Simulation of $^{137}$Cs activities off the Fukushima coast

Kazuhiro Misumi, Daisuke Tsumune, Takaki Tsubono and Yutaka Tateda

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The earthquake on Mar. 11, 2011 and subsequent tsunami resulted in accidental release of $^{137}\text{Cs}$ to the environment.
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Atmospheric deposition

Terada et al. (2012)
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**Direct release to the ocean**

Buesseler et al. (2011)
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### Atmospheric deposition

Terada et al. (2012)

### Direct release to the ocean

- **Fukushima No.1 Nuclear Power Plant (1F NPP)**
- **Japan 1960-2010 baseline**

Buesseler et al. (2011)
To investigate $^{137}$Cs dispersion in the ocean
To investigate $^{137}$Cs dispersion in the ocean

ROMS (Fukushima)
Tsumune et al. (2012 & 2013)
To investigate $^{137}$Cs dispersion in the ocean

WRF + CAMx
Hayami et al. (in prep.)

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Atmospheric deposition
Direct release from 1F NPP
Inflow from boundary sections
To investigate $^{137}$Cs dispersion in the ocean

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- **Food Chain Transfer Model**
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**Food Chain Transfer Model**
Tateda et al. (2013)
ROMS (Fukushima)

Domain: 34°54’ N-40°00’ N; 139°54’ E-147°00’ E
Resolution: 1 km x 1 km, 30 layers in s-coordinate (Max. 1000 m)
Scheme: 3rd-order upwind both momentum & tracers
Biharmonic viscosity & diffusivity; KPP
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Forcings

Surface boundary
Reanalysis data (5 km x 5 km) using WRF & JMA data
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Surface boundary
Reanalysis data (5 km x 5 km) using WRF & JMA data

Ocean Interior
JCOPE2 reanalysis data (1/10° x 1/10°) (Miyazawa et al., 2009)
Temp. & Salinity (in the whole domain)
Sea Surface Height & Horizontal Currents (to calculate the lateral boundary condition)
Atmospheric deposition of $^{137}$Cs

A $^{137}$Cs release scenario to the atmosphere (Terada et al., 2012)
Atmospheric deposition of $^{137}$Cs

A $^{137}$Cs release scenario to the atmosphere (Terada et al., 2012)

CAMx driven by WRF
Atmospheric deposition of $^{137}\text{Cs}$

A $^{137}\text{Cs}$ release scenario to the atmosphere (Terada et al., 2012)

The total amount of $^{137}\text{Cs}$ deposited in the ocean: 1.1 PBq
Direct release of $^{137}\text{Cs}$ to the ocean
Direct release of $^{137}\text{Cs}$ to the ocean

Nearest grid point from 1F NPP

$^{137}\text{Cs}_{\text{model}}$  

1 Bq sec$^{-1}$  

Mar. 26-Apr. 6
Direct release of $^{137}$Cs to the ocean

Nearest grid point from 1F NPP

$^{137}$Cs$_{\text{model}}$

1 Bq sec$^{-1}$

$^{137}$Cs$_{\text{obs}}$

Mar. 26-Apr. 6

Observed $^{137}$Cs activity nearby 1F NPP

Bq m$^3$

Mar. 1

Sep. 1

Mar. 1

2011

2012
Direct release of $^{137}$Cs to the ocean

Nearest grid point from 1F NPP

$$1 \text{ Bq sec}^{-1} \times \frac{^{137}\text{Cs}}{^{137}\text{Cs}_{\text{model}}^{}}$$

Mar. 26-Apr. 6

$$f = \frac{^{137}\text{Cs}_{\text{obs}}^{}}{^{137}\text{Cs}_{\text{model}}^{}}$$

Observed $^{137}$Cs activity nearby 1F NPP

Bq m$^{-3}$

Mar. 1 2011  Sep. 1  Mar. 1 2012

(a) $^{137}\text{Cs}_{\text{obs}}^{\text{Mar. 26-Apr. 6}}$
Direct release of $^{137}\text{Cs}$ to the ocean

$1\text{ Bq sec}^{-1}$  

$^{137}\text{Cs}_{\text{model}}$  

Nearest grid point from 1F NPP

Mar. 26-Apr. 6

$\frac{^{137}\text{Cs}_{\text{obs}}}{^{137}\text{Cs}_{\text{model}}}$

Release rate = $f \times 1\text{ Bq sec}^{-1}$

= $2.2 \times 10^{14}\text{ Bq day}^{-1}$
Direct release of $^{137}$Cs to the ocean

Nearest grid point from 1F NPP

$1 \text{ Bq sec}^{-1}$

$^{137}\text{Cs}_{\text{model}}$

Mar. 26-Apr. 6

$^{137}\text{Cs}_{\text{obs}}$

Release rate $= f \times 1 \text{ Bq sec}^{-1}$

$= 2.2 \times 10^{14} \text{Bq day}^{-1}$

After Apr. 6, we assumed that the $^{137}$Cs release rates follow the temporal trend of the observed $^{137}$Cs activities nearby 1F NPP.
Direct release of $^{137}\text{Cs}$ to the ocean

Nearest grid point from 1F NPP

$^{137}\text{Cs}_{\text{model}}$

$1 \text{ Bq sec}^{-1}$

Mar. 26-Apr. 6

Estimated direct release rates of $^{137}\text{Cs}$

$$f = \frac{^{137}\text{Cs}_{\text{obs}}}{^{137}\text{Cs}_{\text{model}}}$$

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Direct release of $^{137}$Cs to the ocean

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After Apr. 6, we assumed that the $^{137}$Cs release rates follow the temporal trend of the observed $^{137}$Cs activities nearby 1F NPP.

Total $^{137}$Cs activity: 3.6 PBq after 1 yr from the accident
Comparison with Buesseler et al. (2012)

Surface $^{137}$Cs activities on **June, 2011**

**Control Case**
Comparison with Buesseler et al. (2012)

Surface $^{137}$Cs activities on June, 2011

**Control Case**

**Direct release only**

Bq/m$^3$

- $10^0$
- $10^1$
- $10^2$
- $10^3$
Comparison with Buesseler et al. (2012)

Surface $^{137}$Cs activities on Dec., 2011
Possible mechanisms transferring $^{137}\text{Cs}$ into sediments
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- Particle scavenging
- Adsorption & Desorption
A lab. experiment showed a slow adsorption rate of Cs to marine particulate matters.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Adsorption rate constants (kg⁻¹ day⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs</td>
<td>304</td>
</tr>
<tr>
<td>Fe</td>
<td>25000</td>
</tr>
<tr>
<td>Th</td>
<td>130000</td>
</tr>
</tbody>
</table>

Nyffeler et al. (1984)
Possible mechanisms transferring $^{137}\text{Cs}$ into sediments
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- Biological uptake
- Particle scavenging
- Adsorption & Desorption
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We developed a sediment model based on Periáñez (2008).

**Bottom water** ($C_{\text{wat}}$)

Dainly mean $^{137}\text{Cs}$ activities in the bottom water (Tsumune et al., 2013)

**Sediment** ($C_{\text{sed}}$)
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Bottom water \( (C_{\text{wat}}) \)

Dainly mean \(^{137}\text{Cs}\) activities in the bottom water (Tsumune et al., 2013)

\[ k_1 \]

Sediment \( (C_{\text{sed}}) \)
\[ k_1 = \chi S = \chi \frac{3L}{RH} \phi (1 - p) \]

(Periáñez, 2008)

- $\chi$ exchange velocity 35.0 mm day\(^{-1}\) (Nyffeler et al., 1984)
- $S$ exchange surface
- $R$ sediment radius spatially varying obs. data
- $\phi$ correction factor 0.01 (Periáñez & Martínez-Aguirre, 1997)
- $p$ sediment porosity 0.6 (Auffret et al., 1974)
- $L$ sediment mixed layer depth
- $H$ thickness of the ocean bottom layer
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Dainly mean \(^{137}\text{Cs}\) activities in the bottom water (Tsumune et al., 2013)

\[ k_1 \quad k_2 \]

\[ 1000 \text{ days} \]

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$K_1$  
$K_2$  
1000 days

$\lambda$  
30 years
Kusakabe et al. (2013)
Kusakabe et al. (2013)

- Heterogeneous spatial distribution

- May 9-14, 2011
- May 23-27
- June 6-10
- June 20-25
- July 5-9
- July 25-31
- Sep. 7-15
- Oct. 13-26
- Dec. 5-16
- Feb. 4-21, 2012
Kusakabe et al. (2013)

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- May 23-27
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• Heterogeneous spatial distribution
Kusakabe et al. (2013)

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• Temporal persistency
Previous obs. studies pointed out factors causing these features.

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  - Spatial distribution of sediment grain size (Otosaka & Kobayashi; Kusakabe et al., 2013)

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  ✓ Spatially varying obs. data of sediment grain size ($R$)

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STN case

- simulate temporal variation of $^{137}$Cs in each monitoring station
- validate model outputs
STN case

• simulate temporal variation of $^{137}$Cs in each monitoring station
• validate model outputs

EXT case

• simulate spatiotemporal variation of $^{137}$Cs allover the domain (extrapolating the obs. data)
• estimate the total amount of $^{137}$Cs in sediment off the Fukushima coast
STN case
STN case

[Graph showing various measurements over time for different stations labeled C3, D3, E3, E5, F3, G0, G3, G4, H3, I0, I3, J2, J3, K2, L3, and their respective depths.]
STN case

composite of the results separated by the station depth

Bottom water (Bq m$^{-3}$)
STN case
composite of the results separated by the station depth

< 200 m

Bottom water
(Bq m⁻³)

Sediment
(Bq kg⁻¹)
STN case
composite of the results separated by the station depth

Bottom water (Bq m$^{-3}$)

Sediment (Bq kg$^{-1}$)

< 200 m

> 200 m
STN case
composite of the results separated by the station depth

Bottom water (Bq m⁻³)

Sediment (Bq kg⁻¹)
STN case

comparison of the simulated $^{137}$Cs activities in sediments with obs. data
STN case
if we use a homogeneous (mean) sediment radius (R)
EXT case

Mar. 25

Bottom water (Bq m$^{-3}$)

Sediment (Bq kg$^{-1}$)
EXT case

Bottom water (Bq m$^{-3}$)

Sediment (Bq kg$^{-1}$)

Mar. 25  

Apr. 10  

C$_{wat}$  

Bq m$^{-3}$  

C$_{sed}$  

Bq kg$^{-1}$  

39°N  

38°N  

37°N  

36°N  

140°E  141°E  142°E  143°E  

140°E  141°E  142°E  143°E  

$1.0\times10^{-3}$  

$1.8\times10^{-3}$  

$3.2\times10^{-3}$  

$5.6\times10^{-3}$  

$1.0\times10^{-2}$  

$1.8\times10^{-2}$  

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$5.6\times10^{-2}$  

$1.0\times10^{-1}$  

$1.8\times10^{-1}$  

$3.2\times10^{-1}$  

$5.6\times10^{-1}$  

$1.0\times10^{0}$  

$1.8\times10^{0}$  

$3.2\times10^{0}$  

$5.6\times10^{0}$  

$1.0\times10^{1}$
EXT case

Bottom water (Bq m⁻³)

Sediment (Bq kg⁻¹)
EXT case

Bottom water (Bq m⁻³)

Sediment (Bq kg⁻¹)
EXT case

Estimate of the total inventory of $^{137}\text{Cs}$ off the Fukushima coast (Kusakabe et al., 2013)
EXT case

Estimate of the total inventory of $^{137}$Cs off the Fukushima coast
EXT case

Estimate of the total inventory of $^{137}\text{Cs}$ off the Fukushima coast
EXT case

Estimate of the total inventory of $^{137}\text{Cs}$ off the Fukushima coast

The total inventory of $^{137}\text{Cs}$ in sediments off the Fukushima coast is $O(0.1)\text{ PBq}$. 
Summary

• Highly contaminated waters (> $10^2$ Bq m$^{-3}$) can be explained by the direct release of $^{137}$Cs to the ocean.

• The activity level of $^{137}$Cs in seawater decreased significantly by one-year after the accident, but that in sediment persisted.

• Spatial pattern of $^{137}$Cs in sediment is likely characterized by history of $^{137}$Cs in the overlying bottom water and by spatial distribution of sediment grain size.

• The total amount of $^{137}$Cs in sediment is estimated to be $O(0.1)$ PBq.
STN case (1-D simulation)