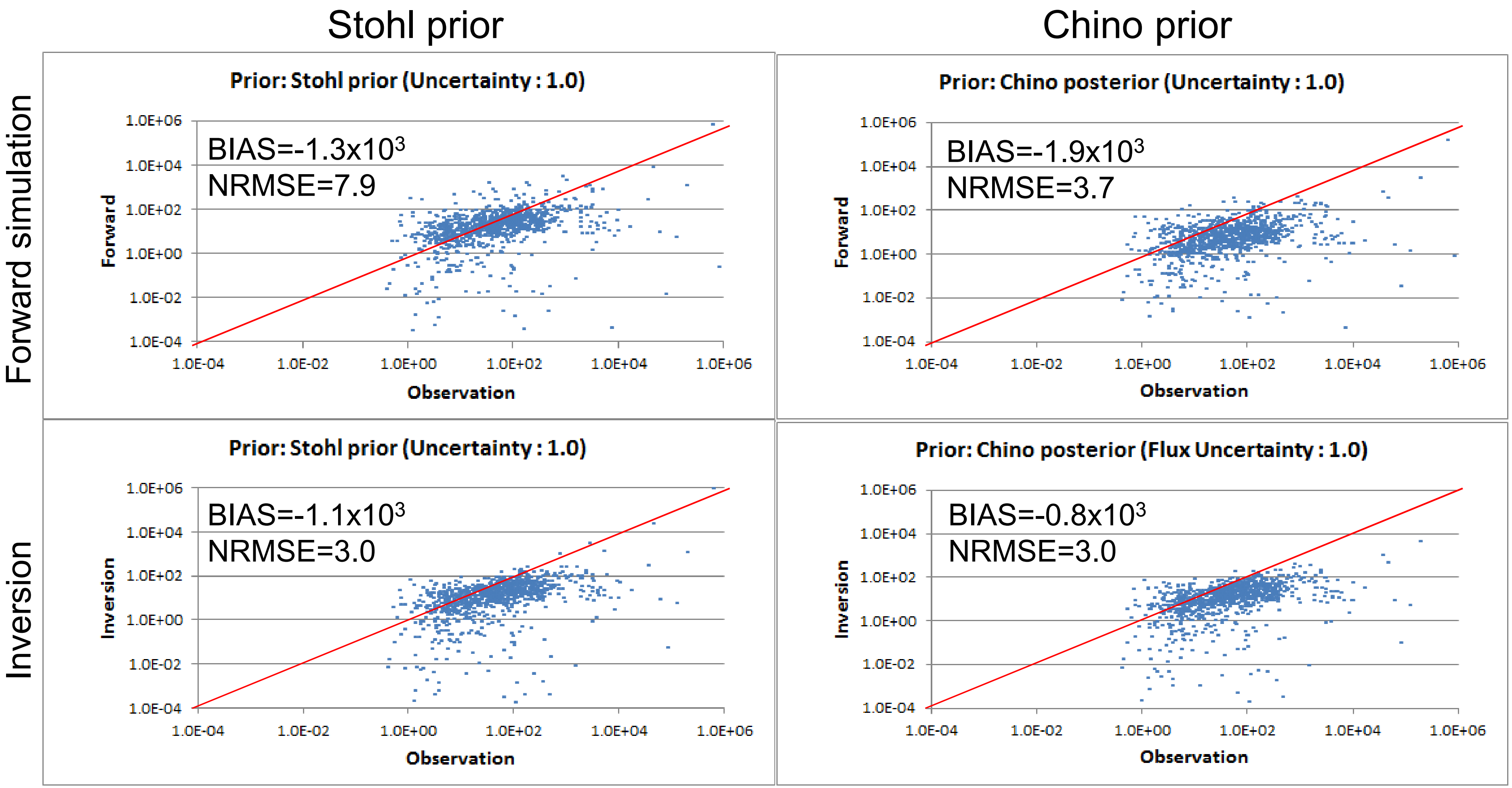
The posterior emission fluxes tend to lager in larger prior flux uncertainties.

The square of the difference between prior and posterior emission shows maximum when prior flux uncertainty is 1.0.

The normalized square of the difference between prior and posterior emission tend to lager.

Considering these points and the difference between Chino prior (9PBq) and Stohl posterior (29PBq), we select prior flux uncertainty as 1.0 (100%).

3-3. Estimated spatial dose rates (^{137}Cs)



Inversed dose rates tend to closer to observation data.

In all experiments, MASINGAR could not reproduce higher dose rates.

Considering from these figures, we select Chino posterior emission time series as our prior emission time series.

$$\mathrm{NRMSE} = \sqrt{\frac{1}{M}\sum_{m=1}^{M}\left(\frac{\mathbf{Ax}-\mathbf{y}_m}{\mathbf{y}_m}\right)^2}$$

3-4. Total ^{137}Cs emission amount

Author	Total Flux	Remarks
This study	18.5 PBq(±3.6PBq)	(3/11-4/19)
JAEA (Chino et al., revised 2011)	9.1 PBq	(3/10-3/31)
Stohl et al. (2012)	36.6 PBq (20.1 – 53.1)	(3/10-4/20)
Winiarek et al. (2012)	10 – 19 PBq	(3/11-3/26)
Aoyama et al. (ms. in preparation)	15.2 – 20.4 PBq	From obs. and numerical model analysis
MELCOR analysis (Gauntt et al.)	16.4 PBq	From Stohl et al. (2012)
IRSN	30 PBq	From Stohl et al. (2012)
ZAMG	66.6 PBq	From Stohl et al. (2012)

Our estimated total radioactive nuclei emission amount is substantially intermediate values of Chino et al. and Stohl et al. and consistent with Winiarek et al.

4-1. Summary

We have constructed a system which estimates emissions from the Fukushima nuclear power plant radiation dose using observational data, our transport model and an inverse model.

According to the inverse analysis system, The total ^{137}Cs release from the Fukushima Daiichi nuclear power plant is 18.5PBq from 11th March to 19th April. The uncertainty of the estimated total release is about 3.6PBq.

Maximum emission takes place on 15th March, we analyzed the emission amount is larger than the a priori information. On the other hand, we could not analyzed the peak daily emissions of 30th March.

Inversed dose rates tend to closer to observations. However, our model could not represent high dose ratio observation data. The limitation of horizontal resolution of the model (about 60km) may be a considerable reason.

To obtain more robust results, we need more observation data and higher resolution chemistry transport model.

4-2. Future plans

We have a plan to estimate a more detailed time series of radioactive nuclei emission amount by utilizing detailed observation data, regional chemistry transport model and inverse model.

#To achieve this objective, we need more high resolution observation data!

We also have a plan to make use of deposition observation data (land and ocean) in our inversion system.

We have a plan to estimate another radioactive nuclei emission time series (^{133}Xe) using this system.

We need to proceed inversion inter-comparison to know how transport model errors affect source term estimation and to obtain robust radioactive nuclei emissions time series.

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