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

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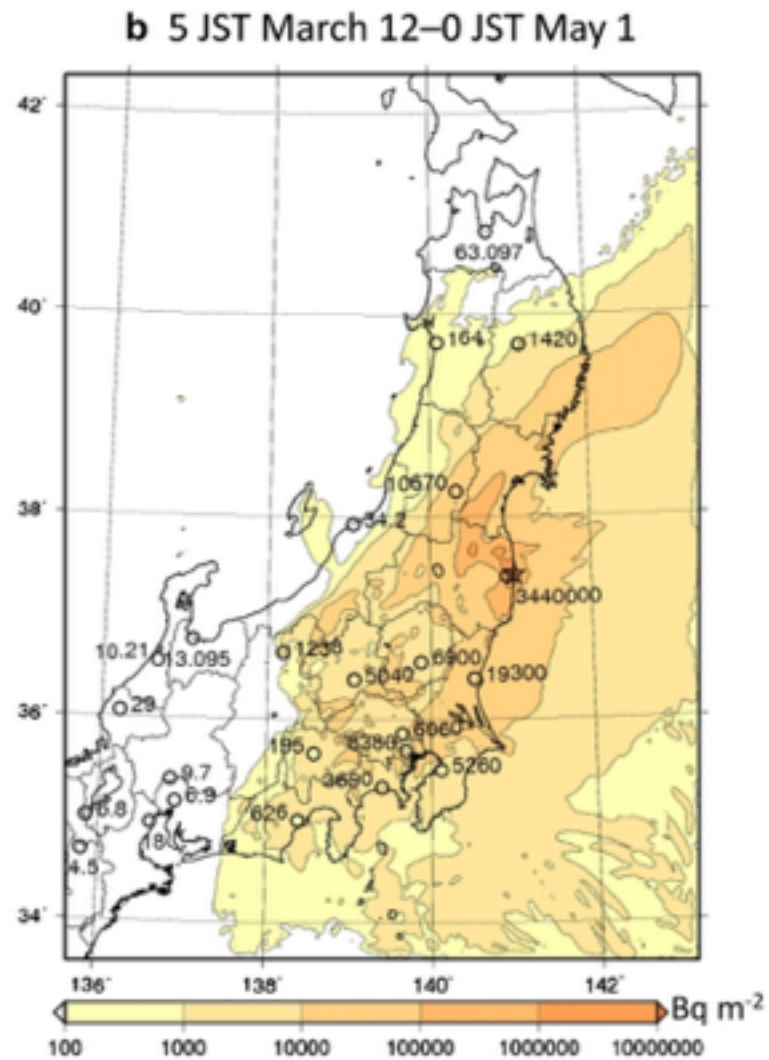


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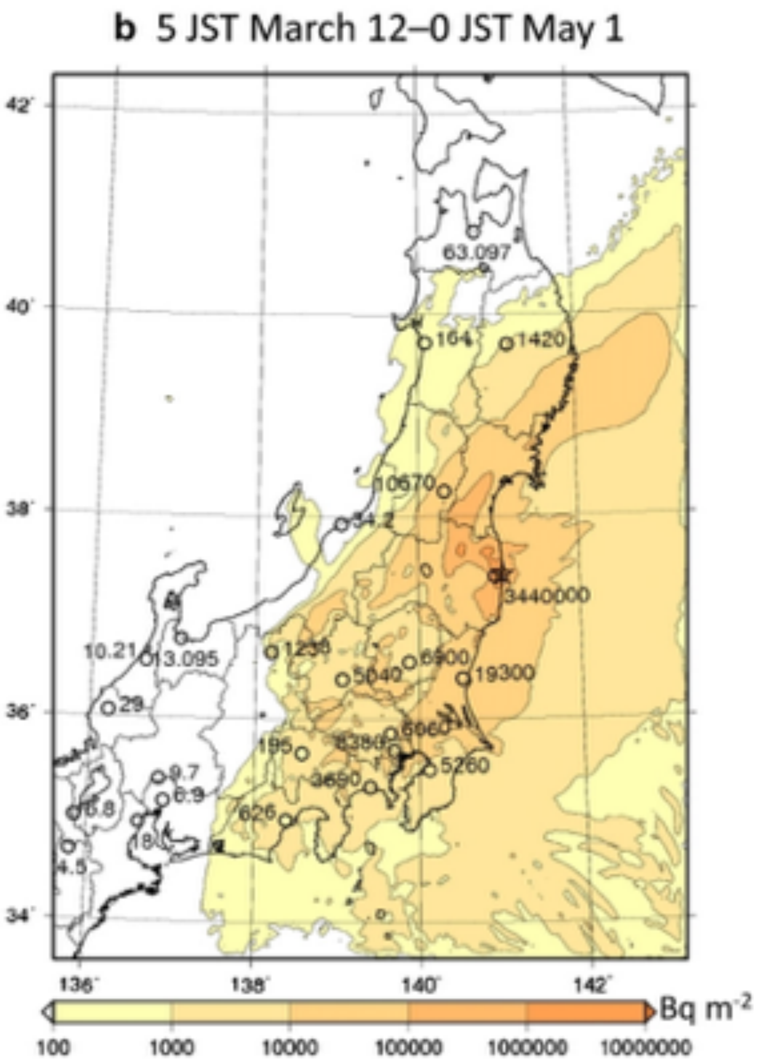


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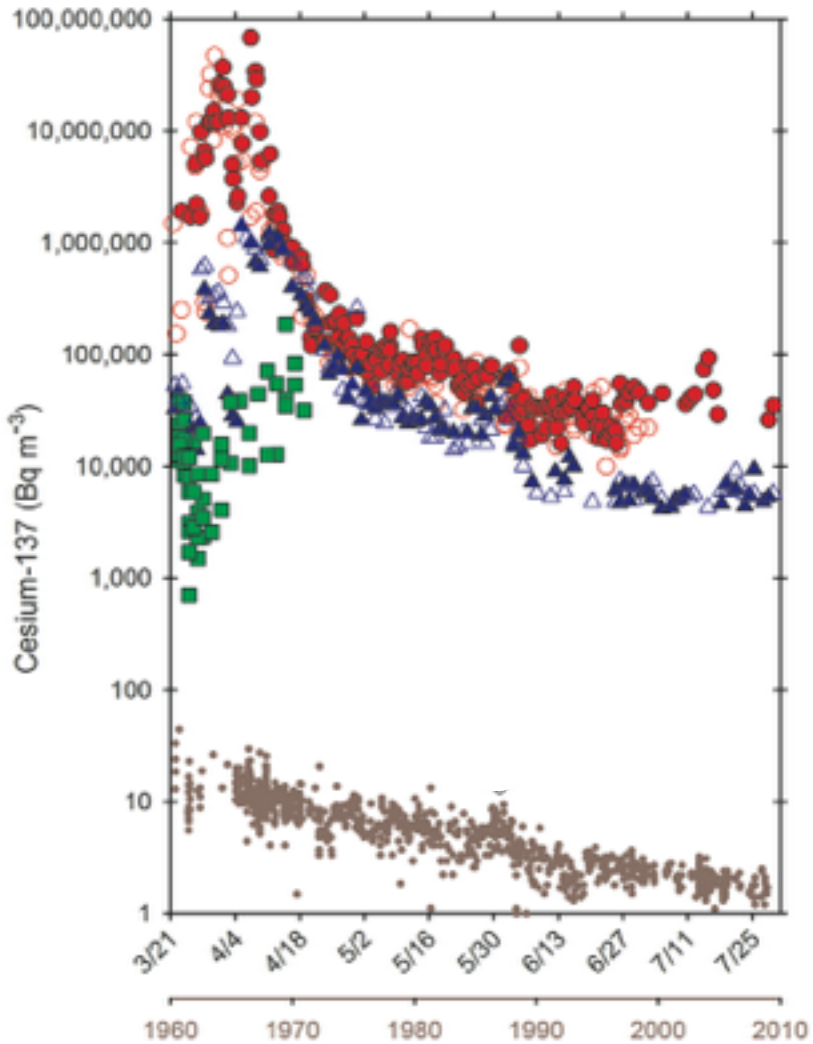
## Direct release to the ocean

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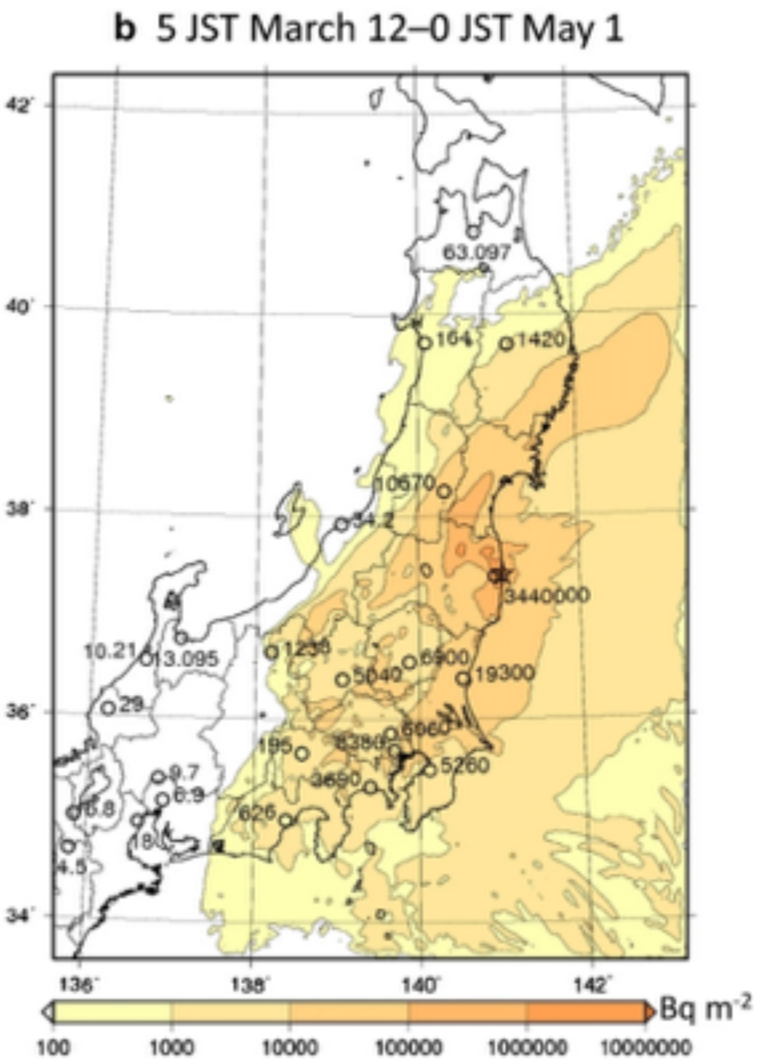


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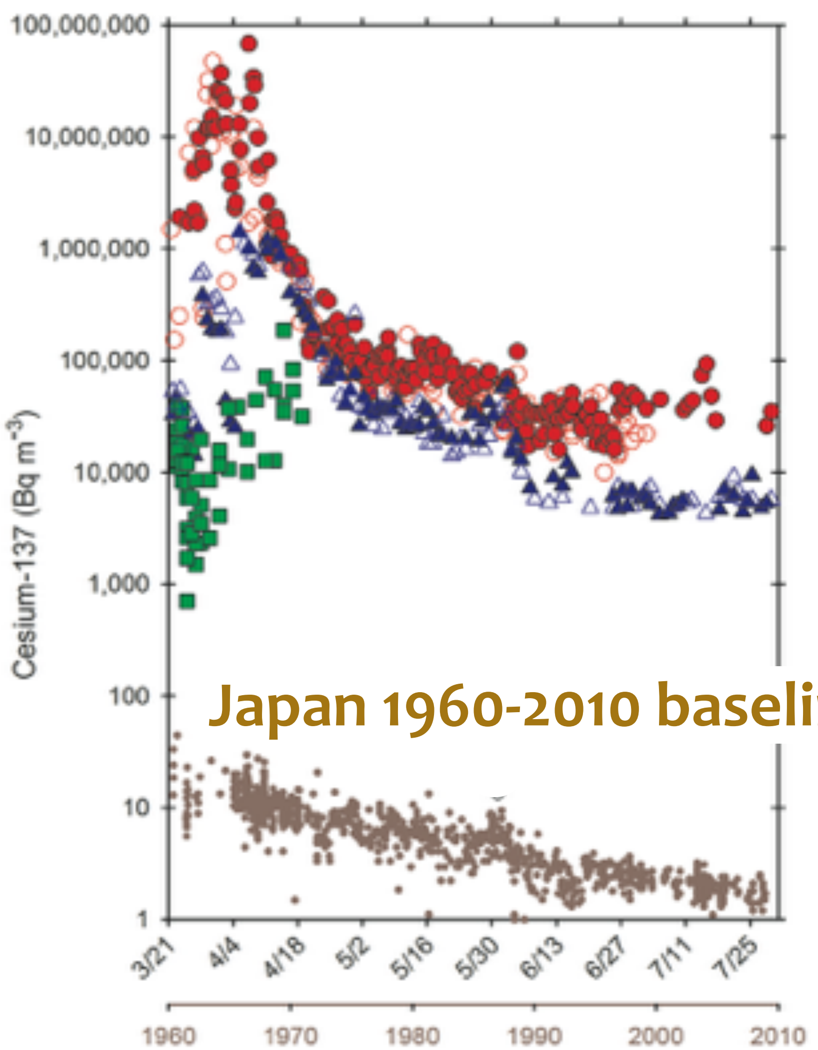


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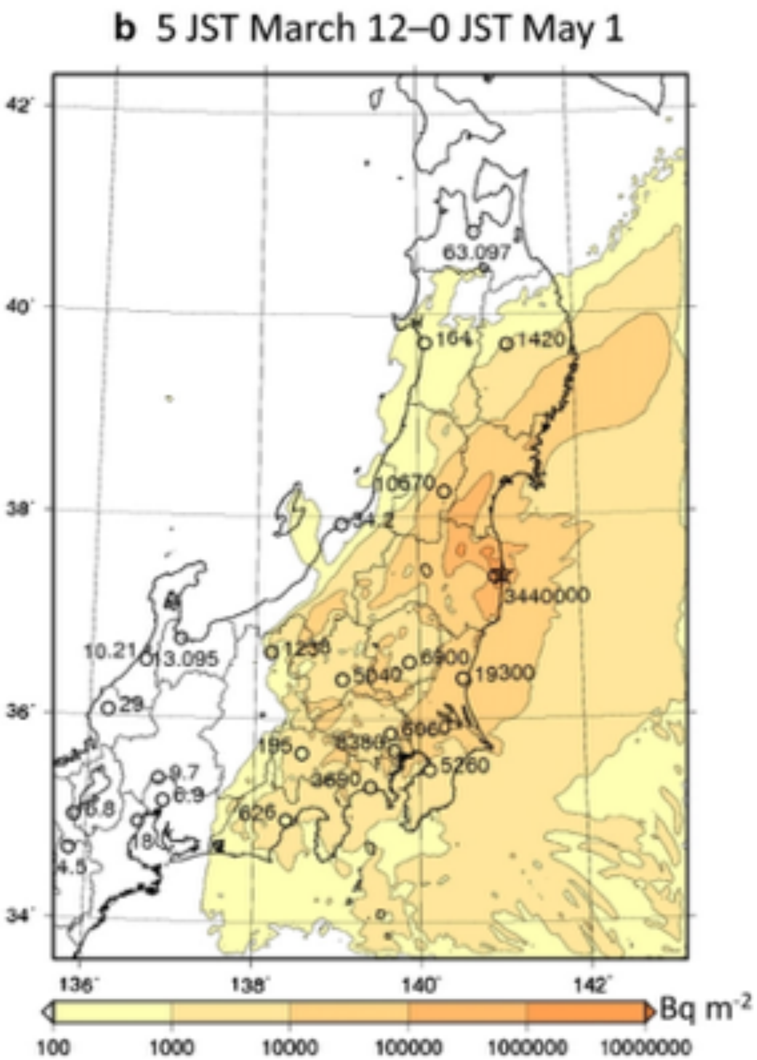


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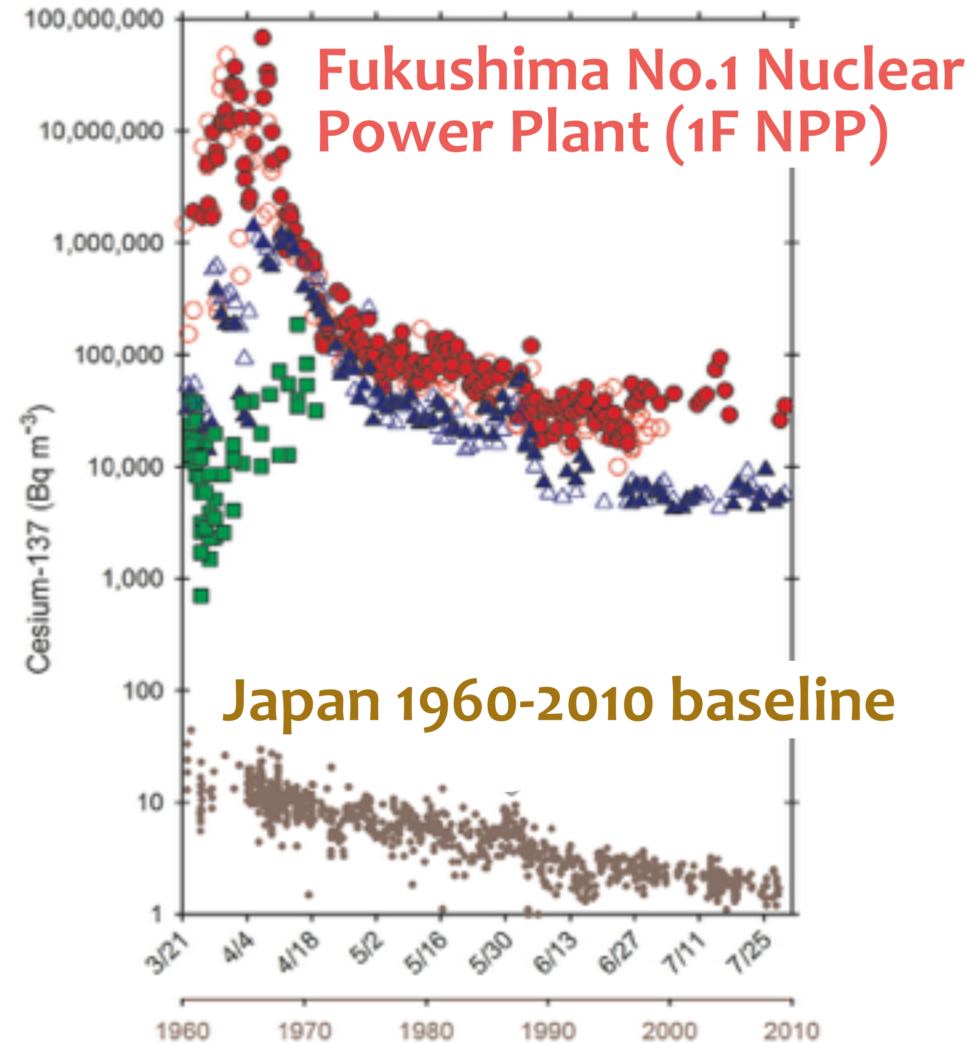


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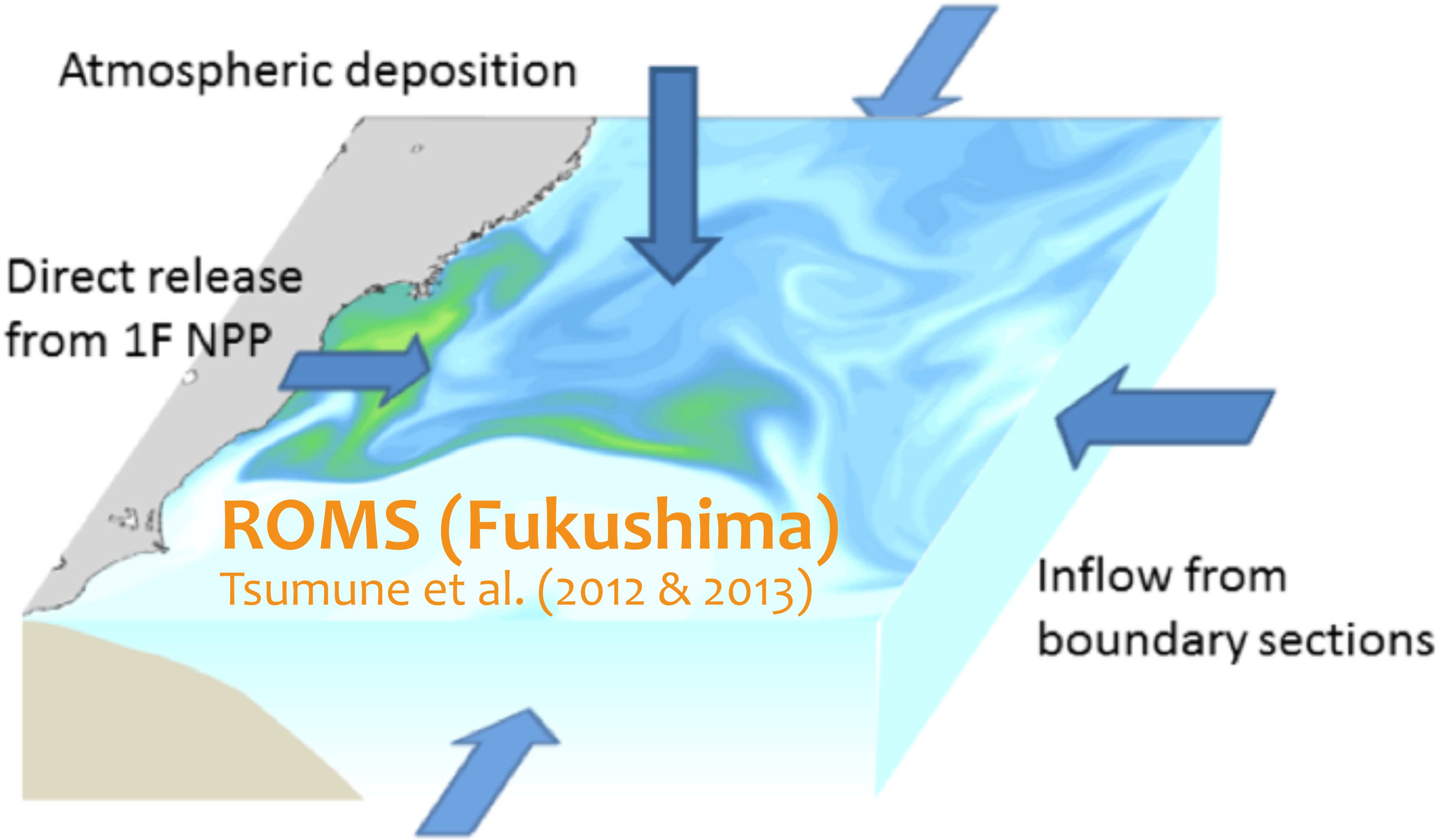

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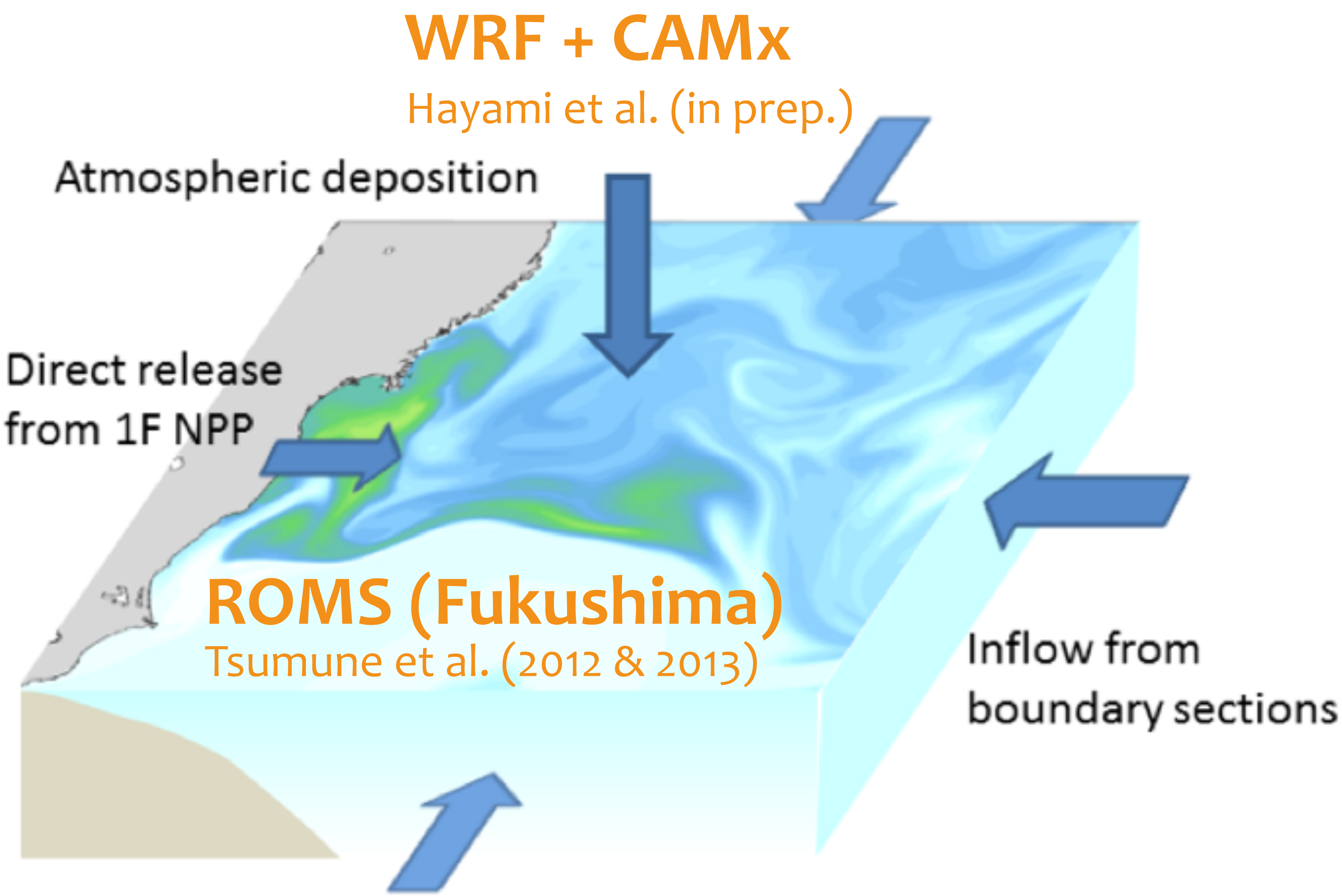

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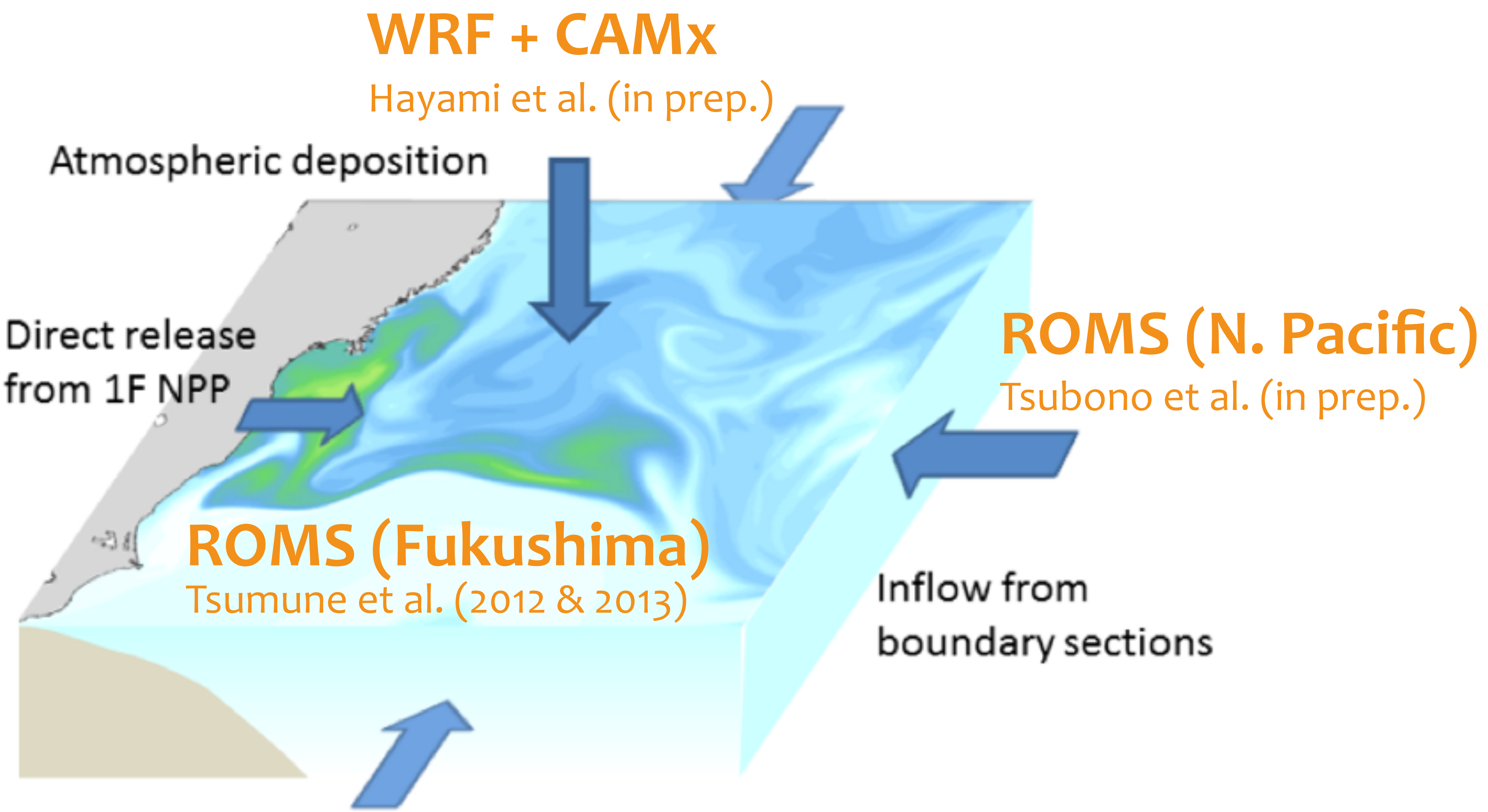

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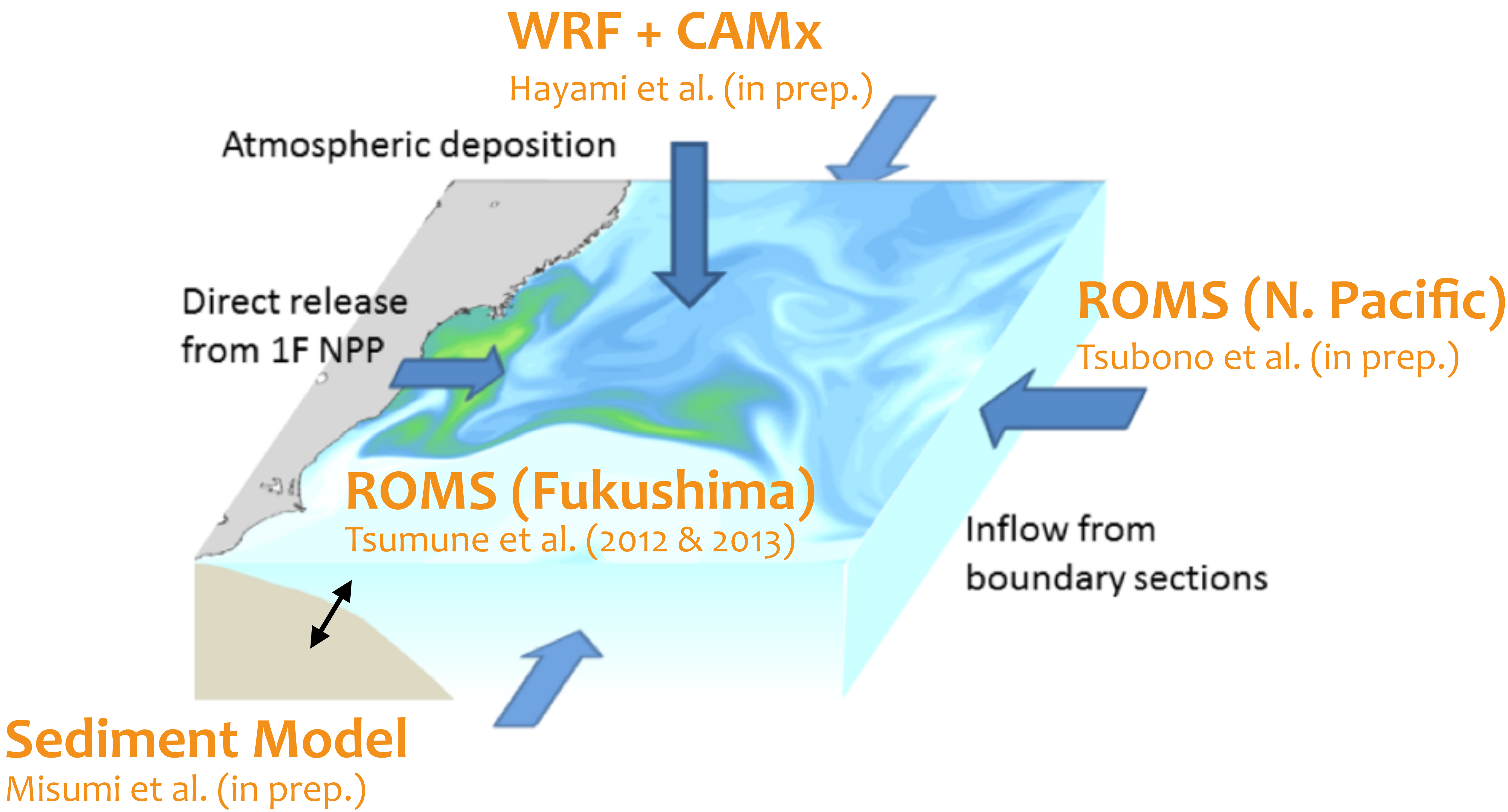

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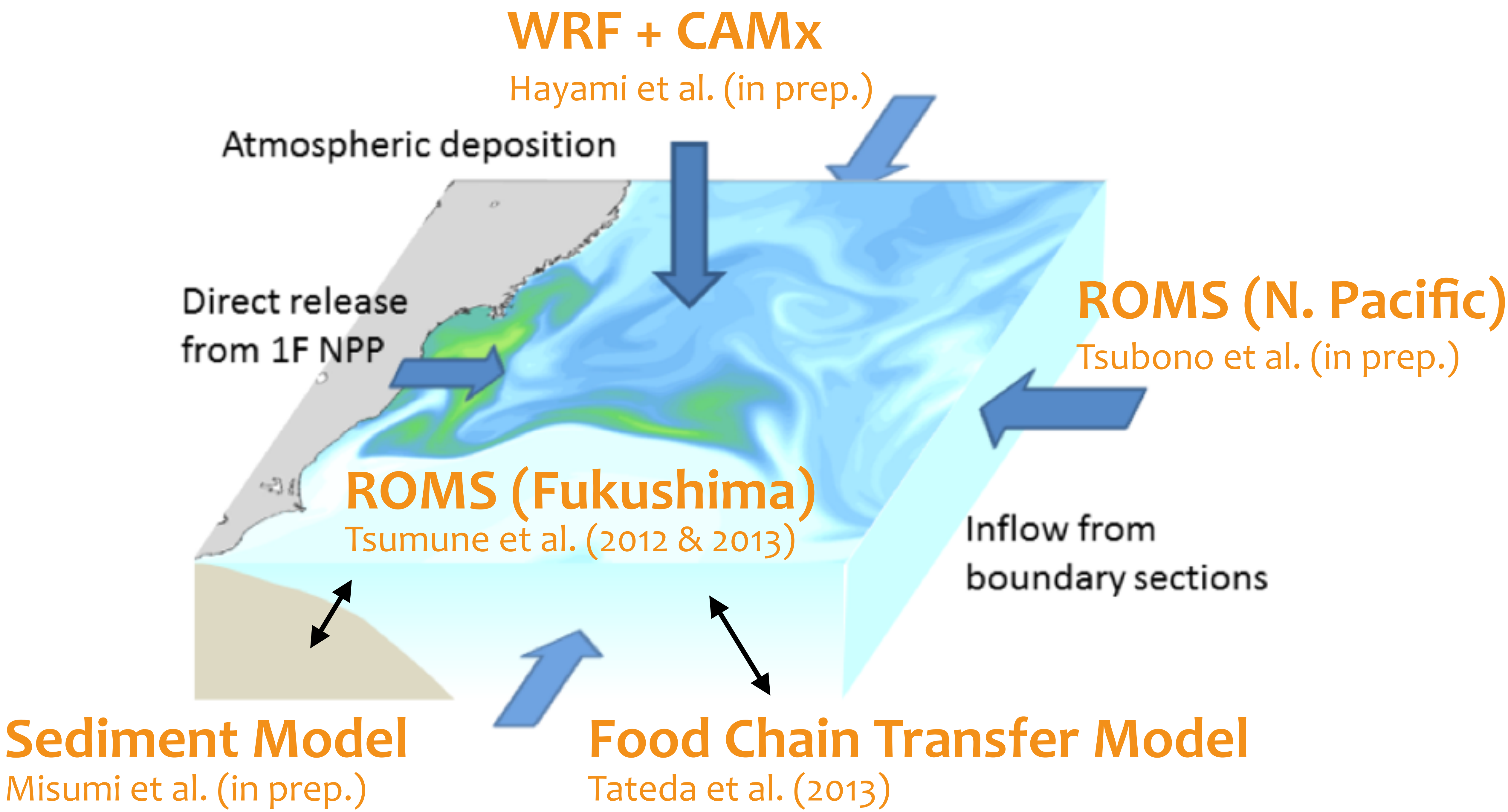

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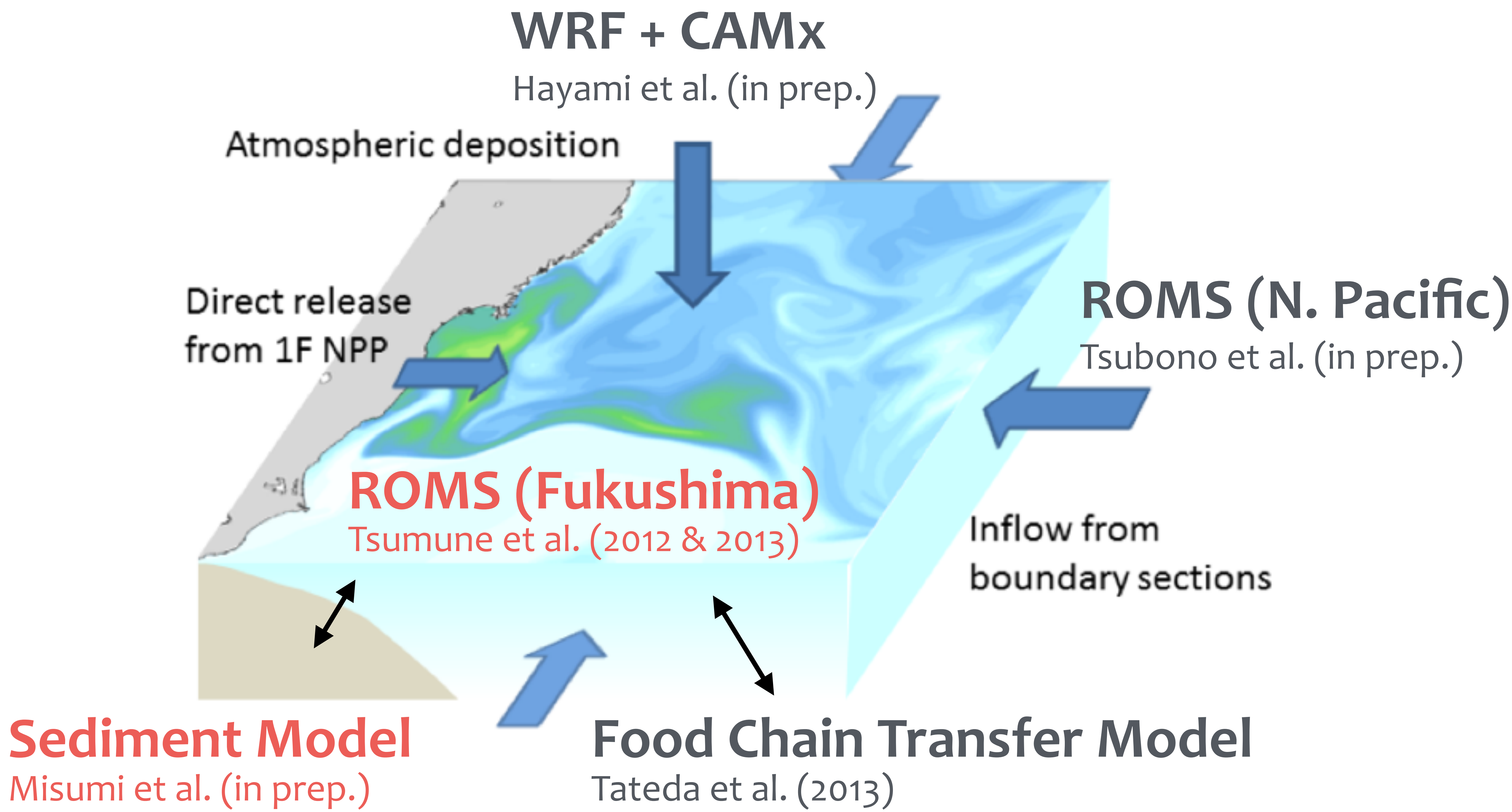

# ROMS (Fukushima)

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

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Reanalysis data (**5 km x 5 km**) using WRF & JMA data

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**Ocean Interior**

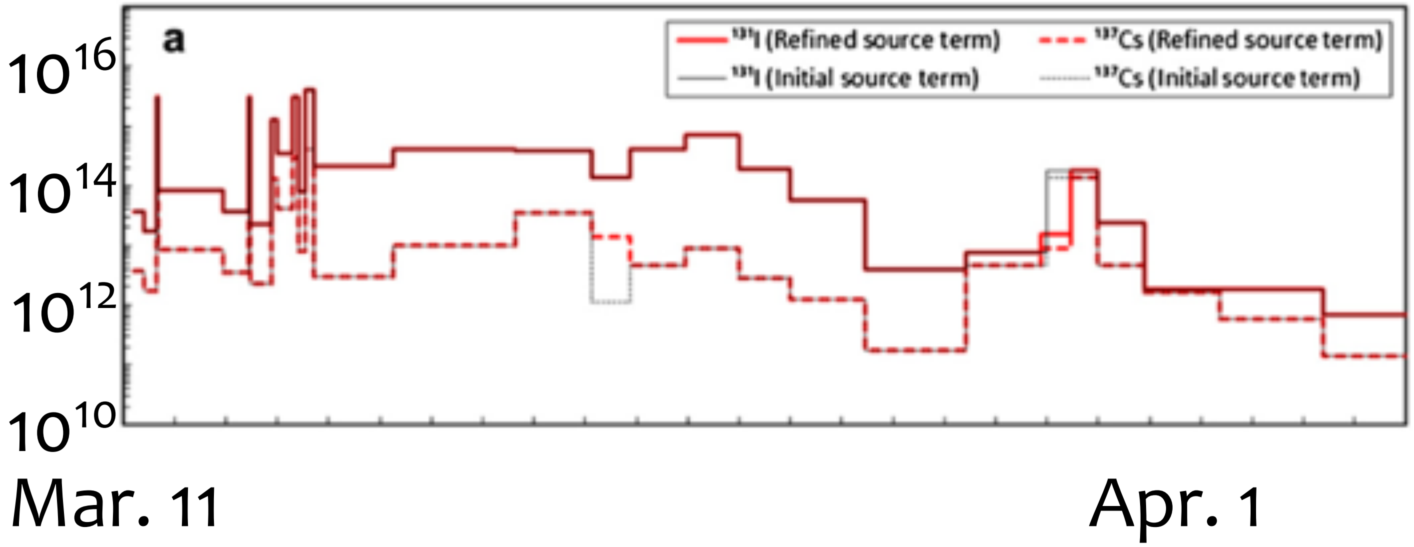
JCOPE2 reanalysis data (**1/10° x 1/10°**) (Miyazawa et al., 2009)

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)



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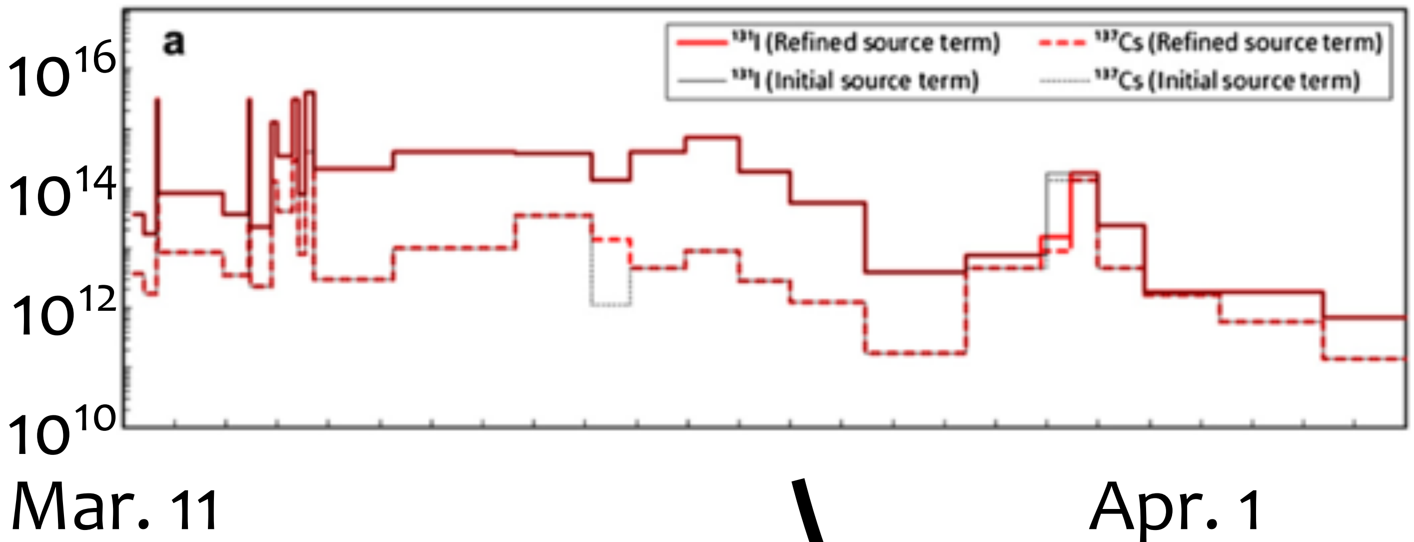


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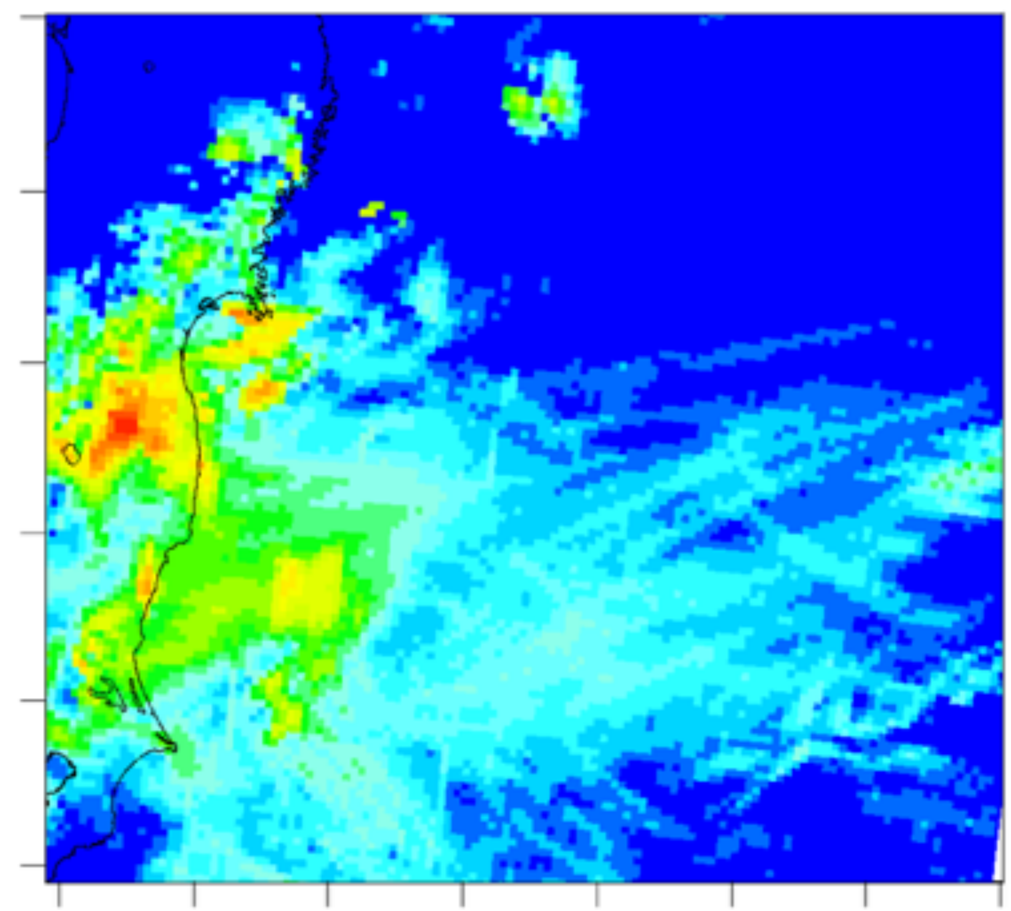

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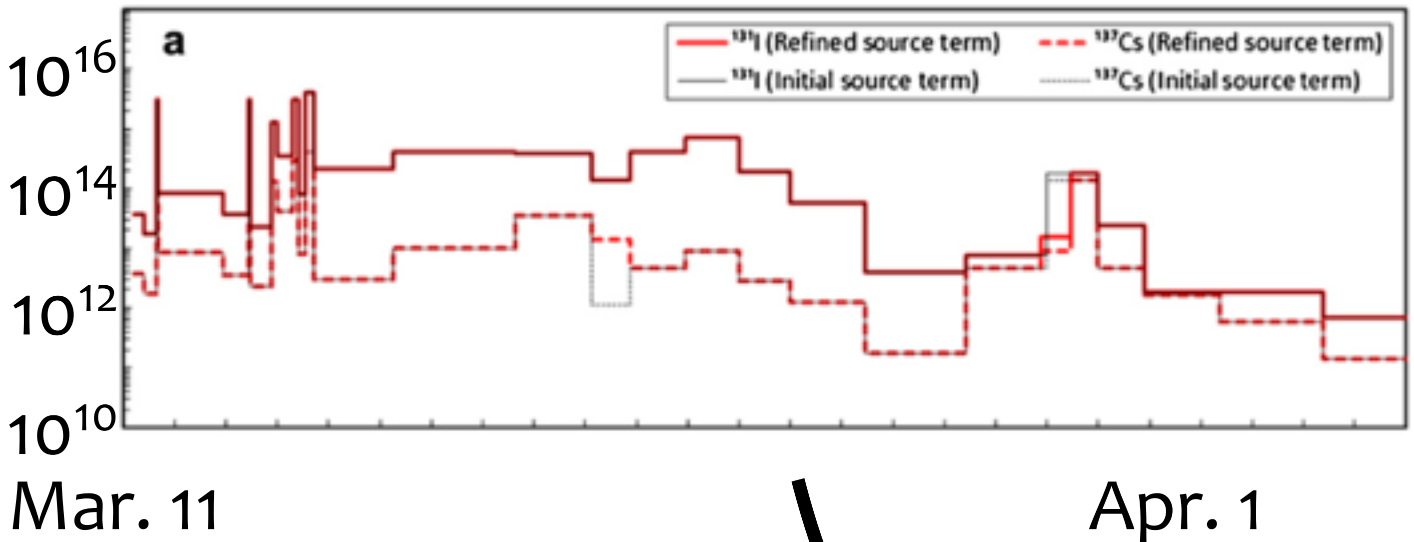


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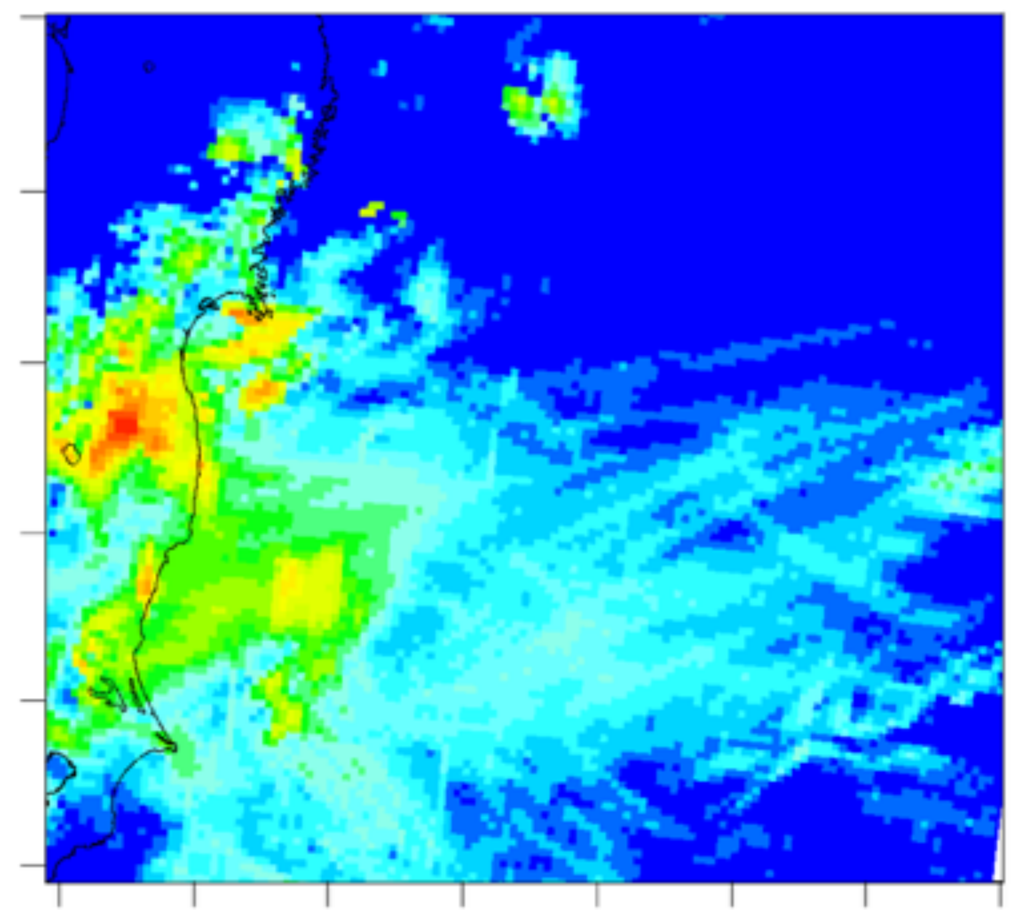

The total amount of $^{137}Cs$ deposited in the ocean: **1.1 PBq**

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

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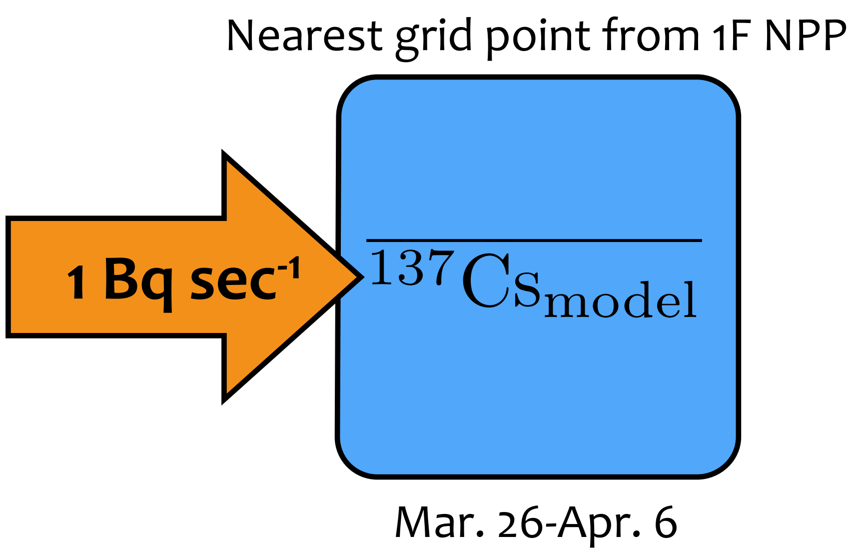

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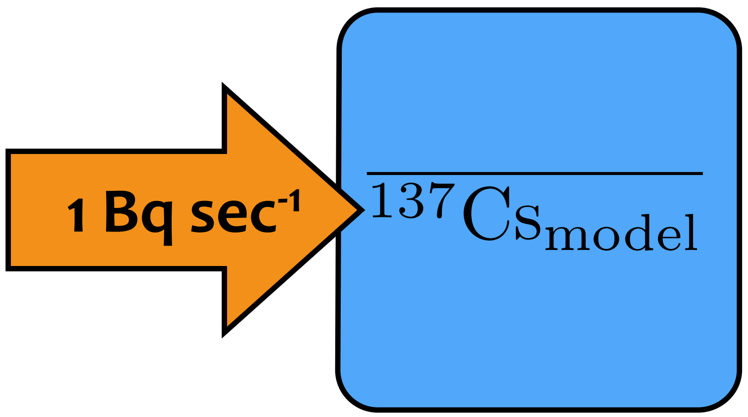
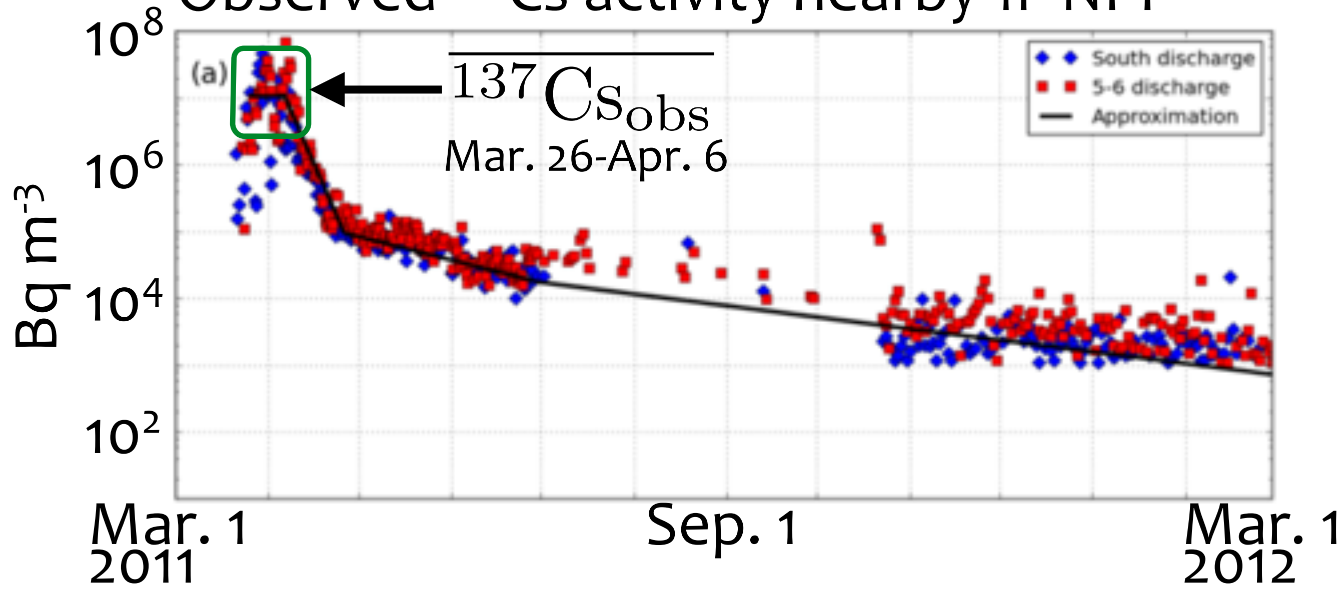
Nearest grid point from 1F NPP




Mar. 26-Apr. 6

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



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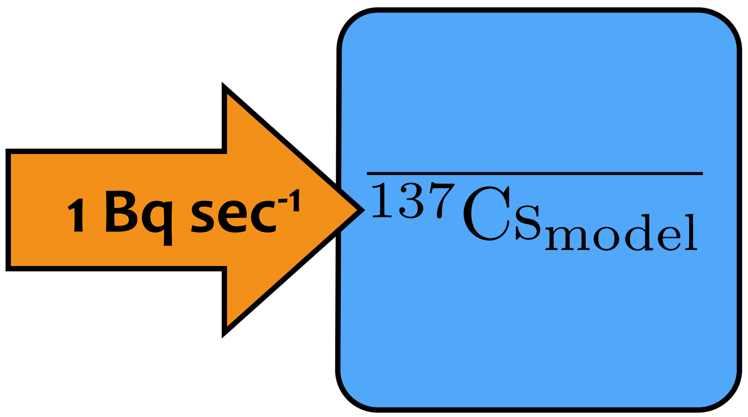


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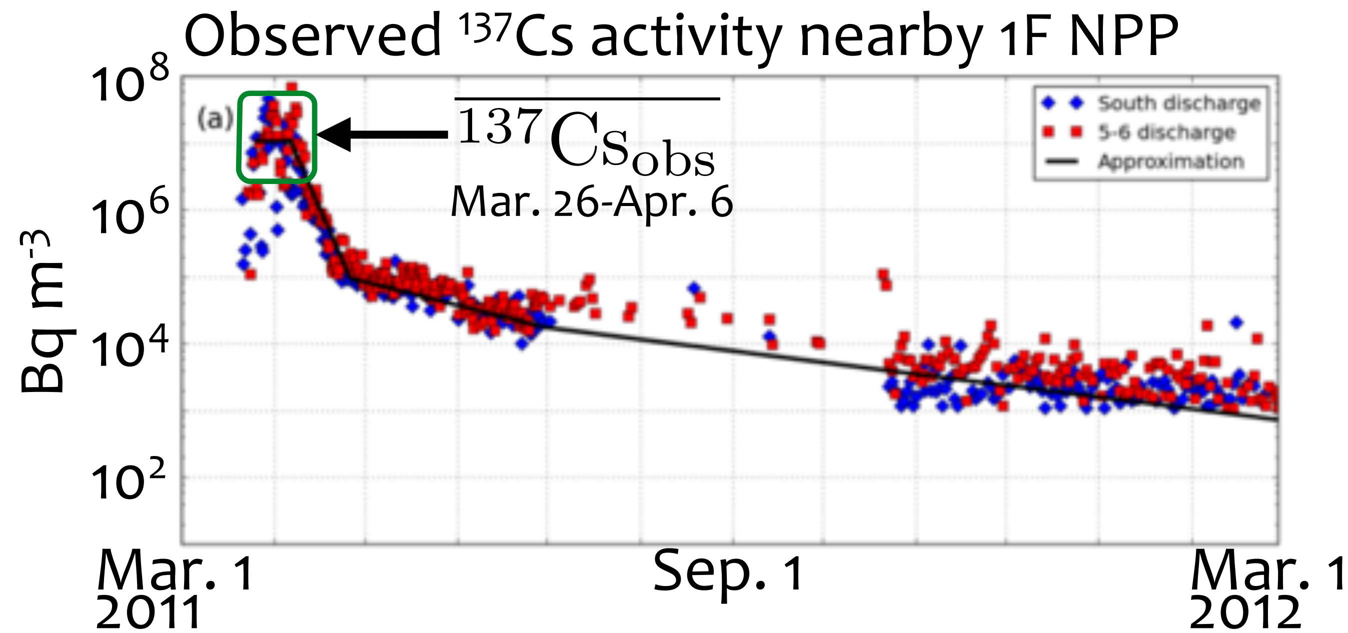


$$f = \frac{\overline{^{137}\mathrm{Cs}_{\mathrm{obs}}}}{\overline{^{137}\mathrm{Cs}_{\mathrm{model}}}}$$

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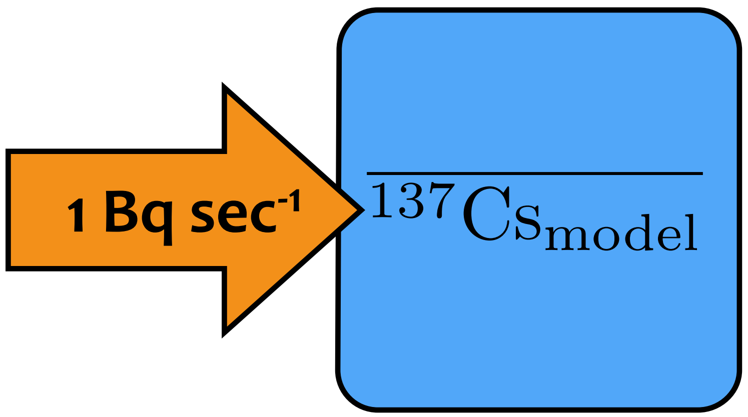


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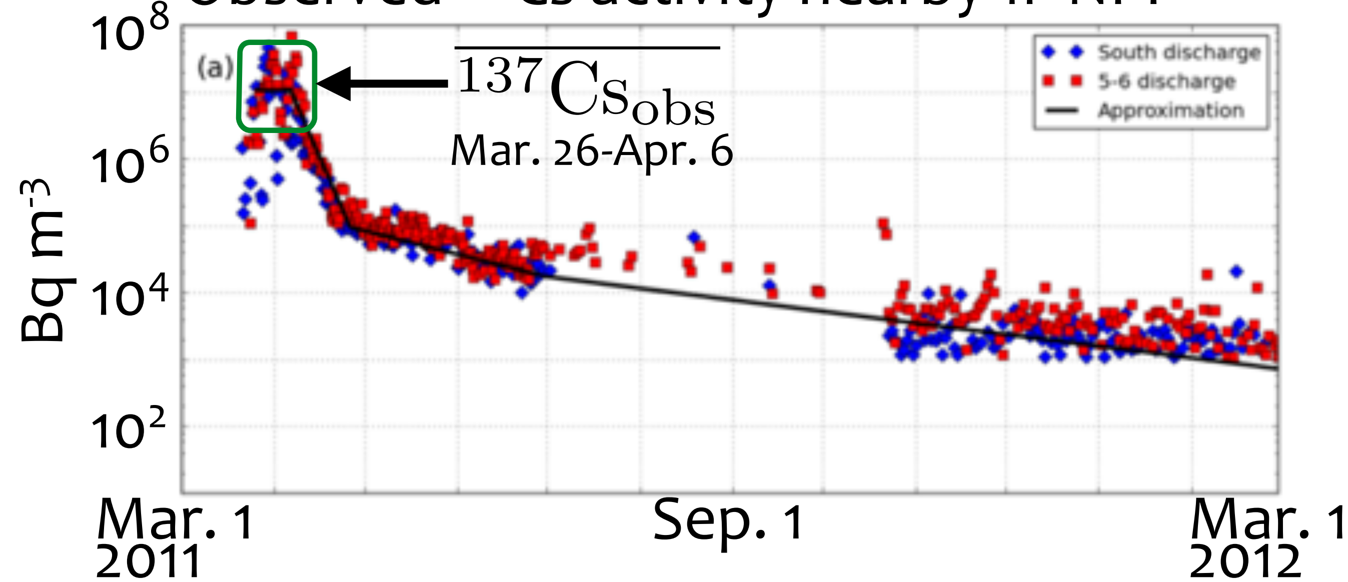


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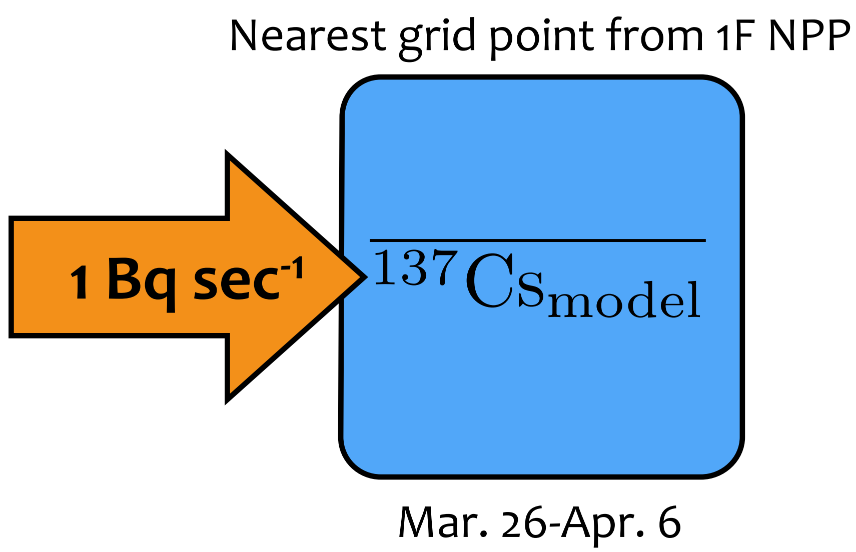


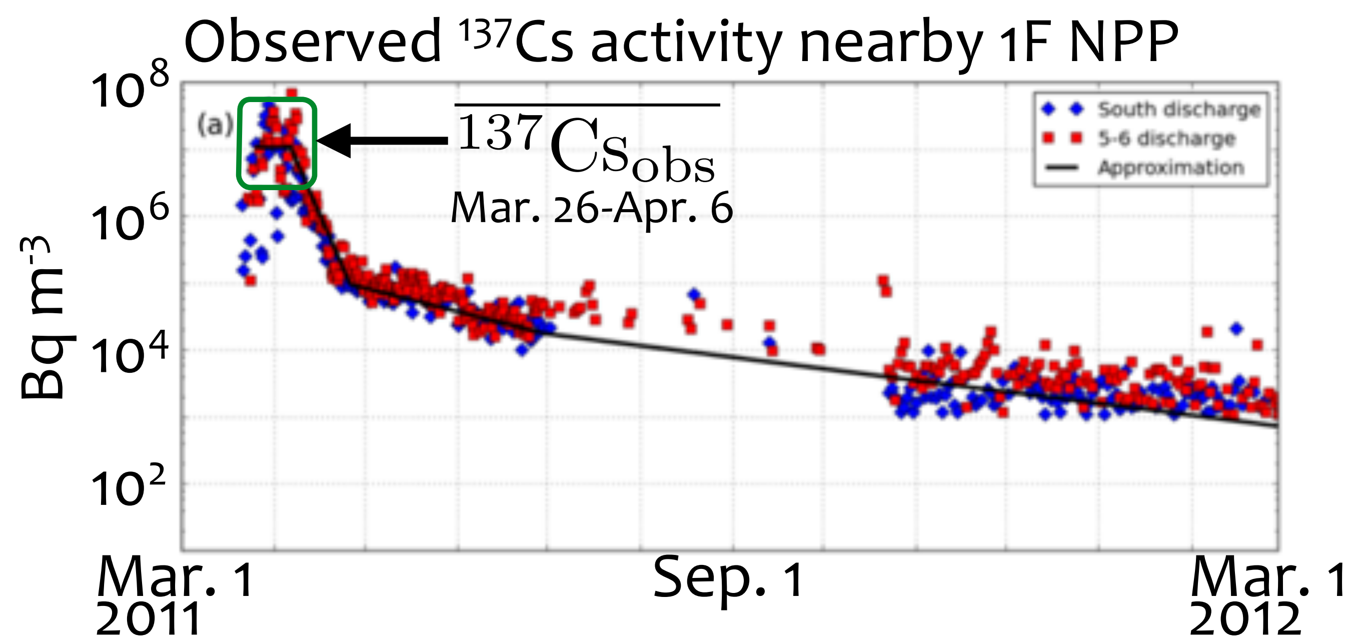


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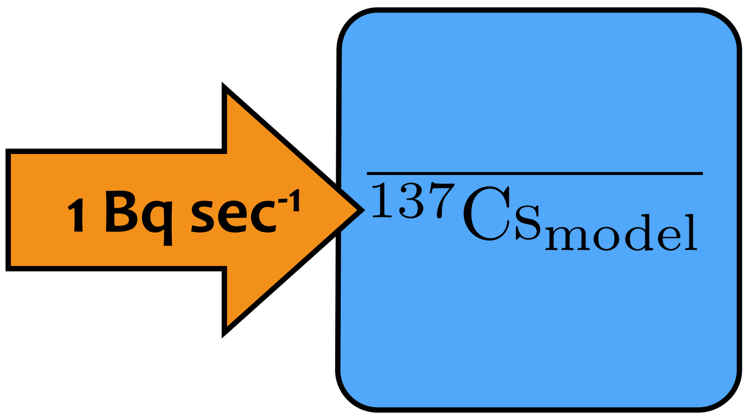


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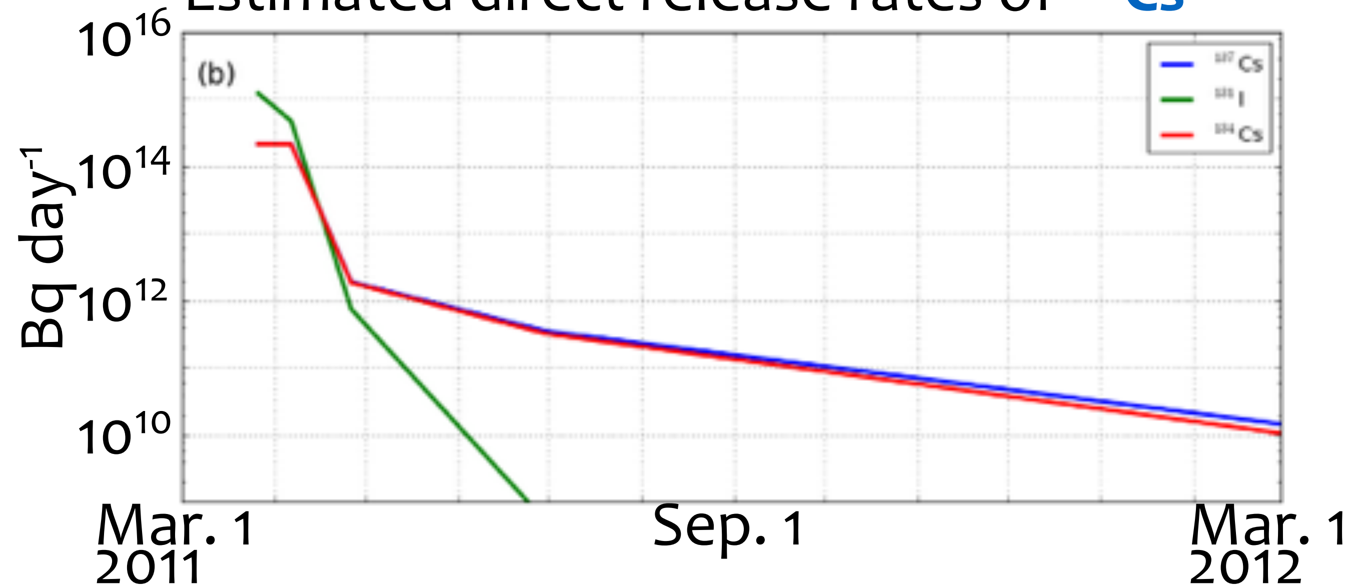


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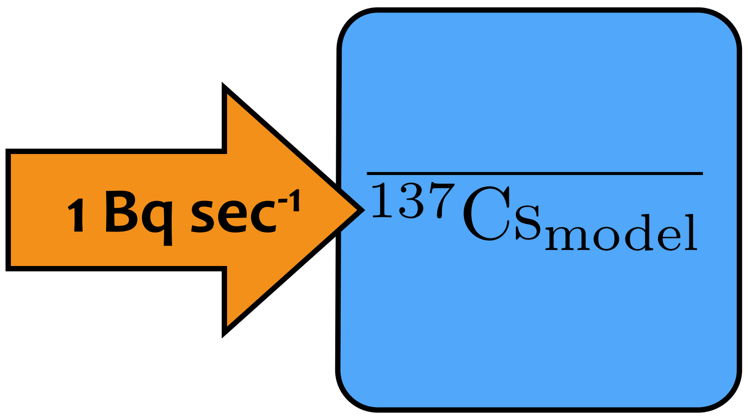


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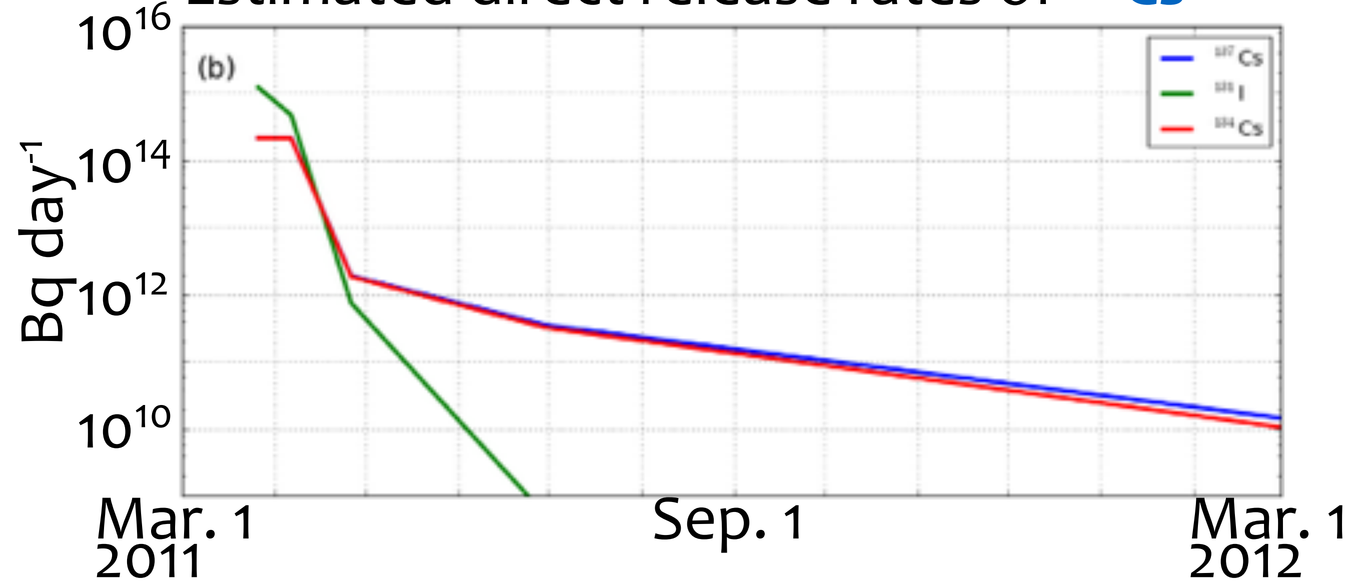


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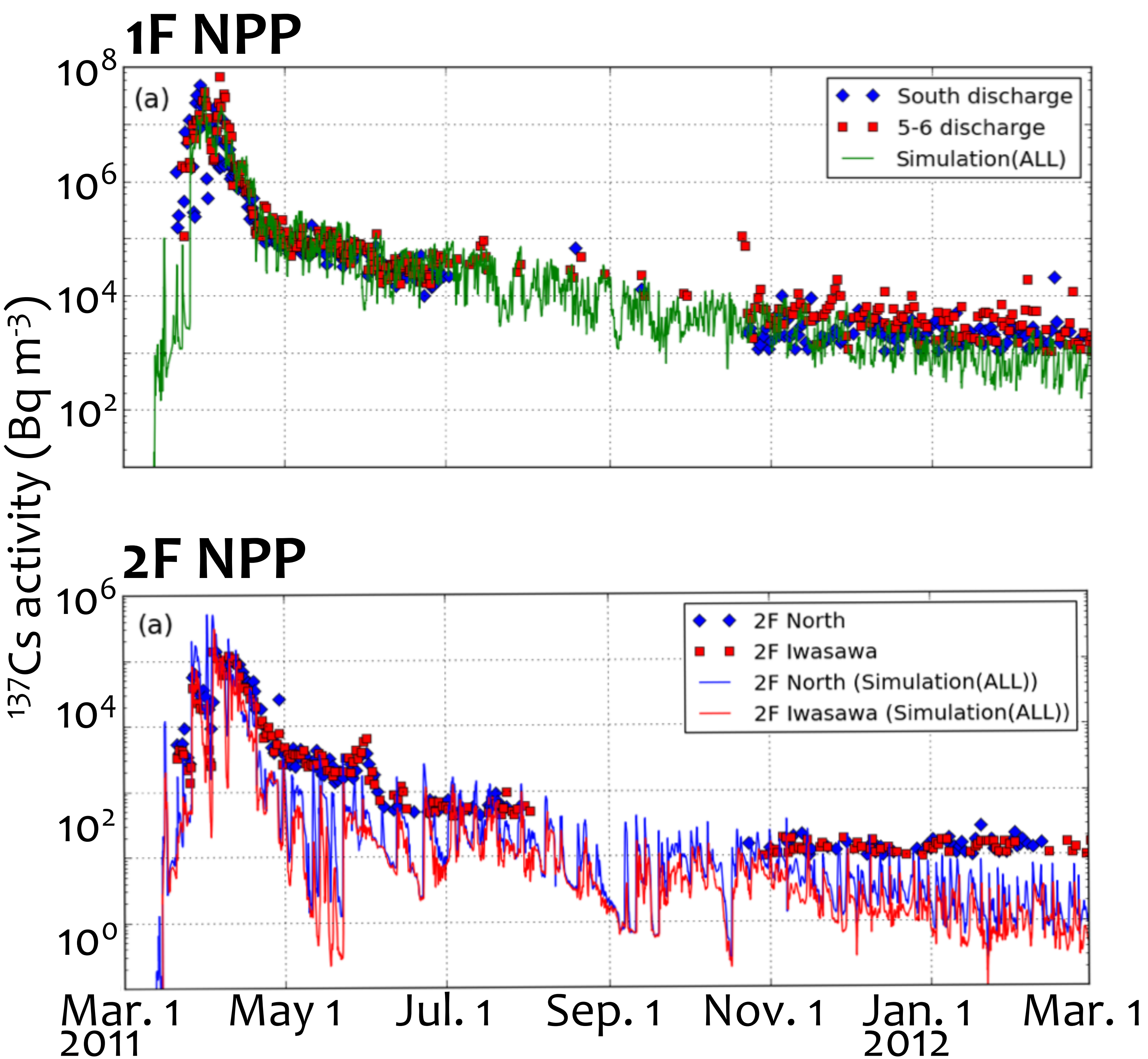
Total $^{137}Cs$ activity: **3.6 PBq** after 1 yr from the accident

相馬
南相馬
1F NPP
2F NPP
いわき

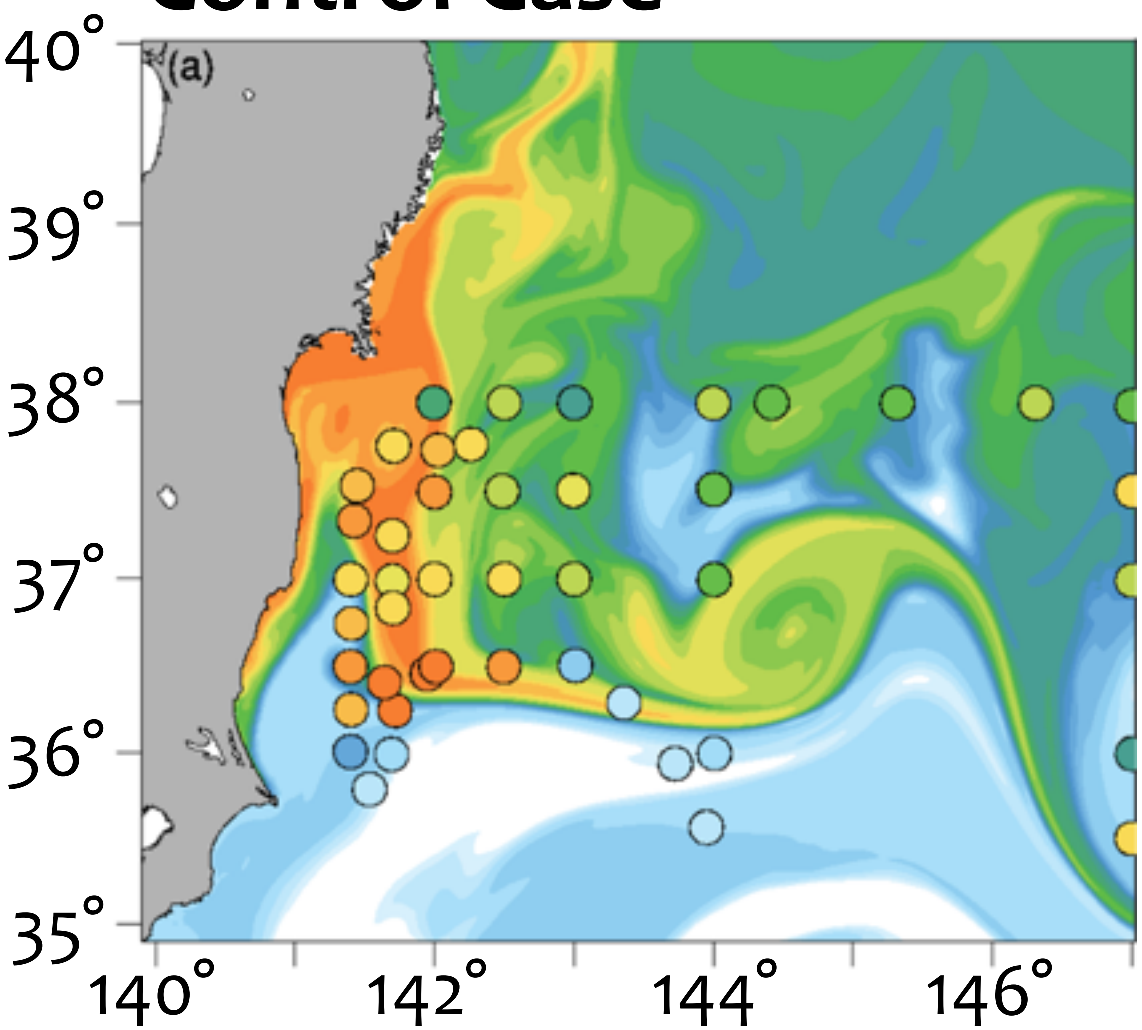



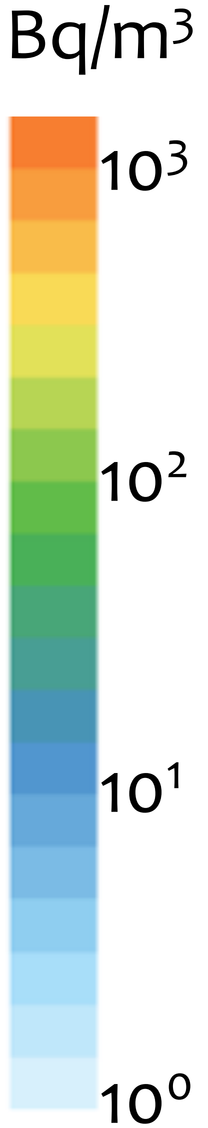
1F NPP
(a)
South discharge
5-6 discharge
Simulation(ALL)
2F NPP
(a)
2F North
2F Iwasawa
2F North (Simulation(ALL))
2F Iwasawa (Simulation(ALL))
137Cs activity (Bq m-3)
Mar. 1 2011
May 1
Jul. 1
Sep. 1
Nov. 1
Jan. 1 2012
Mar. 1

# Comparison with Buesseler et al. (2012)

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

## Control Case



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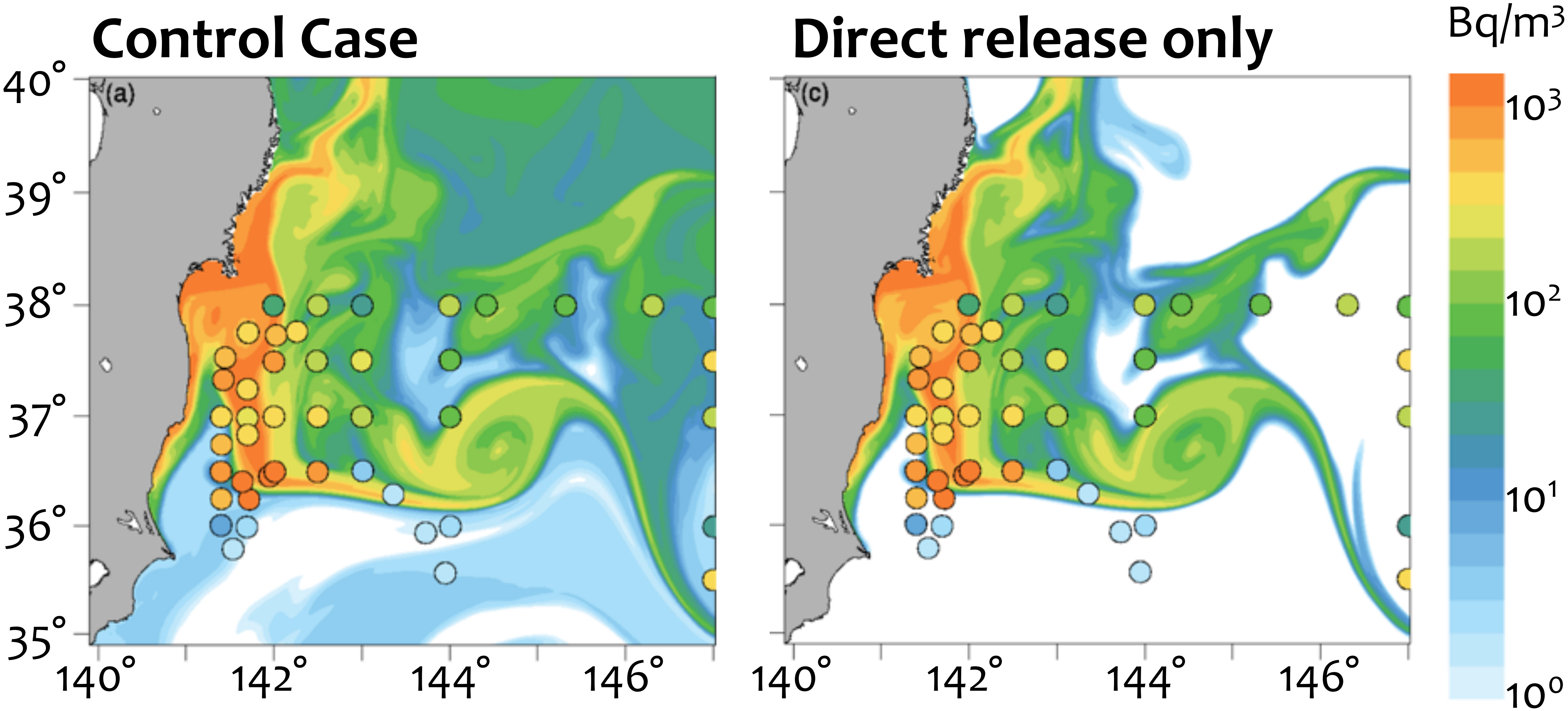

# Comparison with Buesseler et al. (2012)

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

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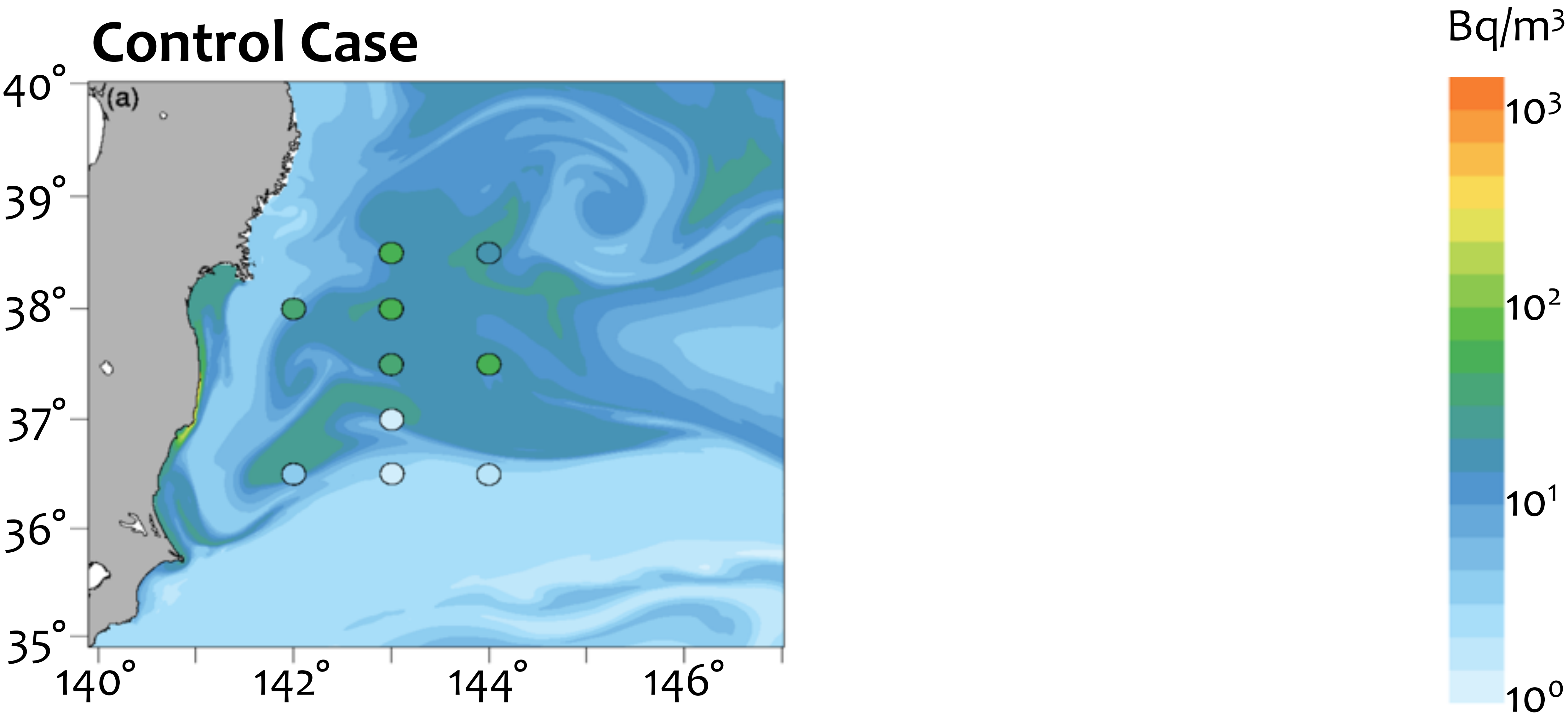
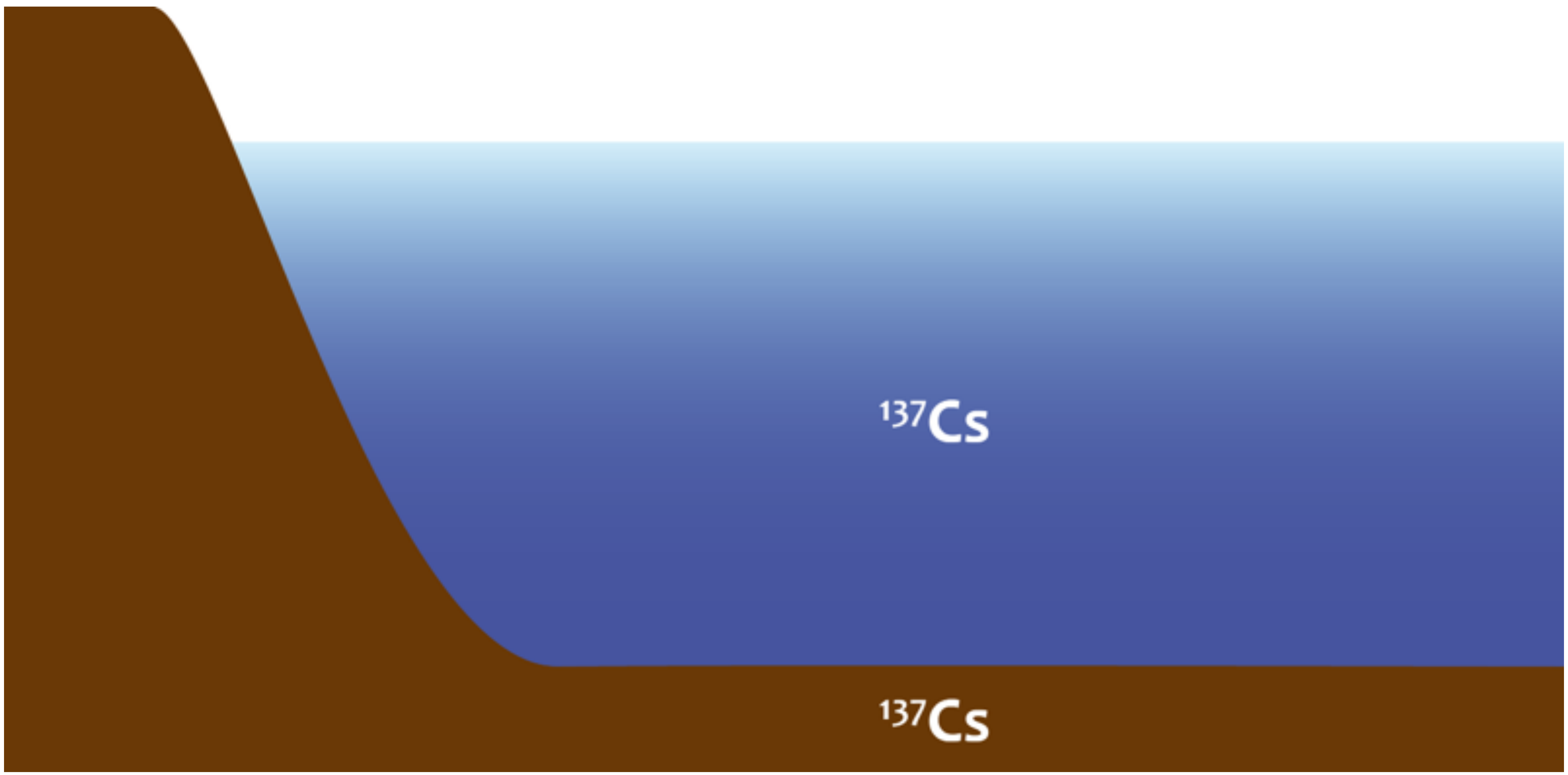


# Possible mechanisms transferring $^{137}Cs$ into sediments



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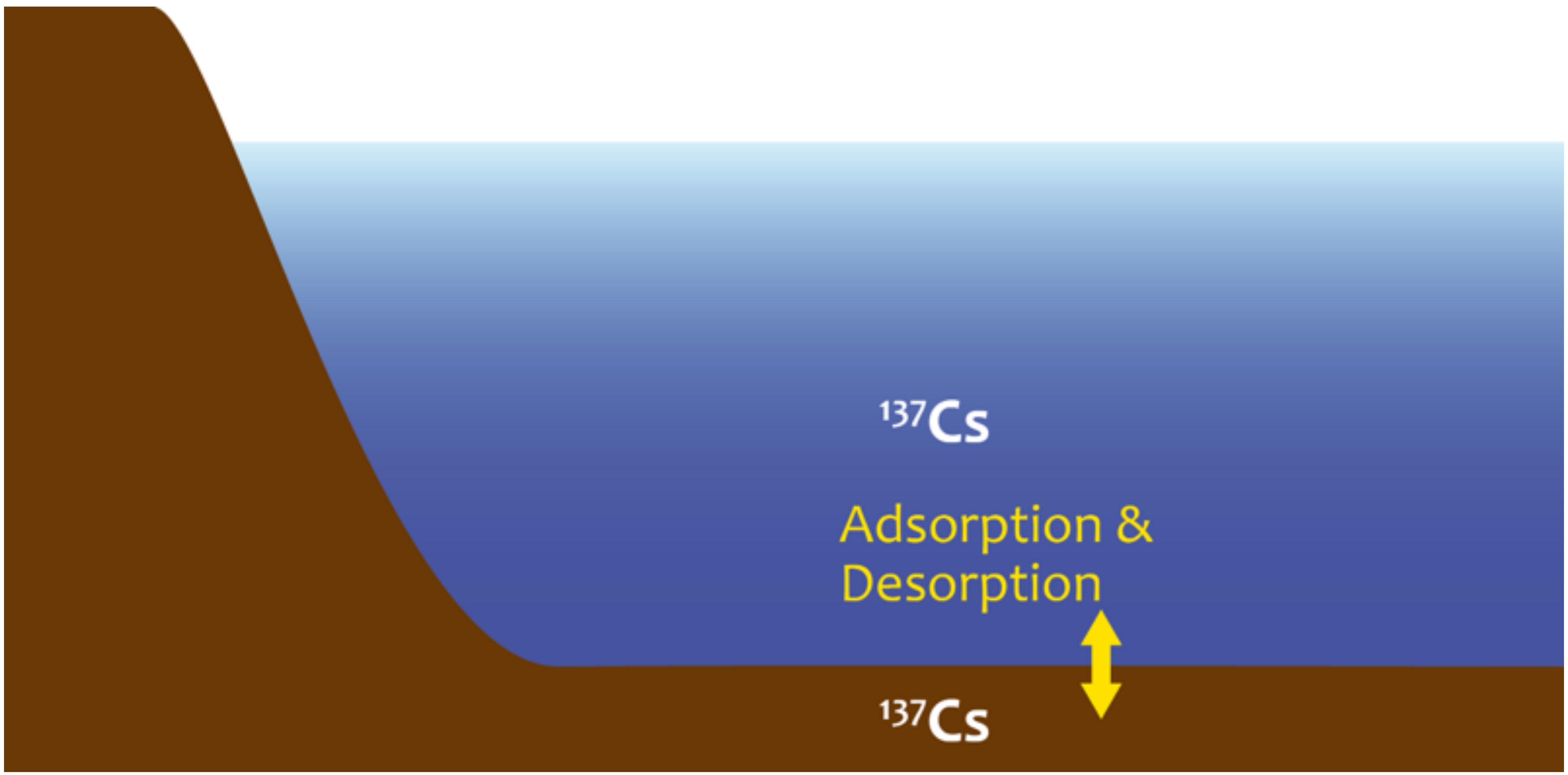

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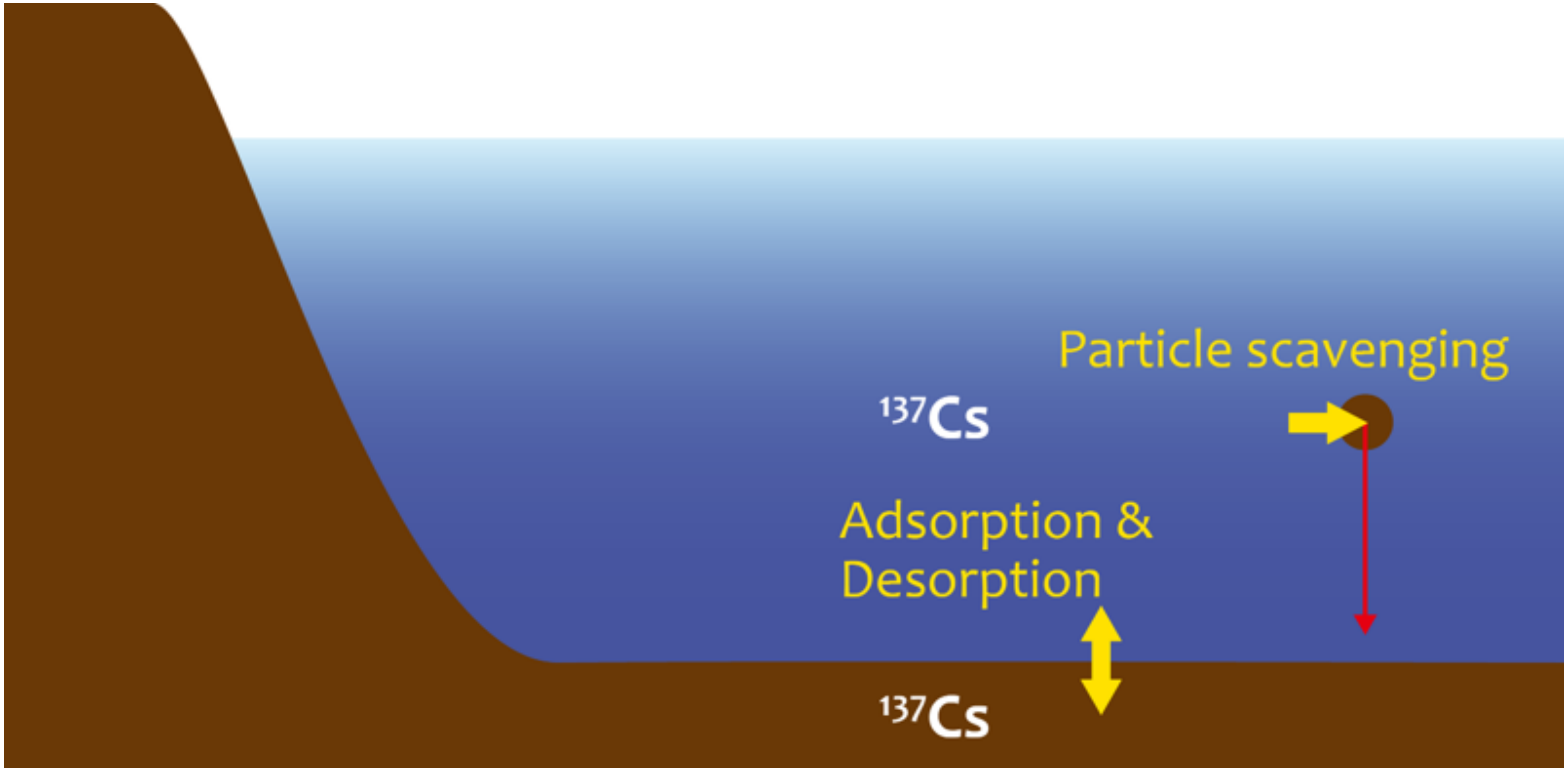

A lab. experiment showed **a slow adsorption rate of Cs to marine particulate matters.**

| Elements | Adsorption rate constants ($kg^{-1}$ $day^{-1}$) |
|---|---|
| Cs | 304 |
| Fe | 25000 |
| Th | 130000 |

Nyffeler et al. (1984)

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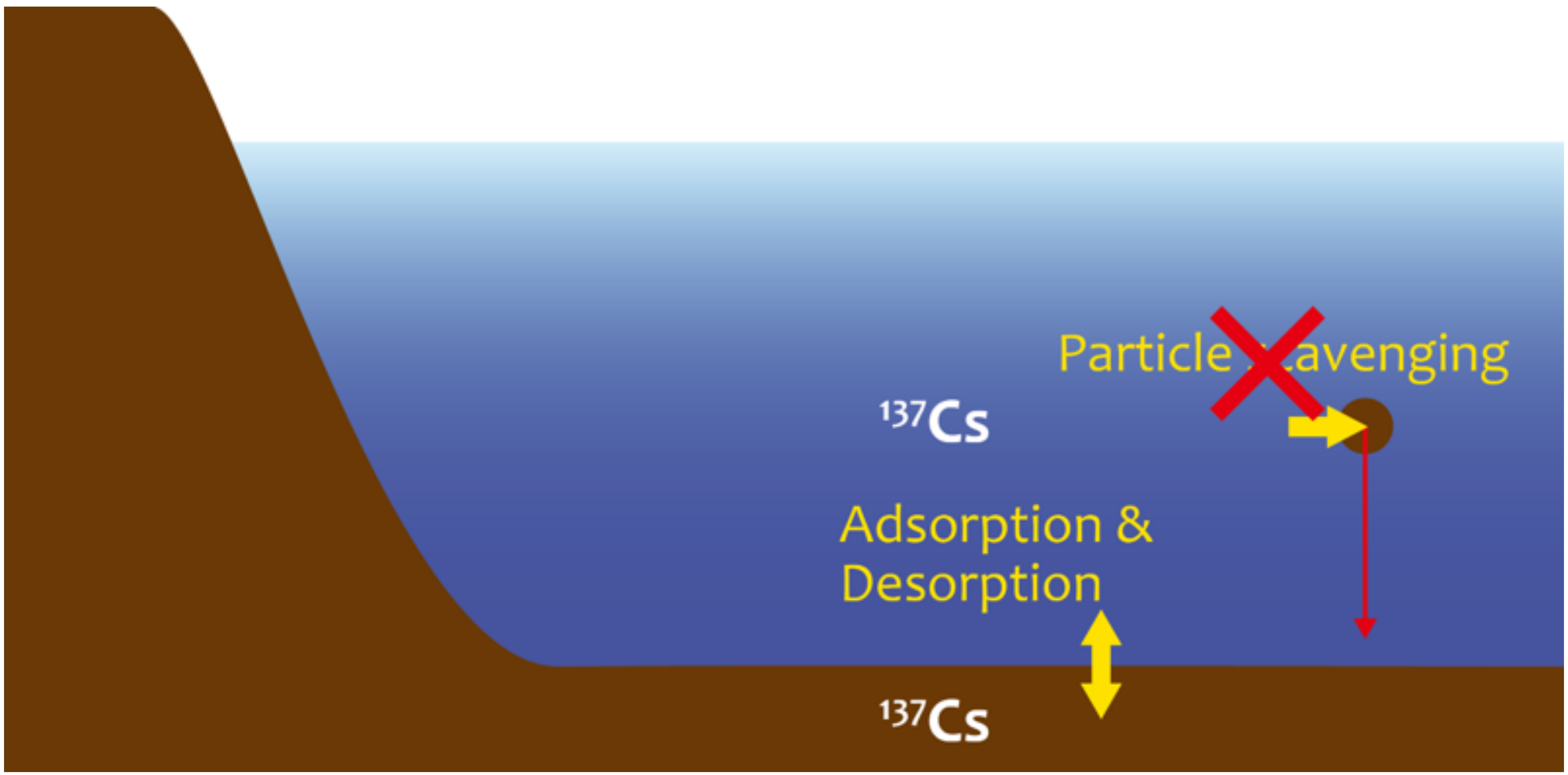

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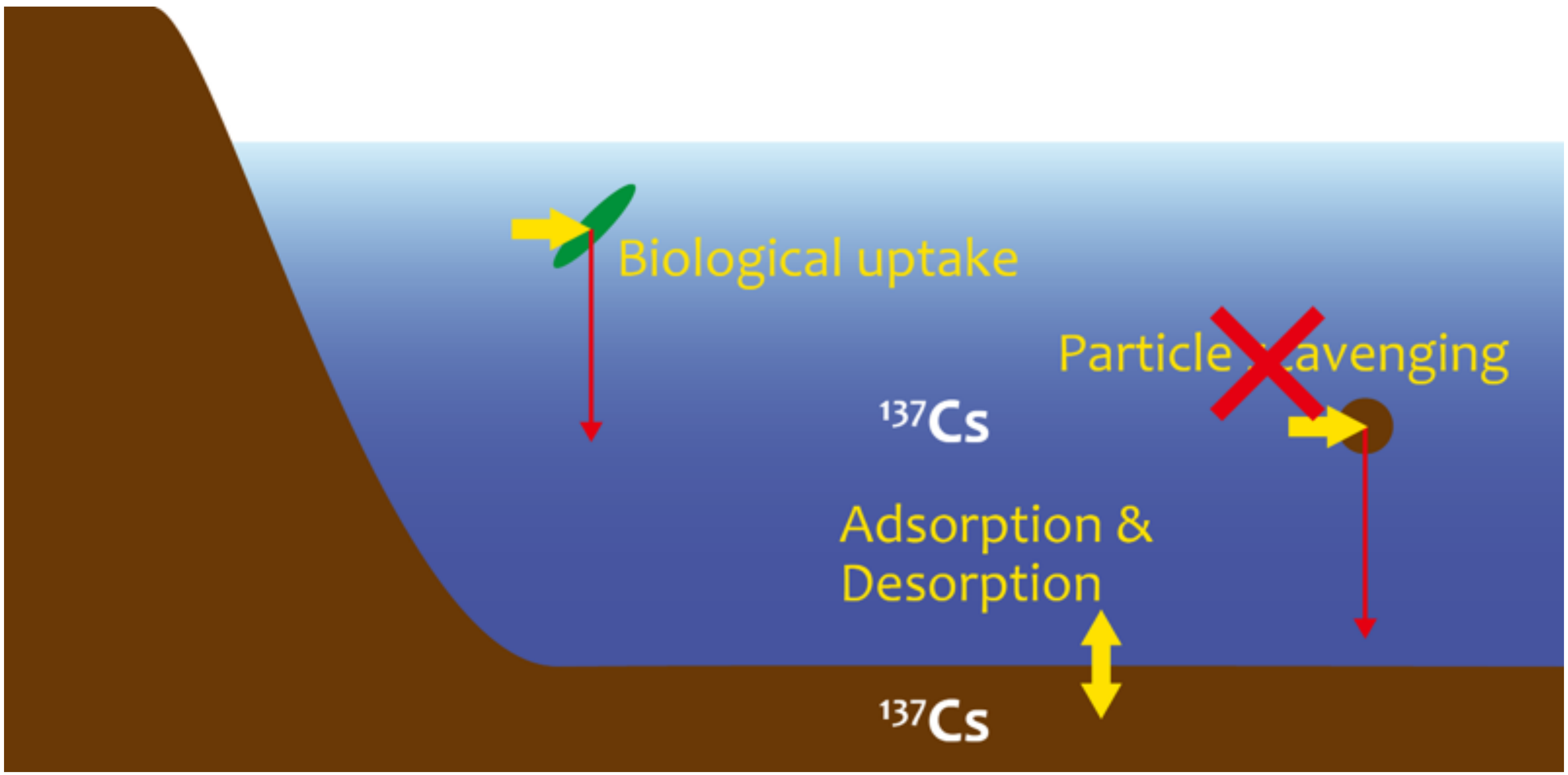

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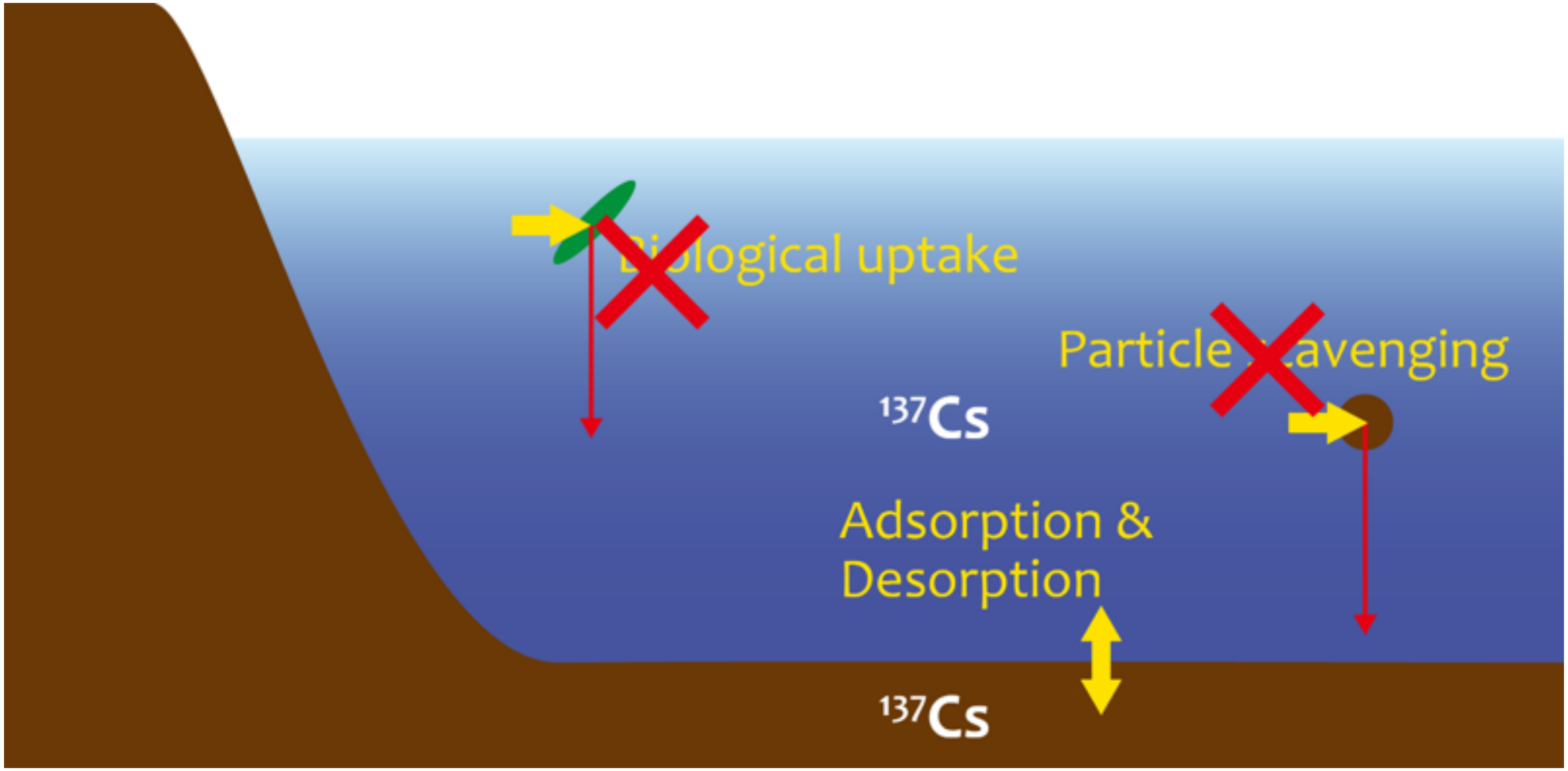
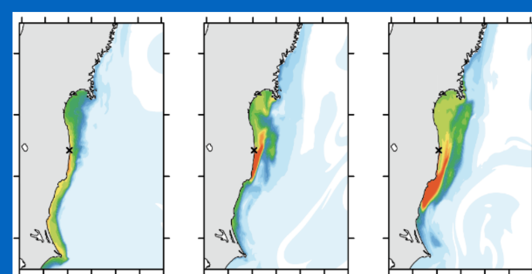


# We developed a sediment model based on Periáñez (2008).

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



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

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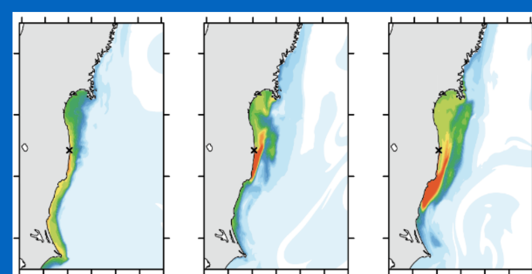

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$k_1$

**Sediment ($C_{sed}$)**

$$k_1 = \chi S = \chi \frac{3L}{RH} \phi (1 - p)$$

(Periáñez, 2008)

| | | |
|---|---|---|
| $\chi$ | exchange velocity | 35.0 mm $day^{-1}$ (Nyffeler et al., 1984) |
| S | exchange surface | |
| ***R*** | **sediment radius** | **spatially varying obs. data** |
| $\varphi$ | 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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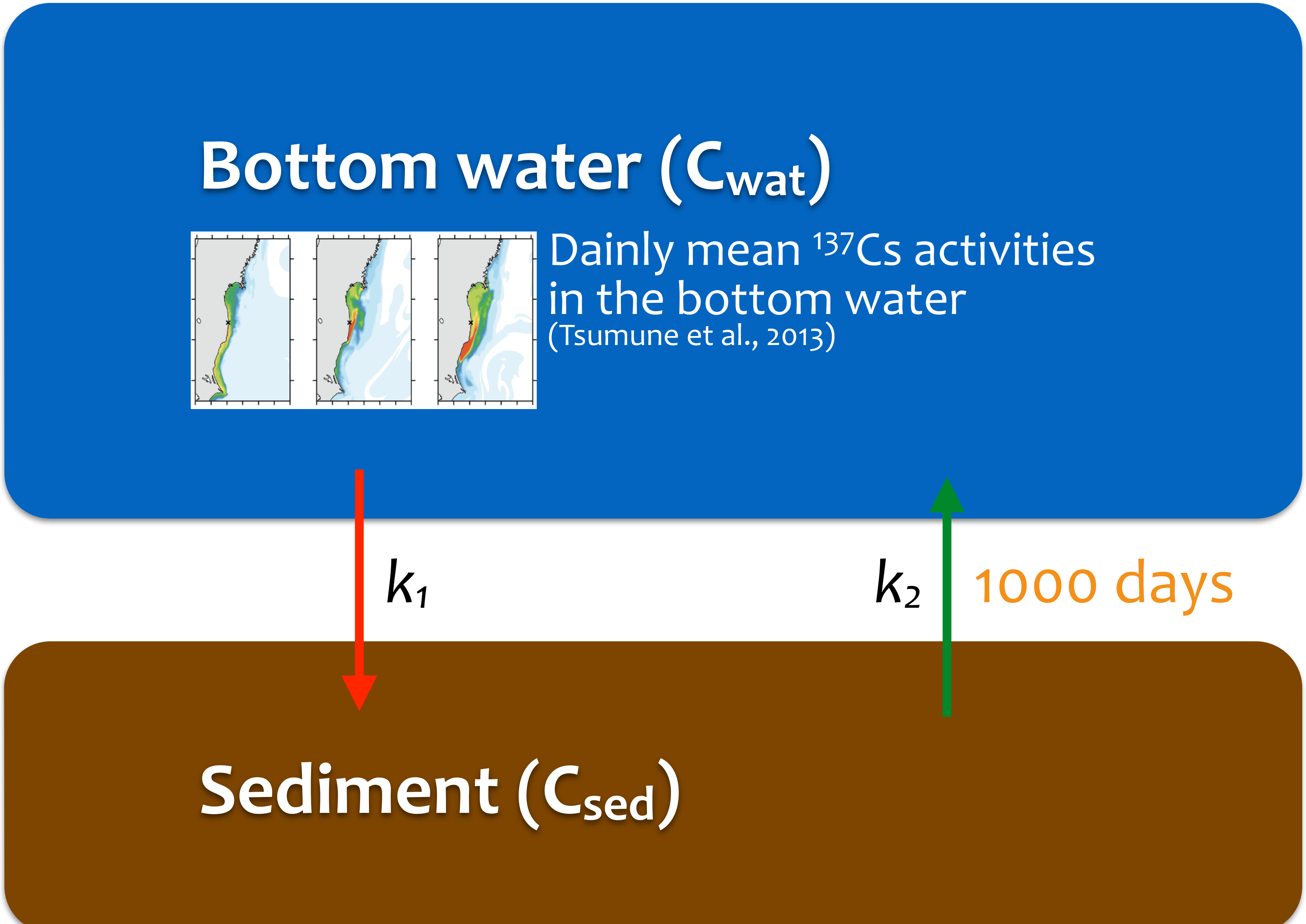

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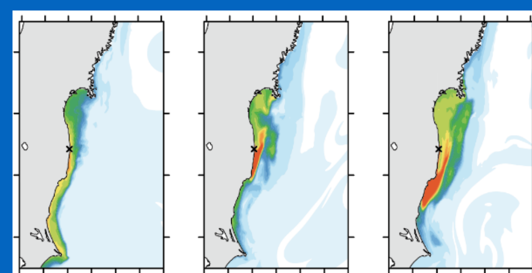

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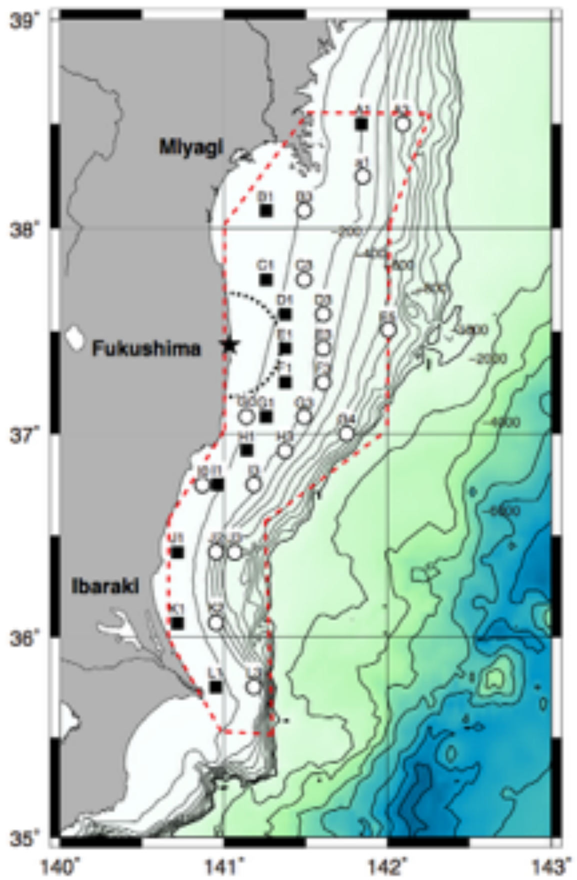
(Tsumune et al., 2013)

$k_1$

$k_2$ 1000 days

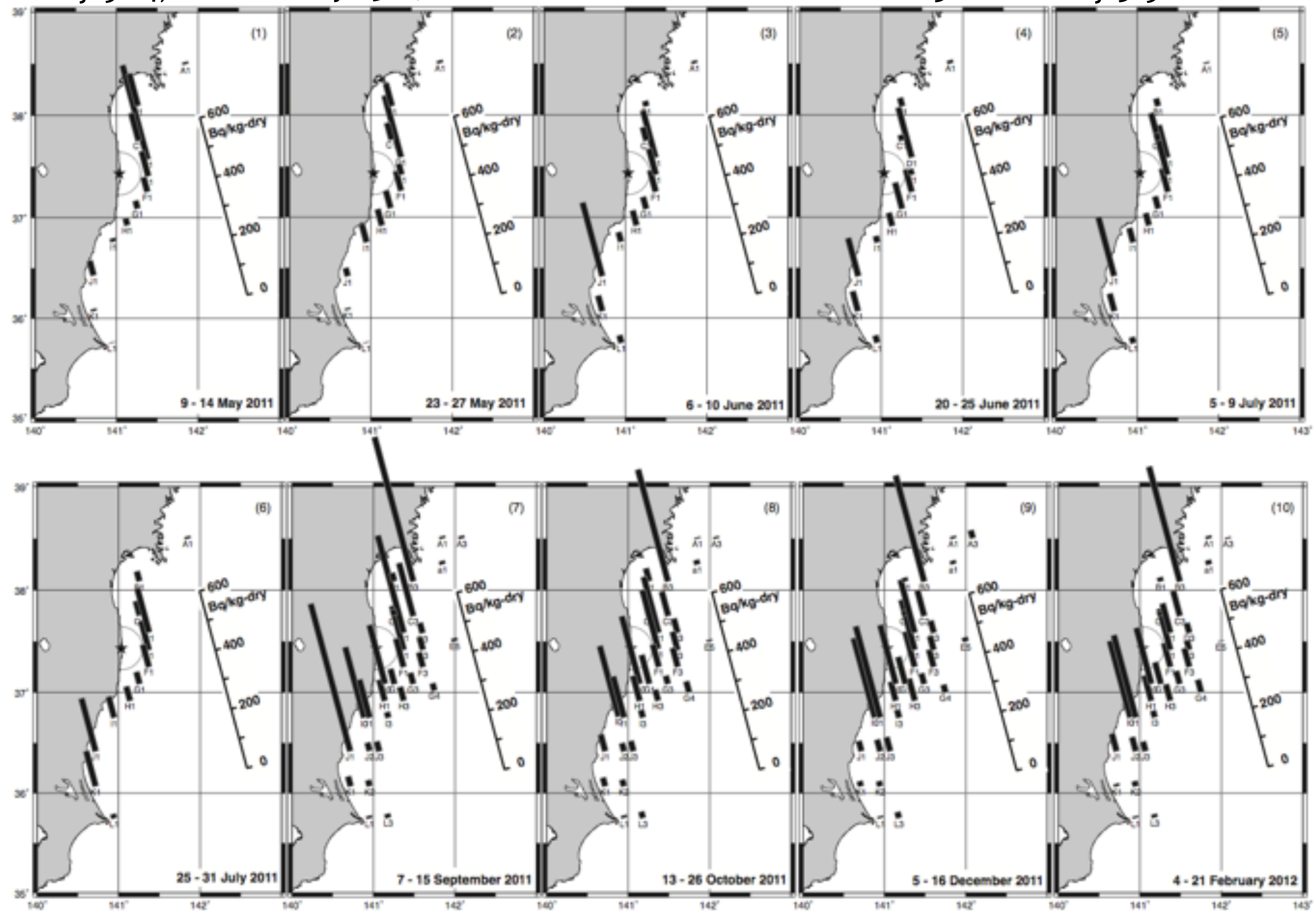
**Sediment ($C_{sed}$)**

$\lambda$ 30 years




Kusakabe et al. (2013)

May 9-14, 2011 | May 23-27 | June 6-10 | June 20-25 | July 5-9

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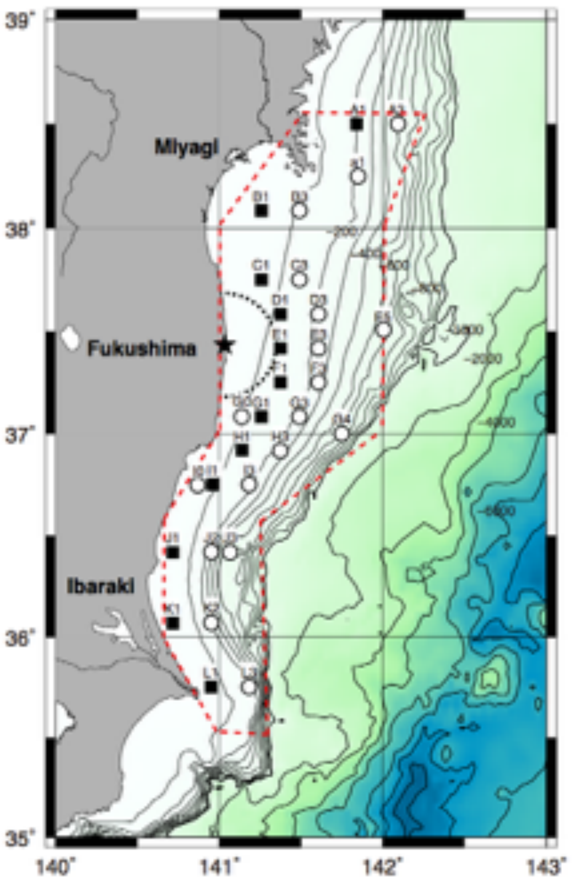


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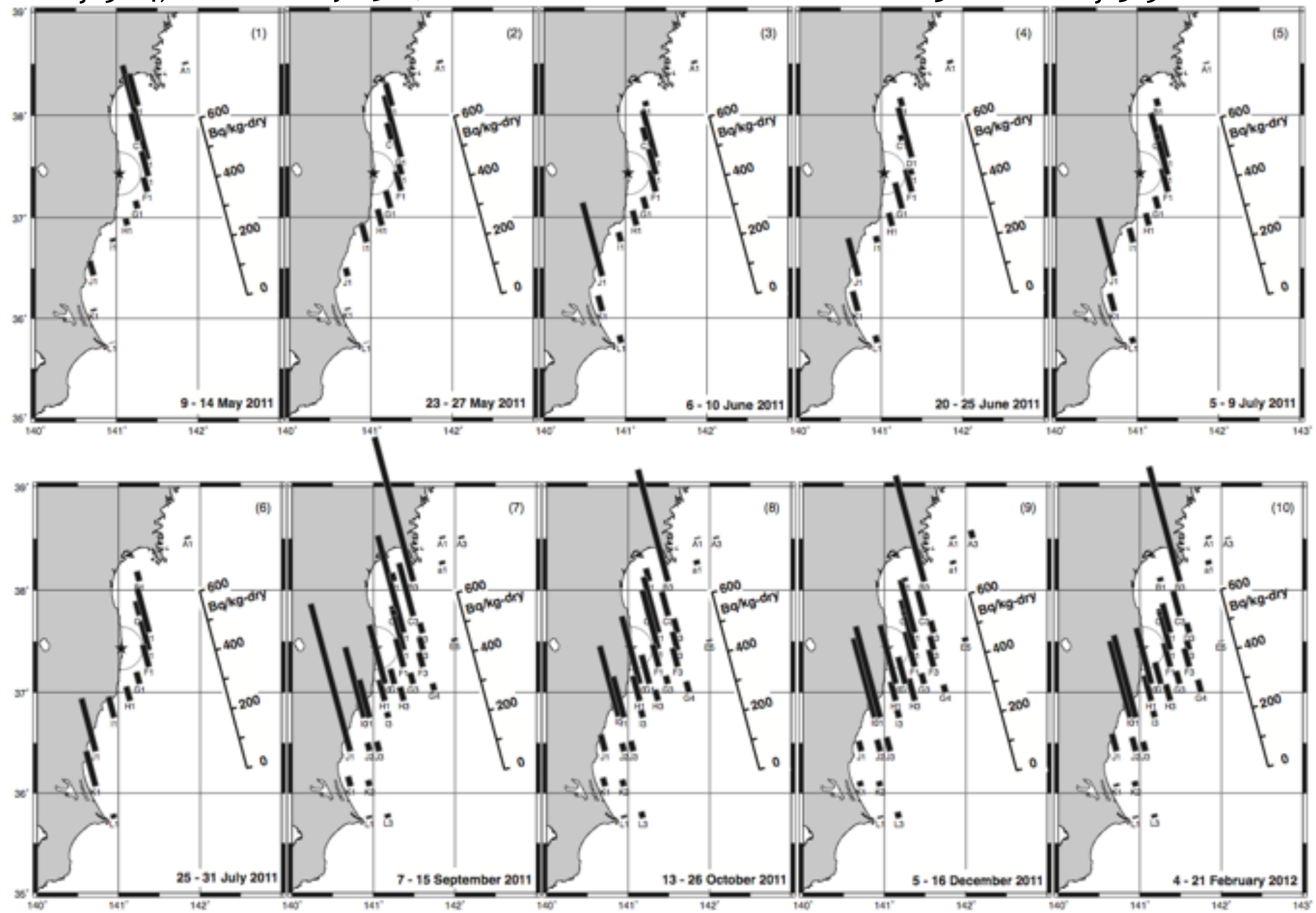


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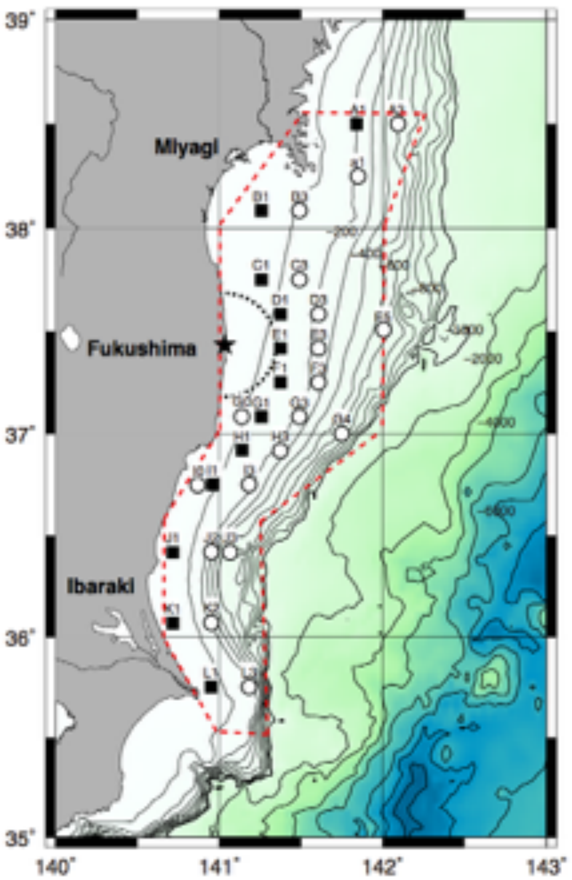
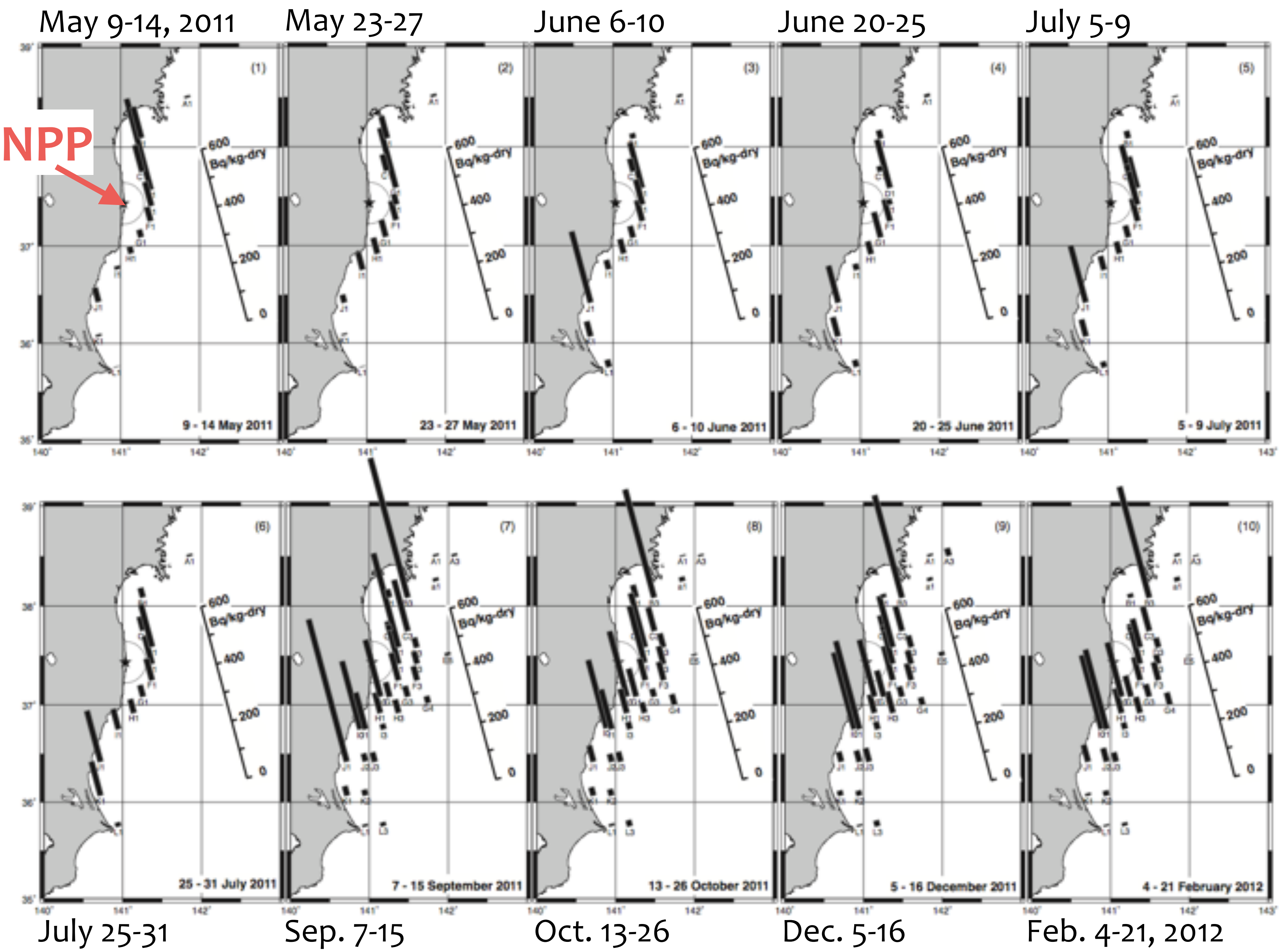
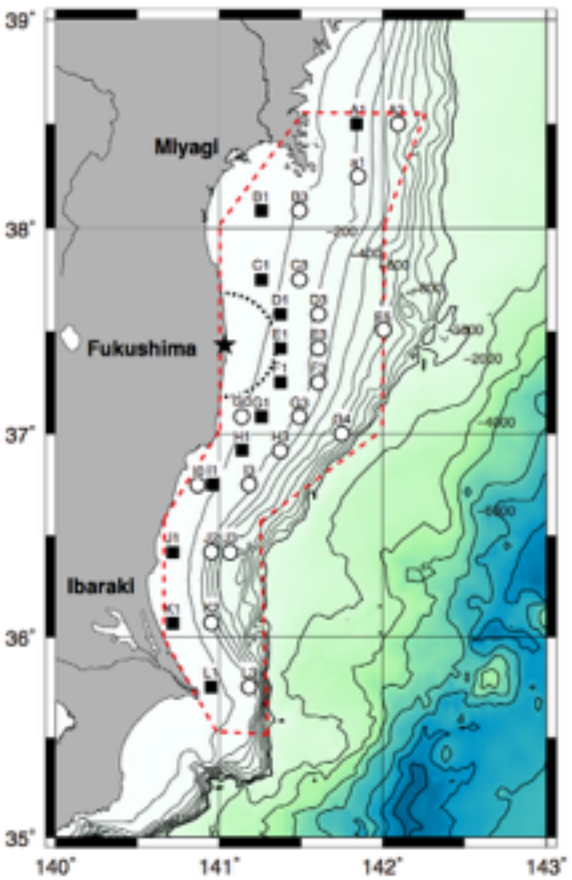
- **Heterogeneous spatial distribution**




Kusakabe et al. (2013)




## • Heterogeneous spatial distribution

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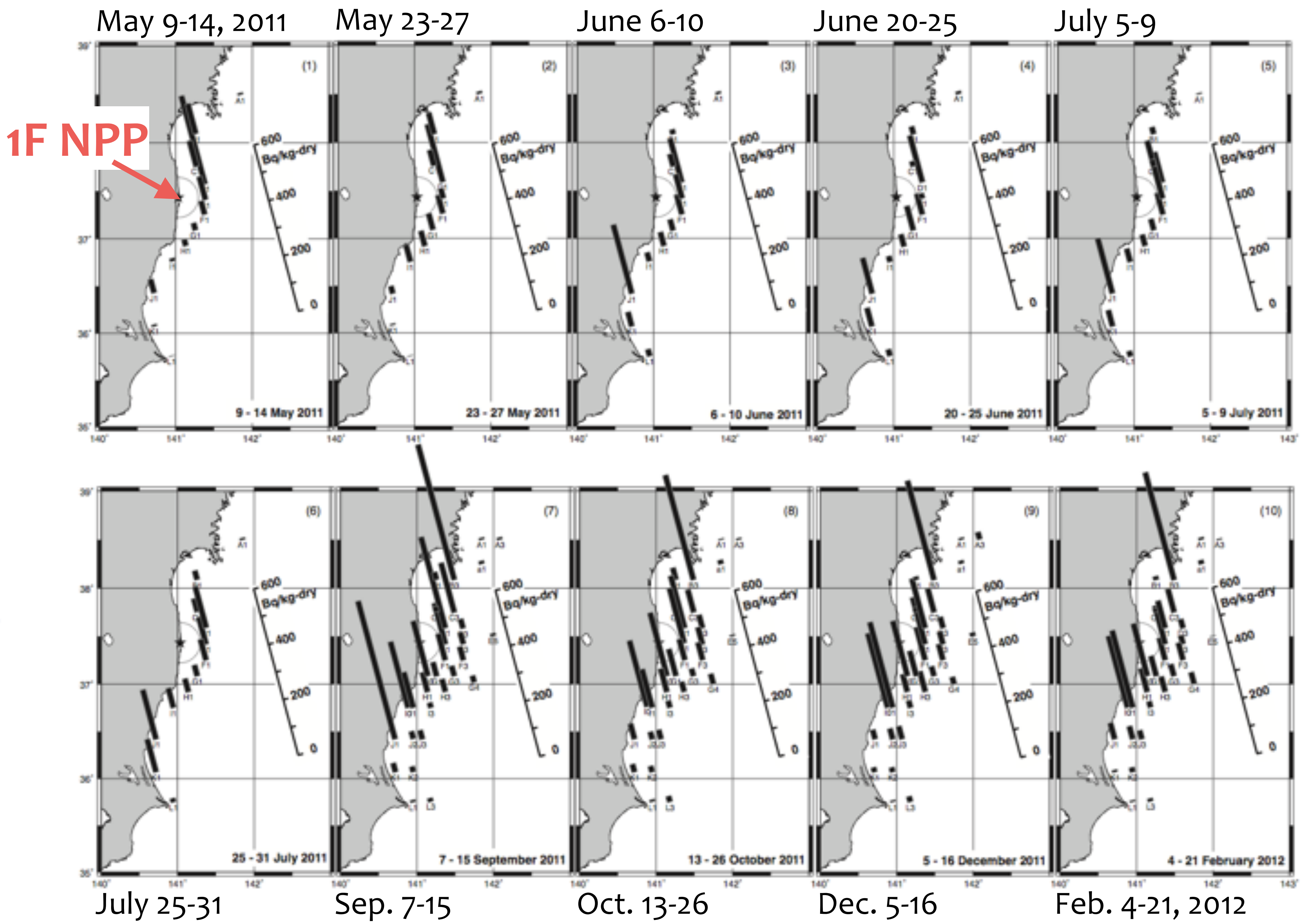


- **Heterogeneous spatial distribution**
- **Temporal persistency**

Previous obs. studies pointed out factors causing these features.

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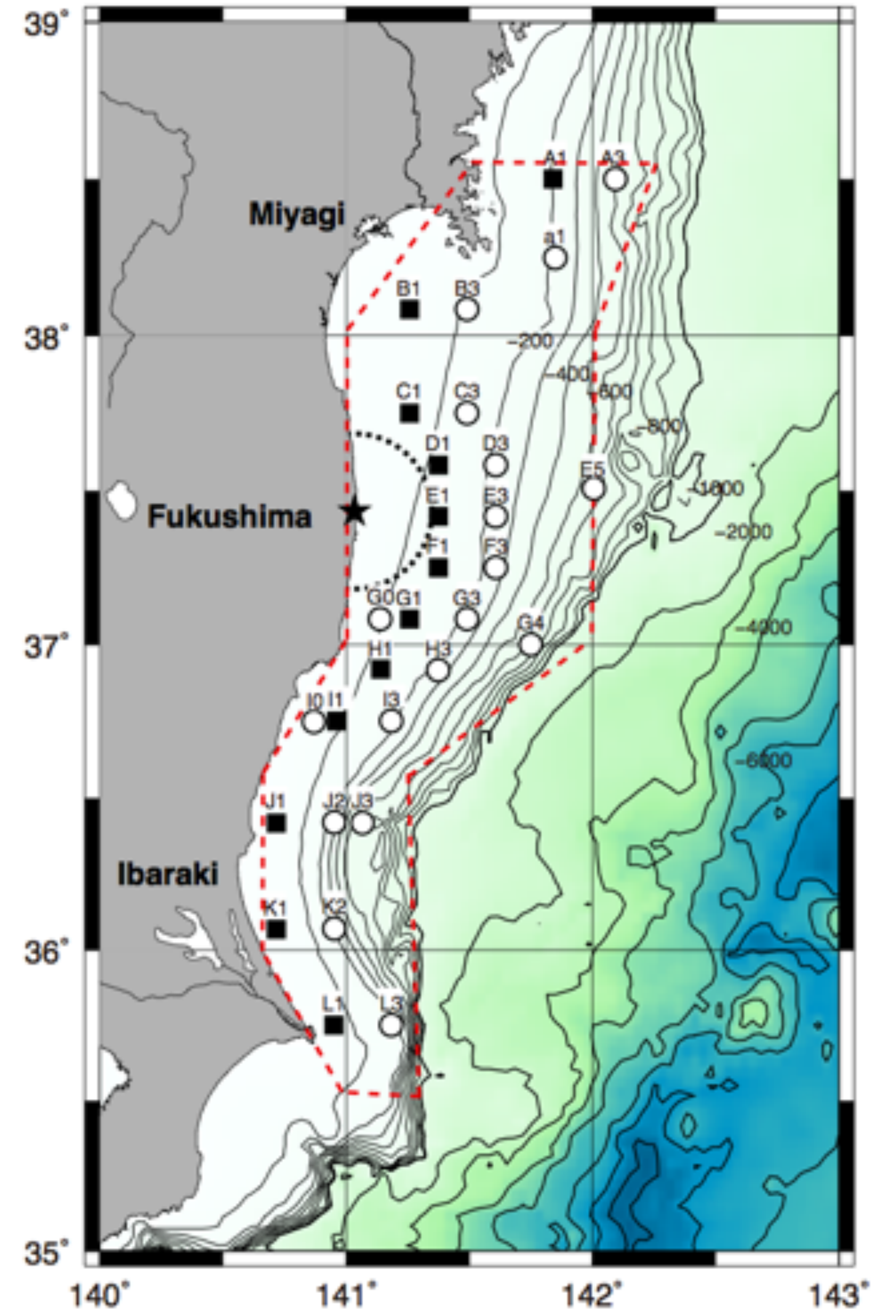
# STN case

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

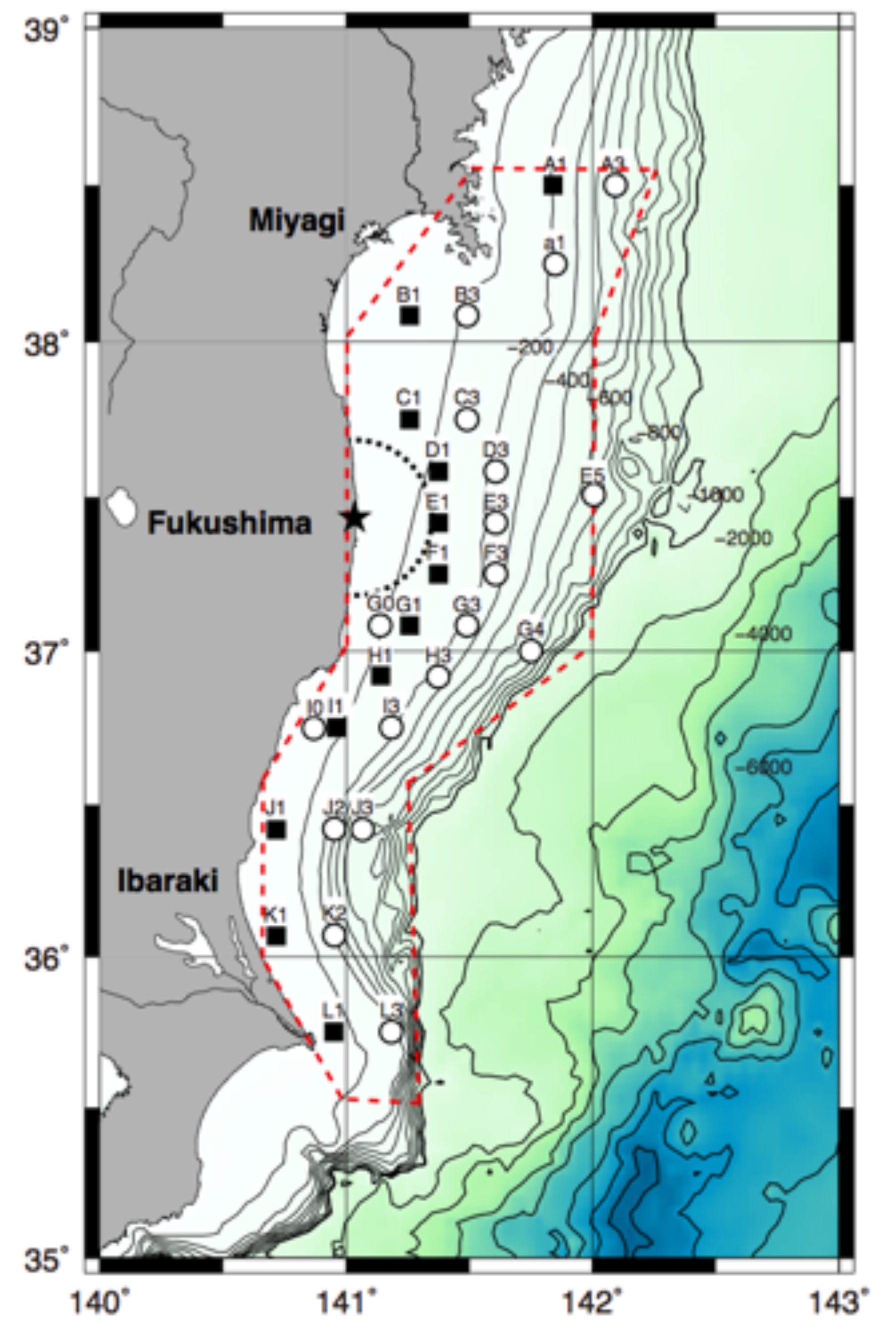


# STN case

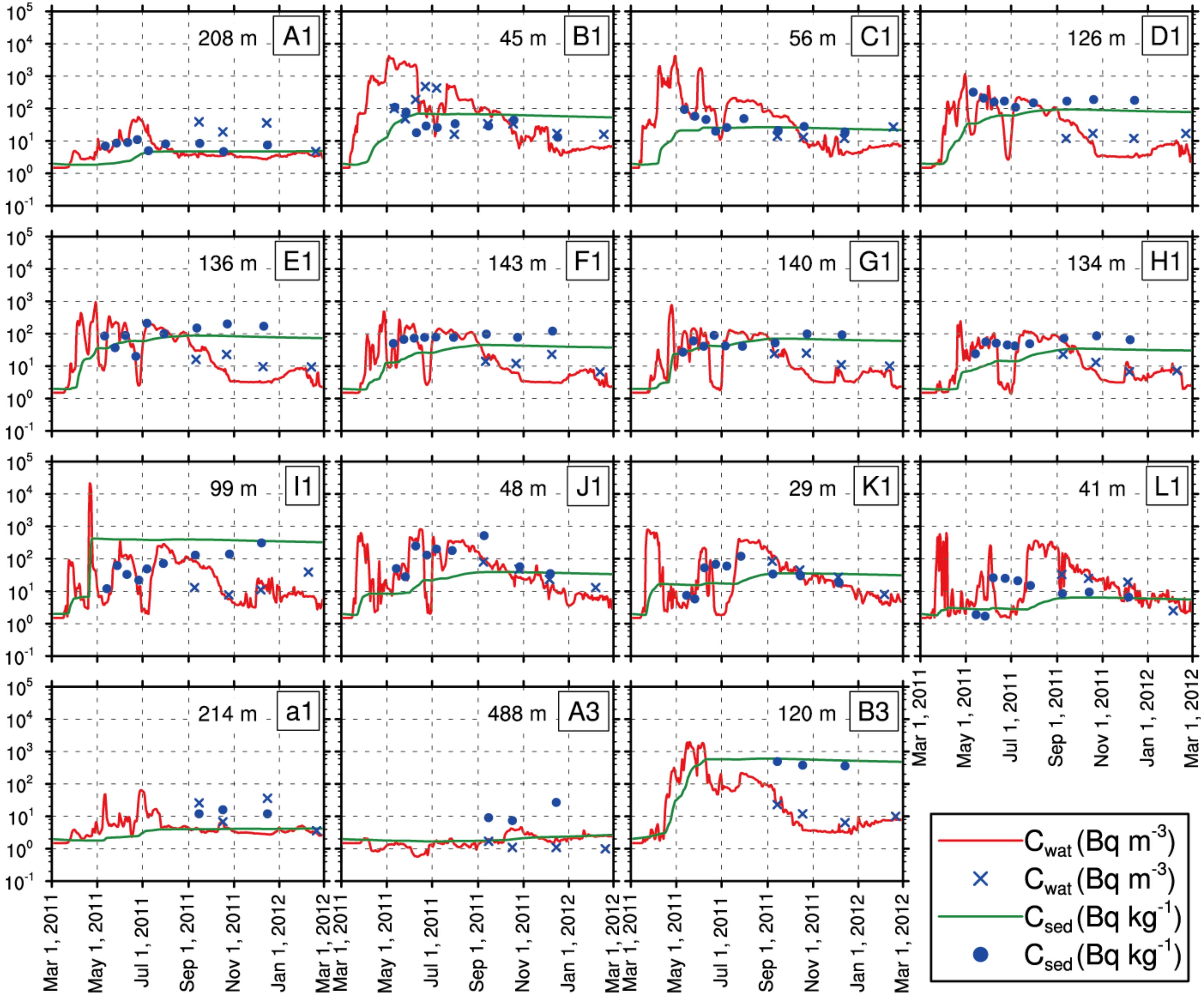
- simulate temporal variation of $^{137}Cs$ in **each monitoring station**
- **validate model outputs**

# 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

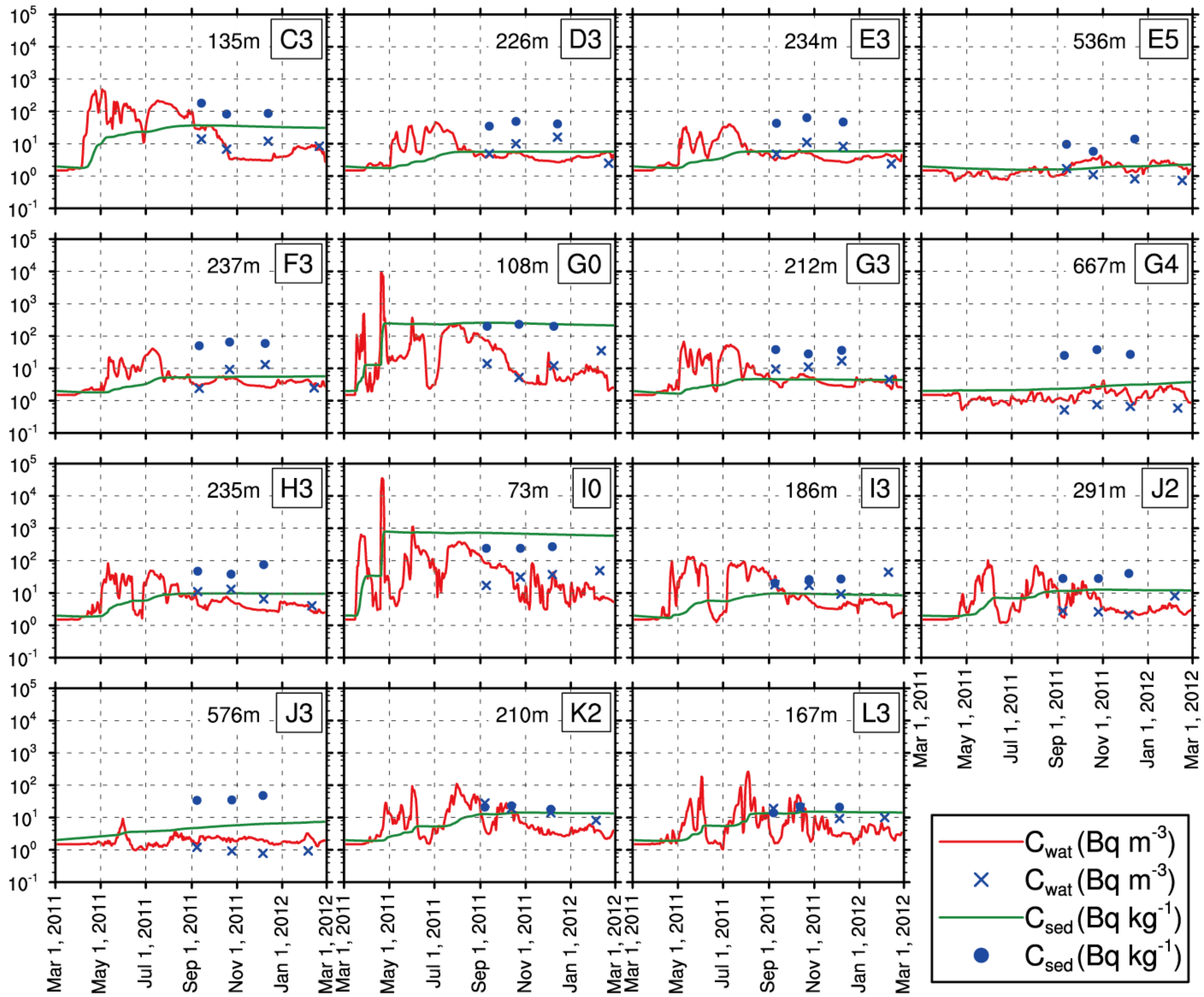


# STN case



208 m
A1
45 m
B1
56 m
C1
126 m
D1
136 m
E1
143 m
F1
140 m
G1
134 m
H1
99 m
I1
48 m
J1
29 m
K1
41 m
L1
214 m
a1
488 m
A3
120 m
B3
Mar 1, 2011
May 1, 2011
Jul 1, 2011
Sep 1, 2011
Nov 1, 2011
Jan 1, 2012
Mar 1, 2012
$C_{wat}$ (Bq m$^{-3}$)
$C_{wat}$ (Bq m$^{-3}$)
$C_{sed}$ (Bq kg$^{-1}$)
$C_{sed}$ (Bq kg$^{-1}$)

# STN case

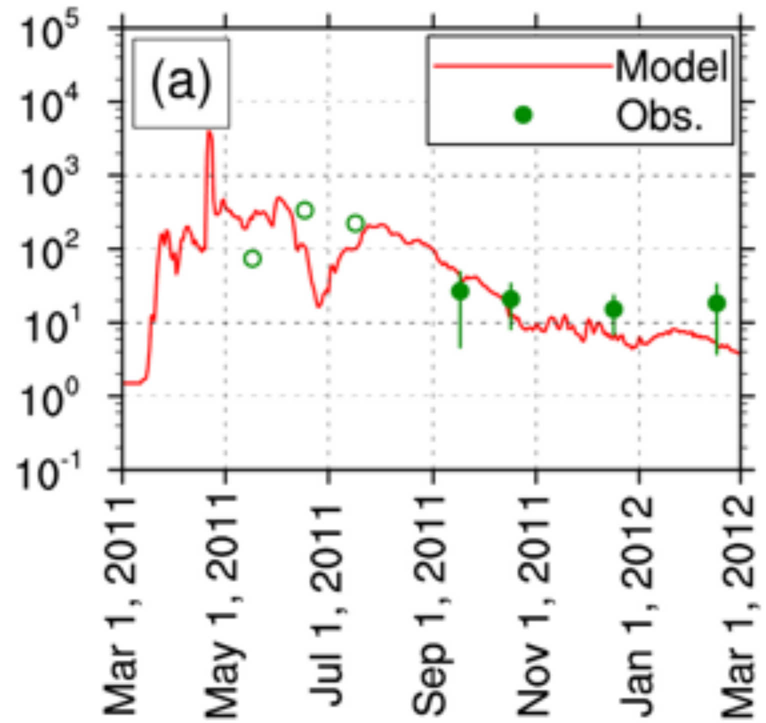

135m C3
226m D3
234m E3
536m E5
237m F3
108m G0
212m G3
667m G4
235m H3
73m I0
186m I3
291m J2
576m J3
210m K2
167m L3
Mar 1, 2011
May 1, 2011
Jul 1, 2011
Sep 1, 2011
Nov 1, 2011
Jan 1, 2012
Mar 1, 2012
$C_{wat}$ (Bq m$^{-3}$)
$C_{wat}$ (Bq m$^{-3}$)
$C_{sed}$ (Bq kg$^{-1}$)
$C_{sed}$ (Bq kg$^{-1}$)

# STN case

composite of the results separated by the station depth

< 200 m

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



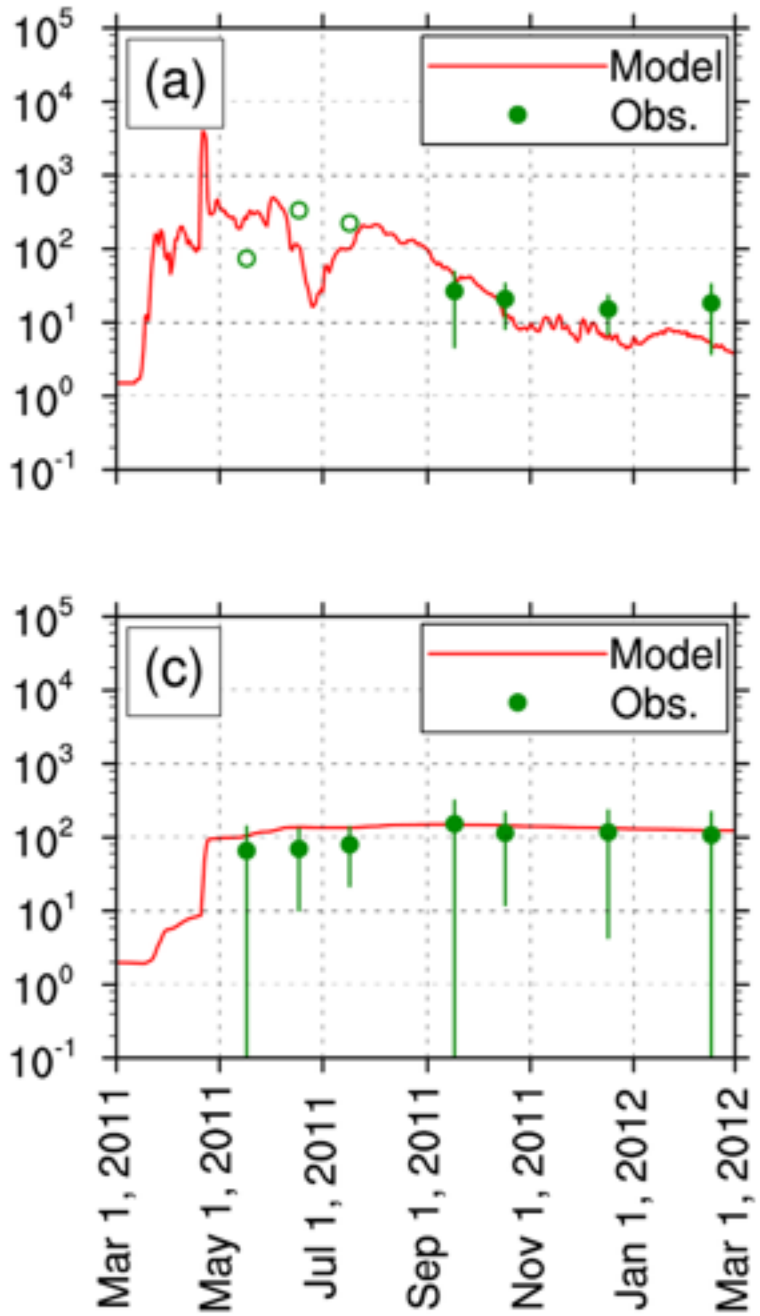
# STN case

composite of the results separated by the station depth

< 200 m

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

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



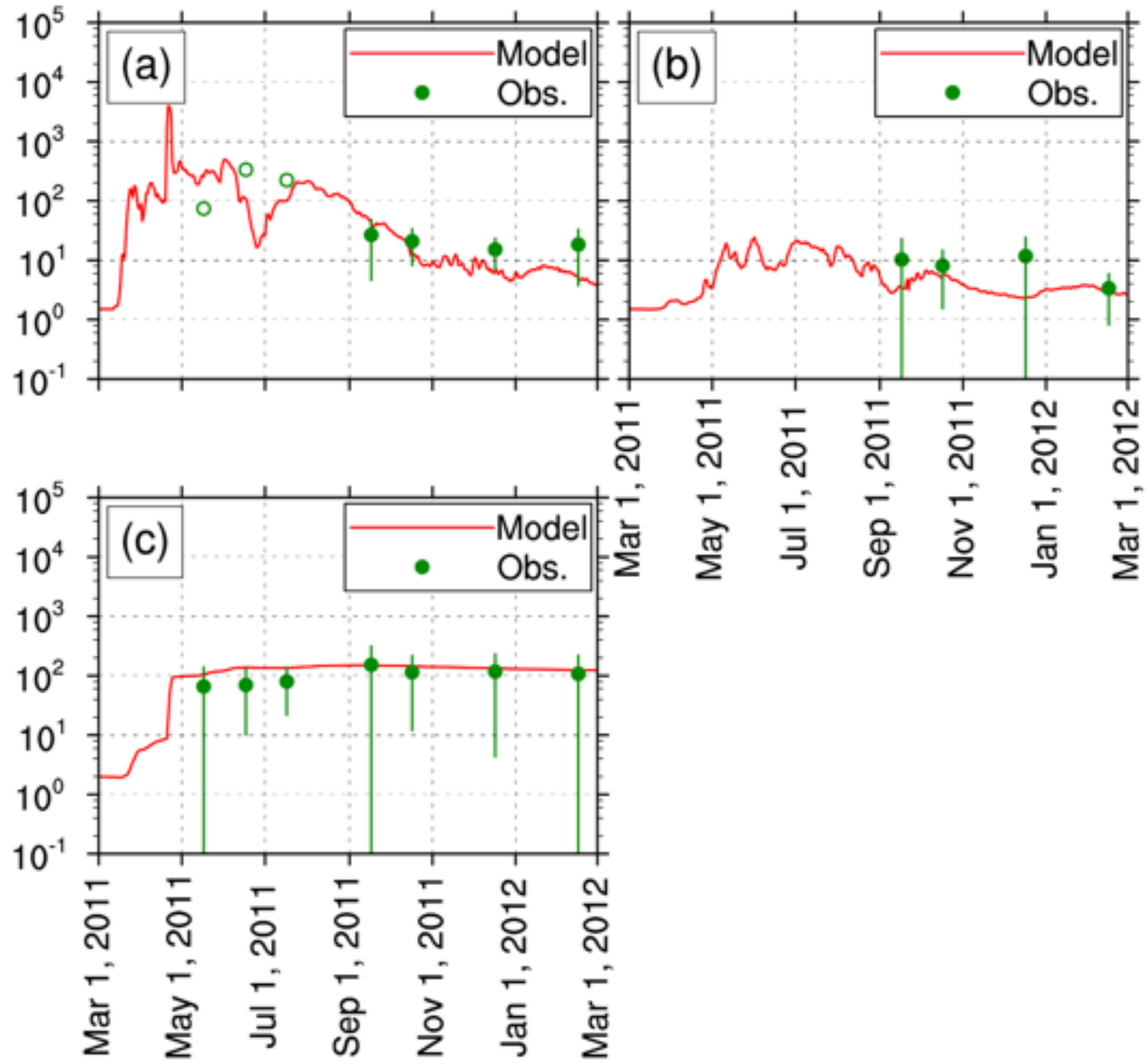
# STN case

composite of the results separated by the station depth

< 200 m        > 200 m

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

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



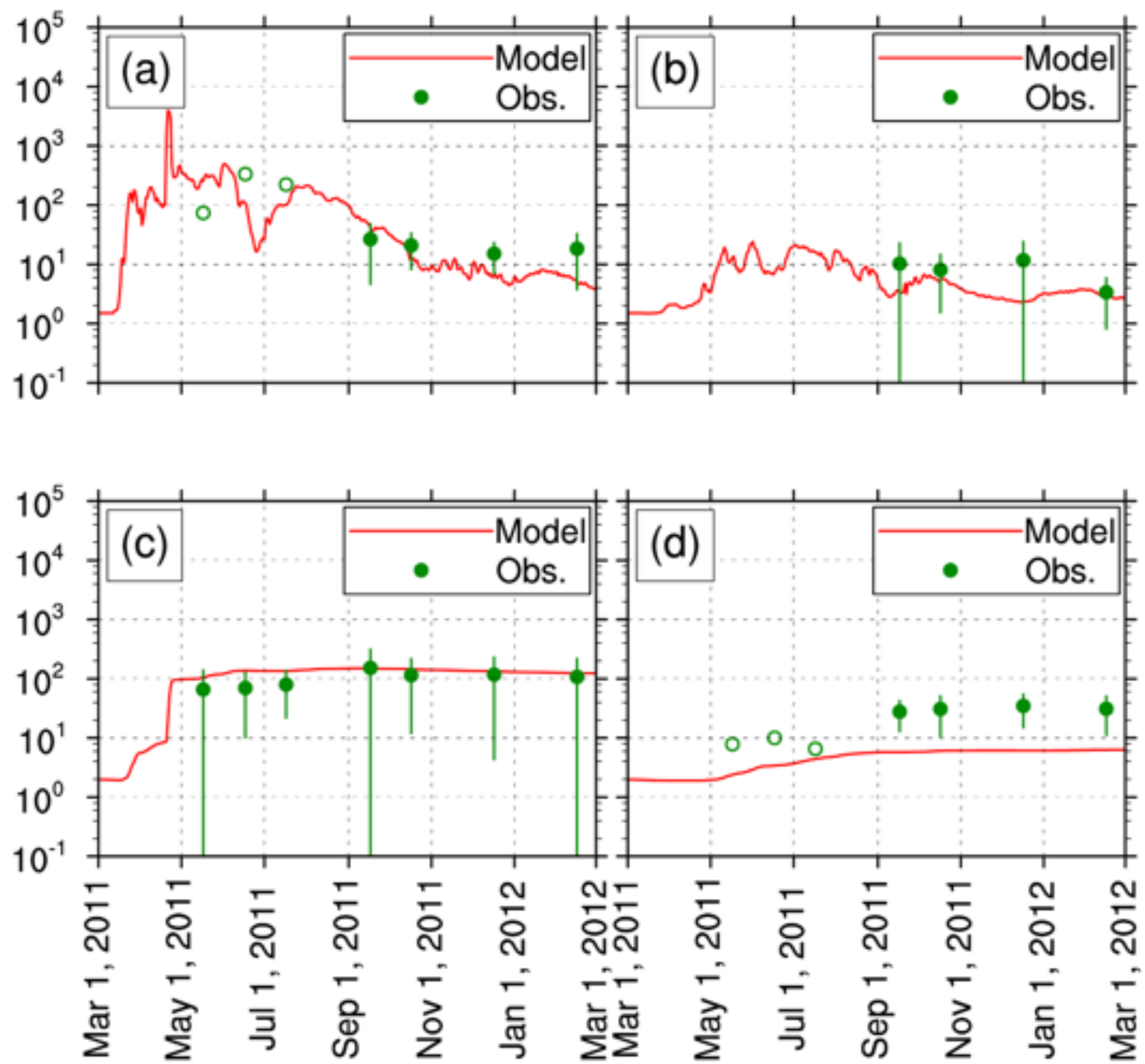
# STN case

composite of the results separated by the station depth

< 200 m　　　　> 200 m

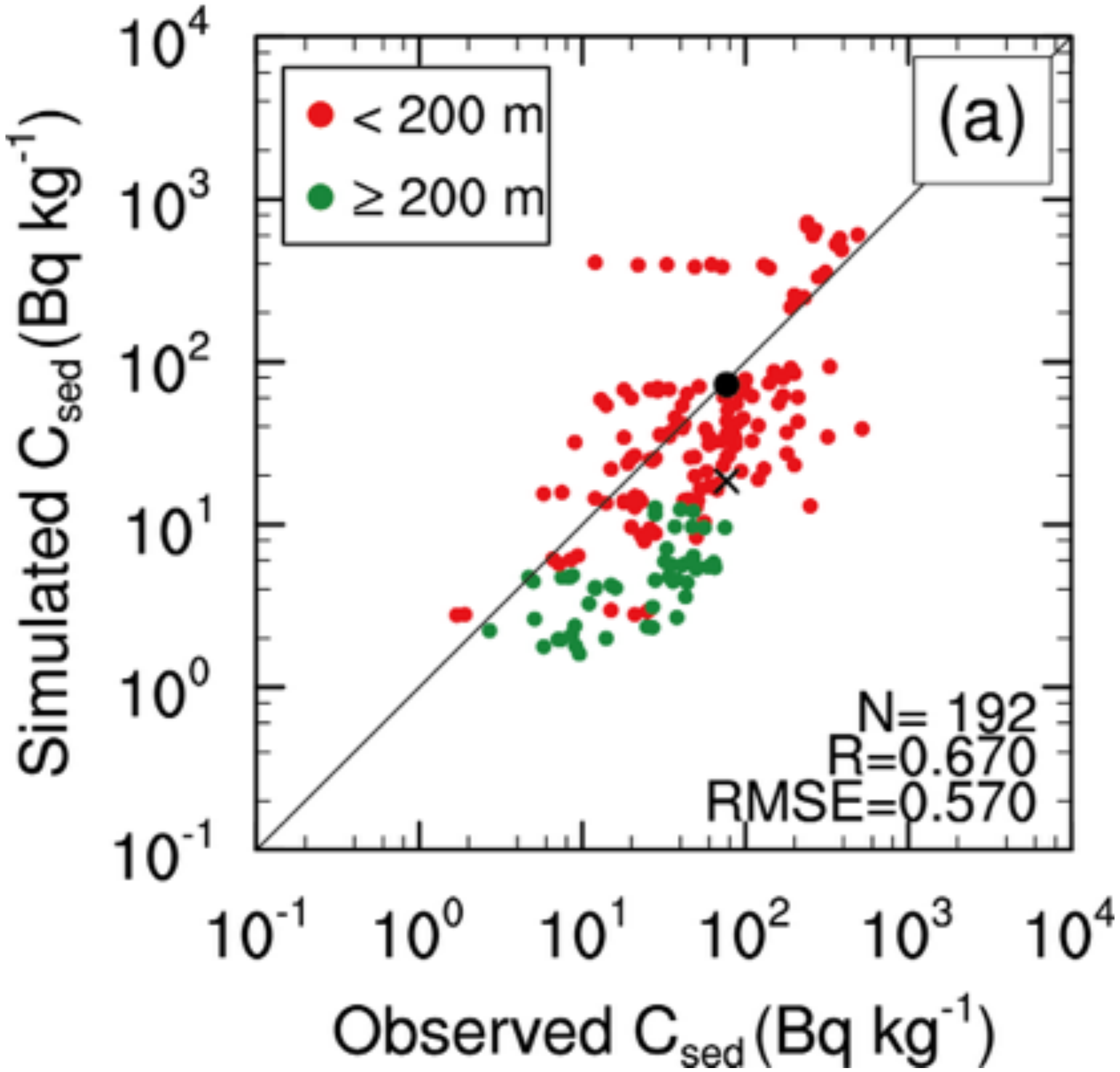
Bottom water (Bq $m^{-3}$)

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



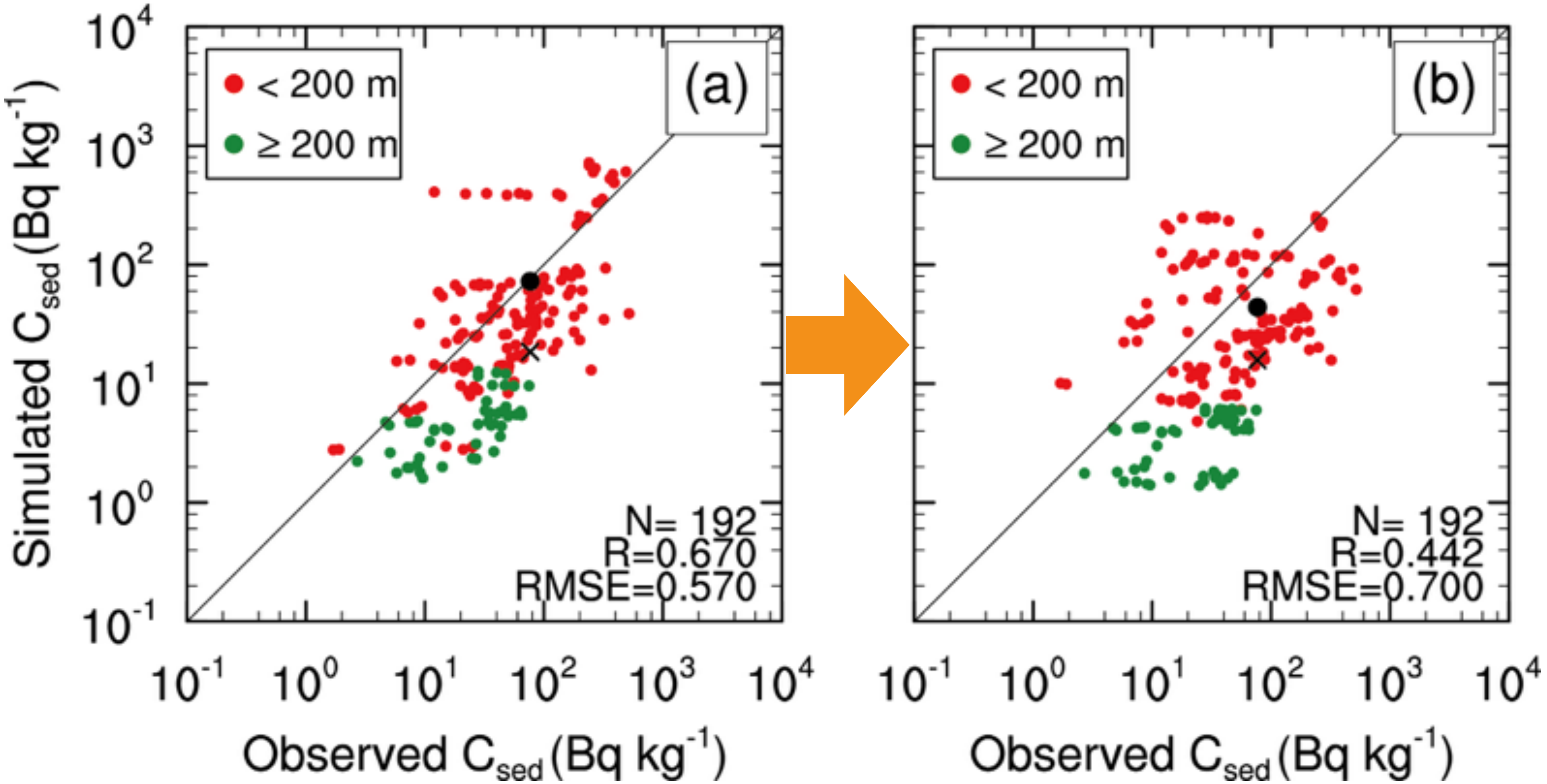
# STN case

comparison of the simulated $^{137}Cs$ activities in sediments with obs. data



# STN case

if we use a homogeneous (mean) sediment radius (*R*)

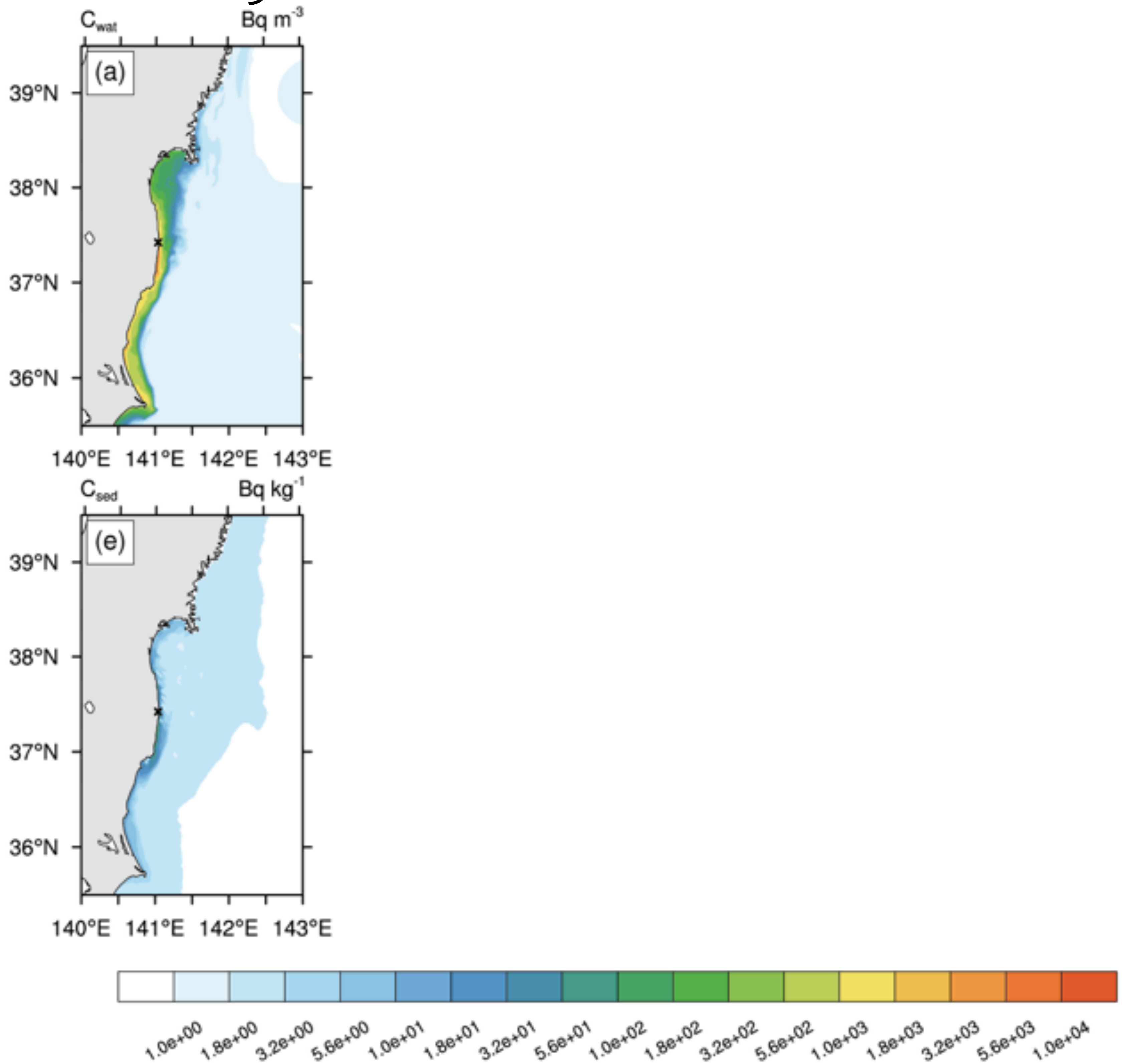


# EXT case

Mar. 25

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

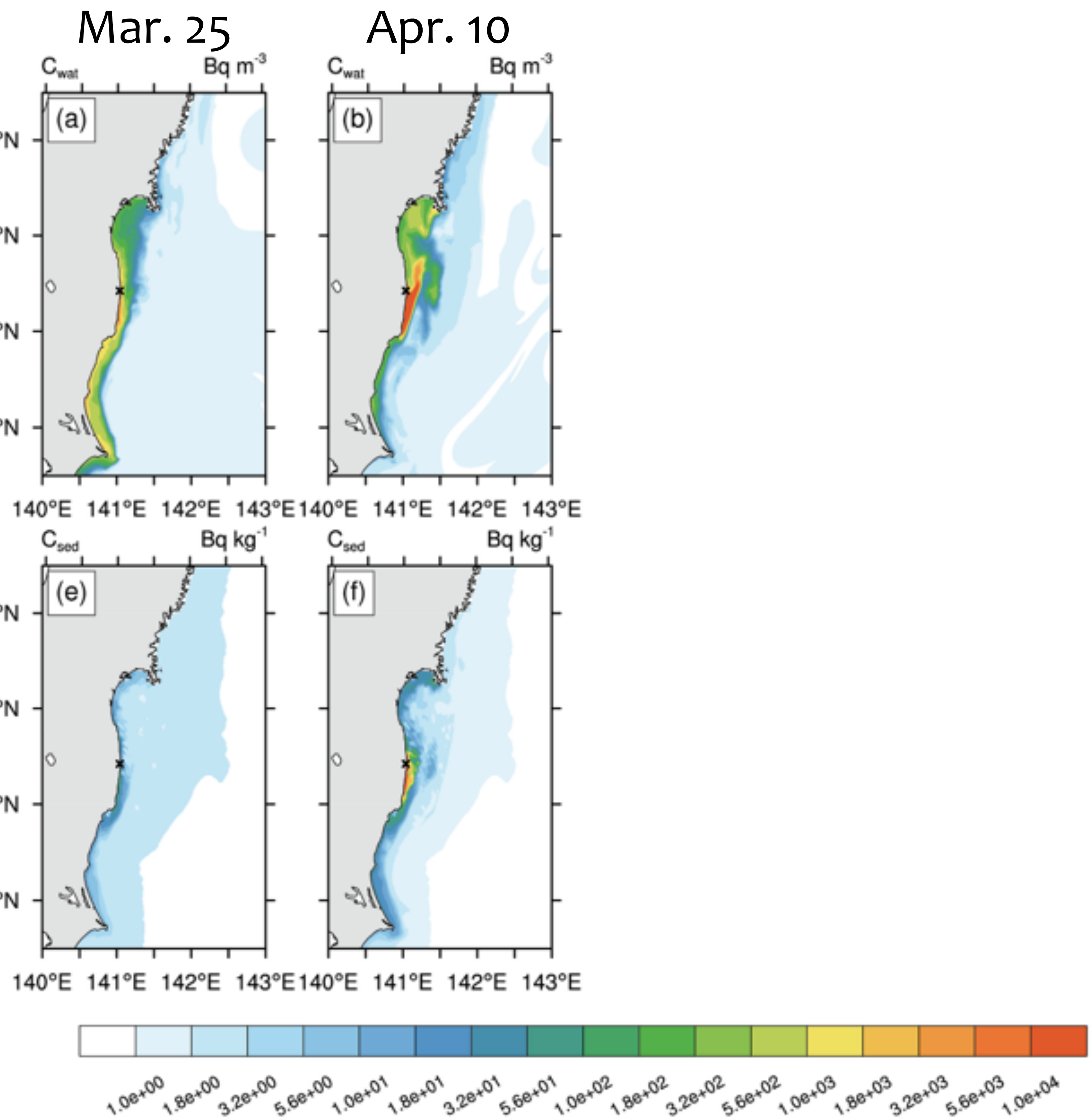
Sediment
(Bq kg$^{-1}$)



# EXT case

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

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



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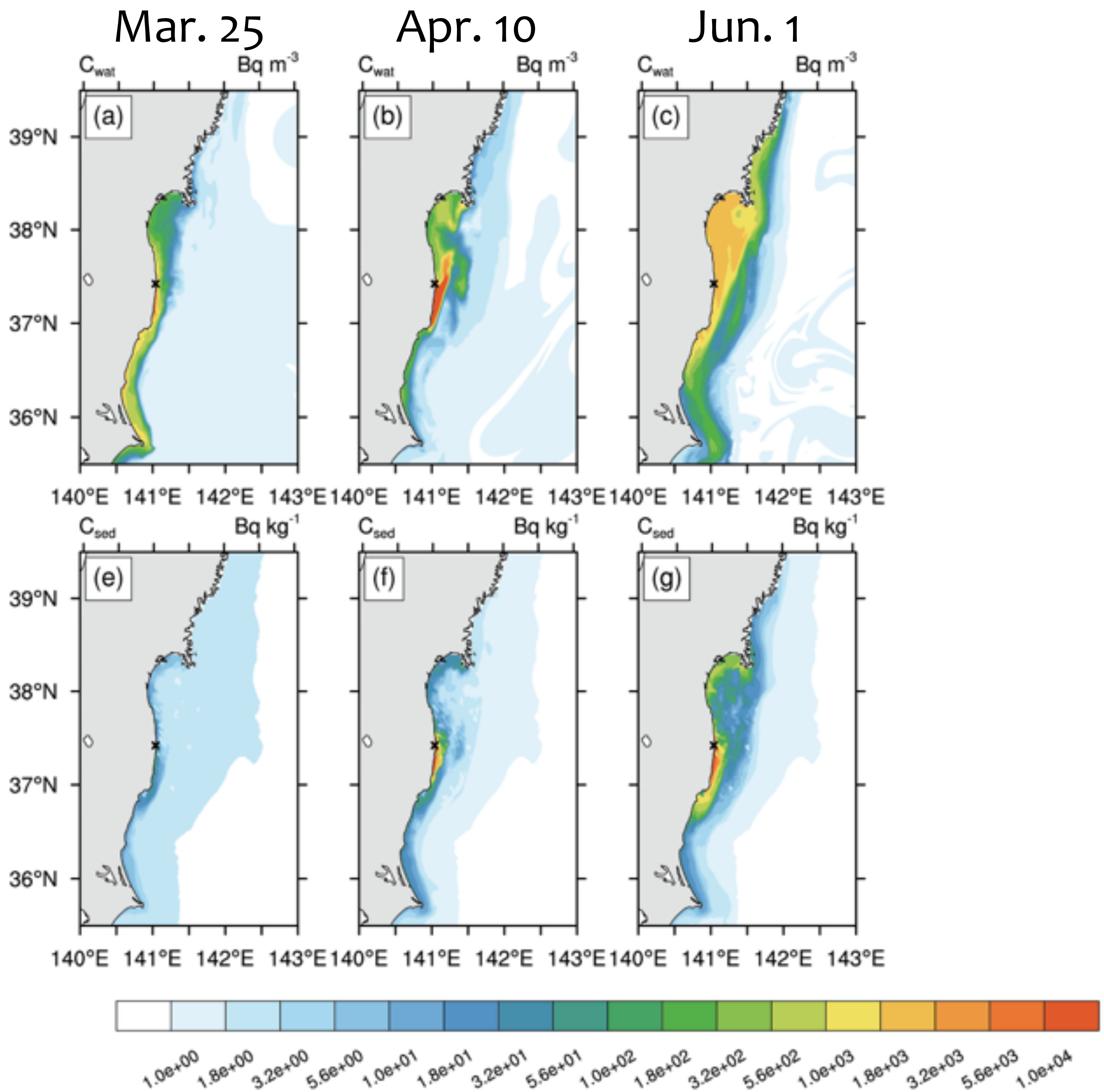
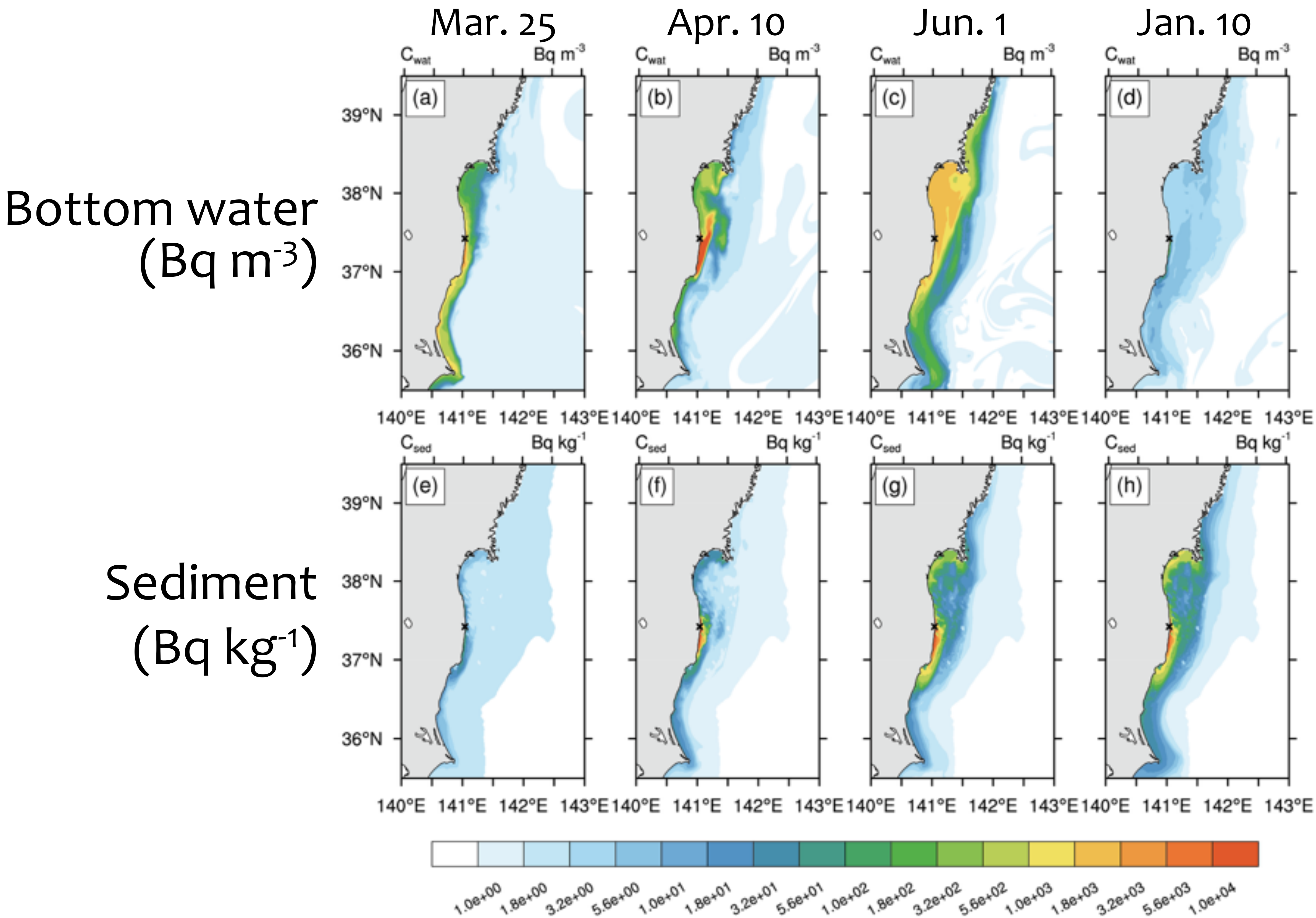
Sediment ($Bq\ kg^{-1}$)

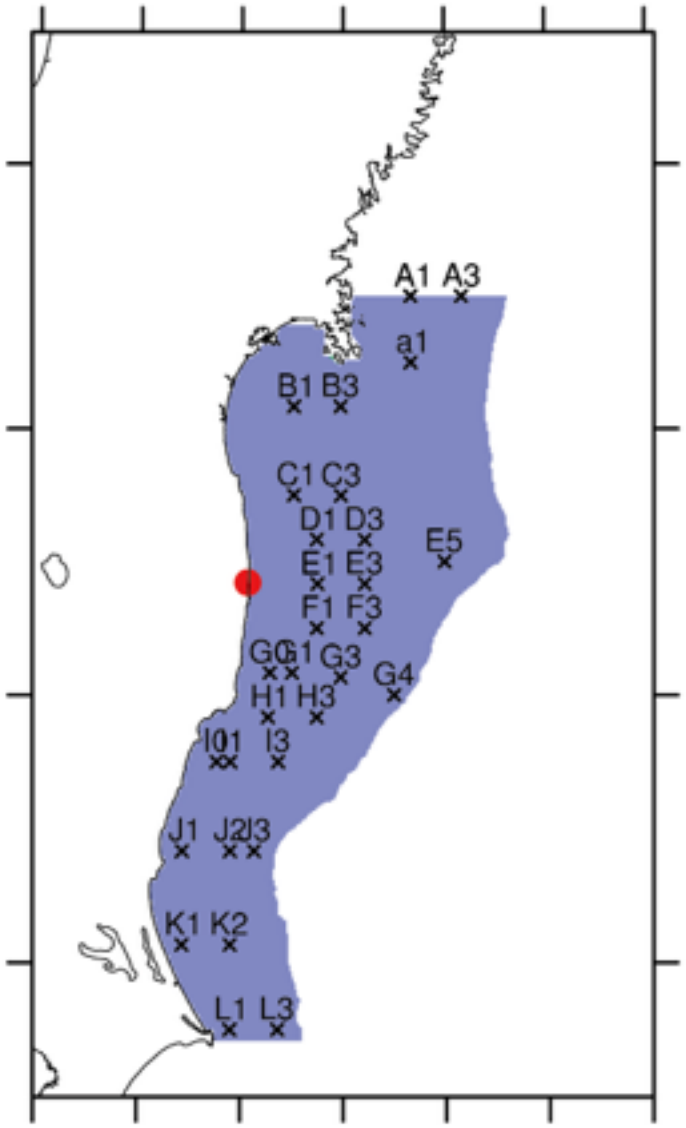


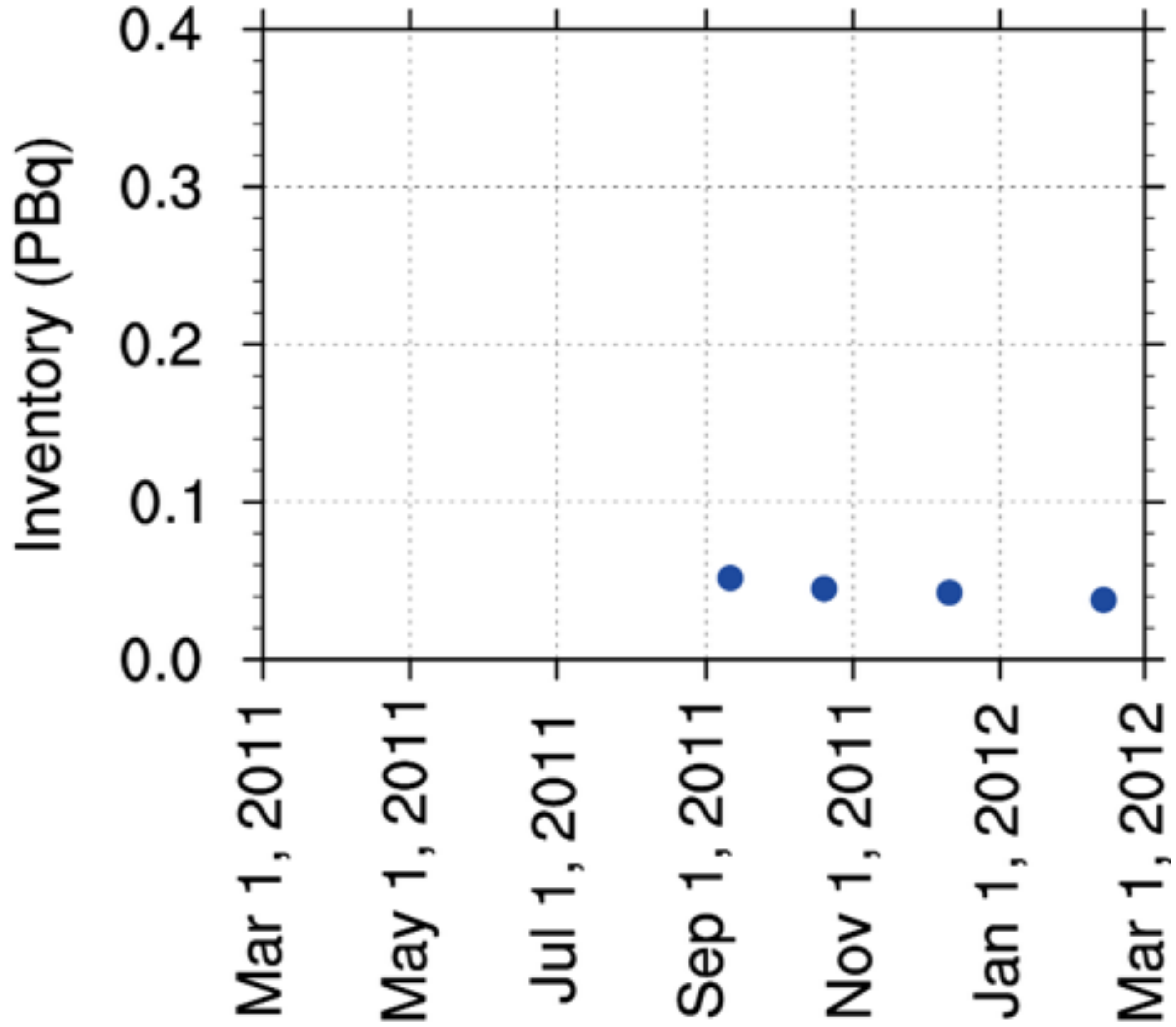
# EXT case


Mar. 25
Apr. 10
Jun. 1
Jan. 10
Bottom water (Bq m-3)
Sediment (Bq kg-1)
C_wat Bq m-3
C_sed Bq kg-1
(a) (b) (c) (d) (e) (f) (g) (h)
39°N 38°N 37°N 36°N
140°E 141°E 142°E 143°E
1.0e+00 1.8e+00 3.2e+00 5.6e+00 1.0e+01 1.8e+01 3.2e+01 5.6e+01 1.0e+02 1.8e+02 3.2e+02 5.6e+02 1.0e+03 1.8e+03 3.2e+03 5.6e+03 1.0e+04

# EXT case

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



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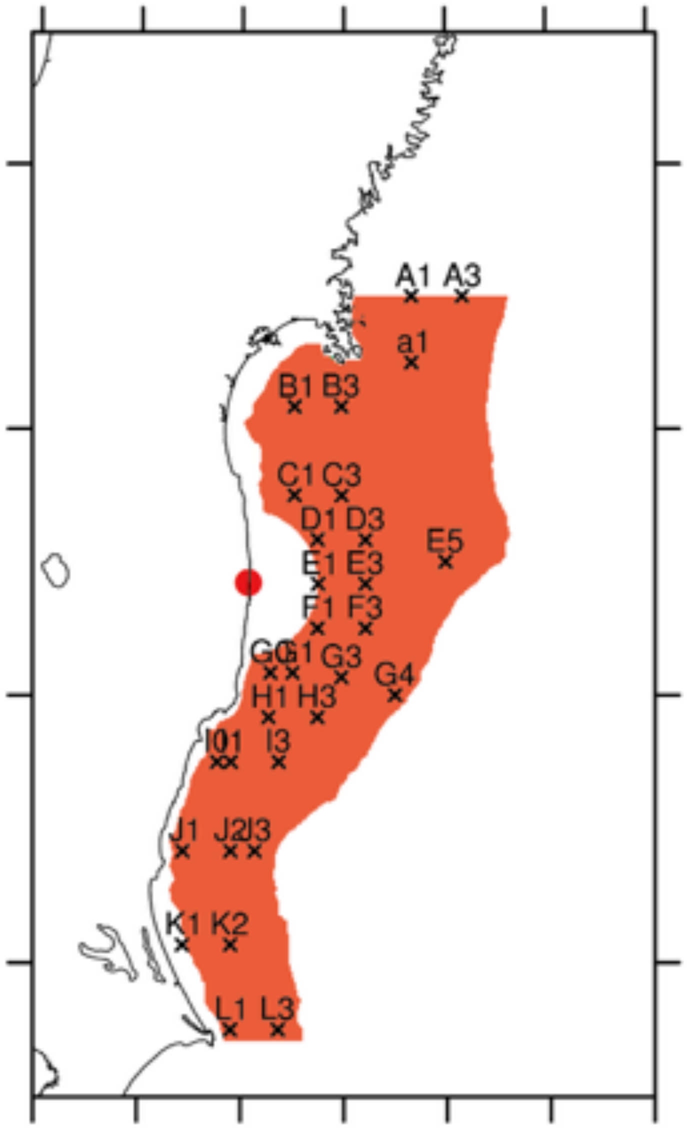


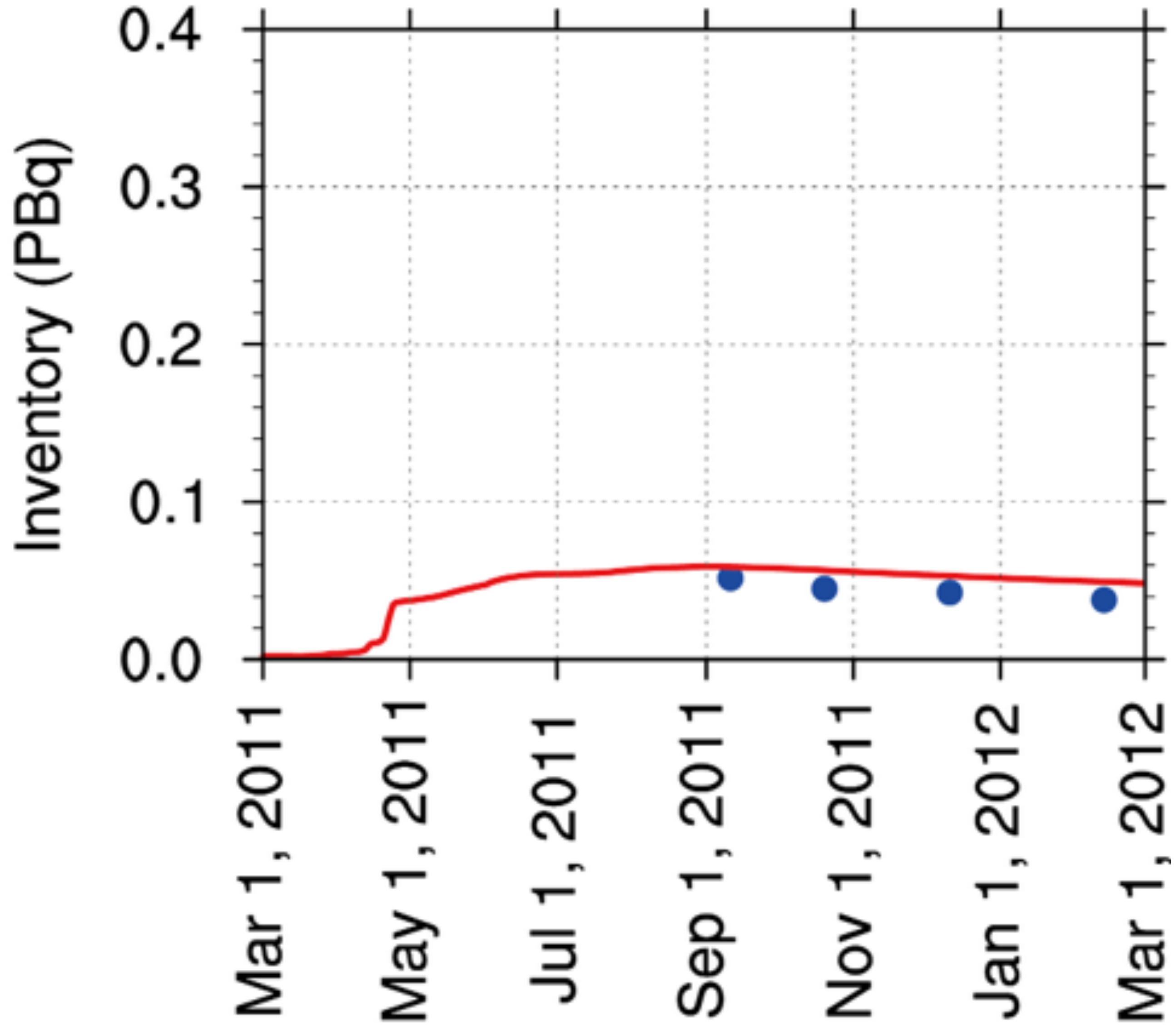

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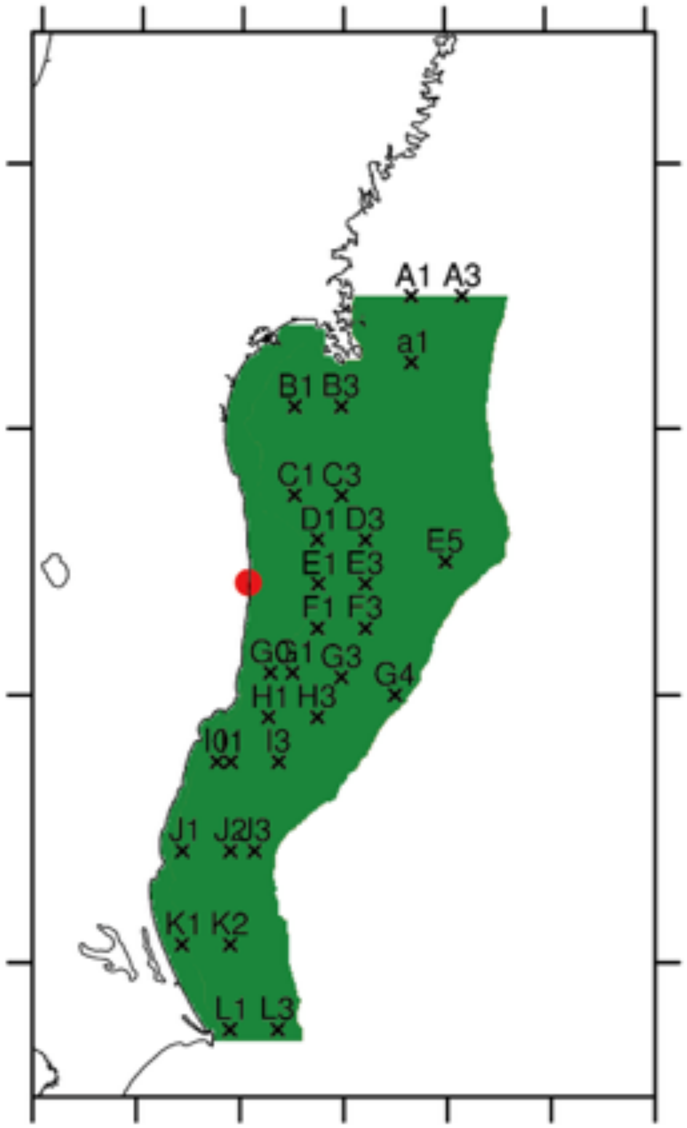


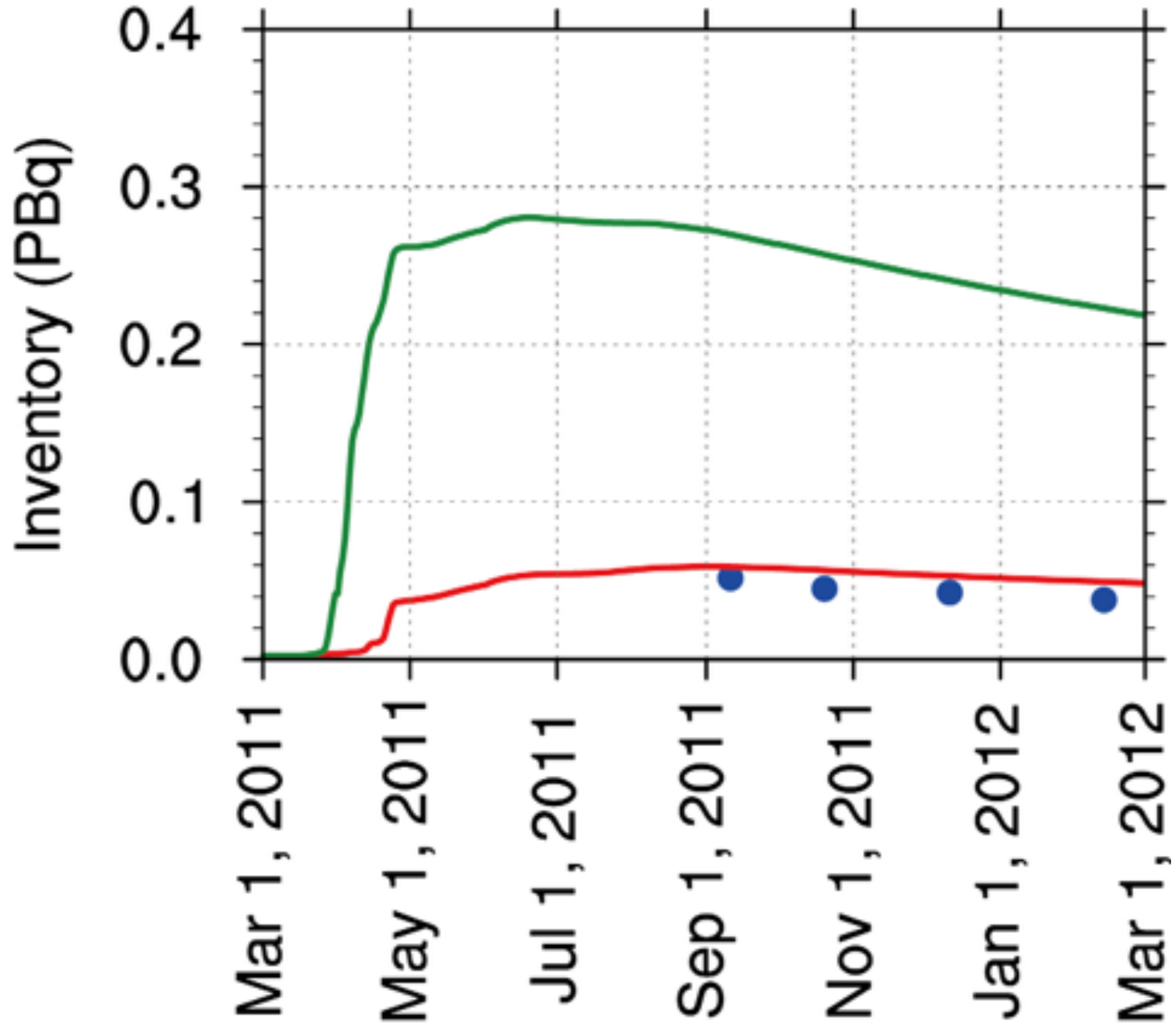

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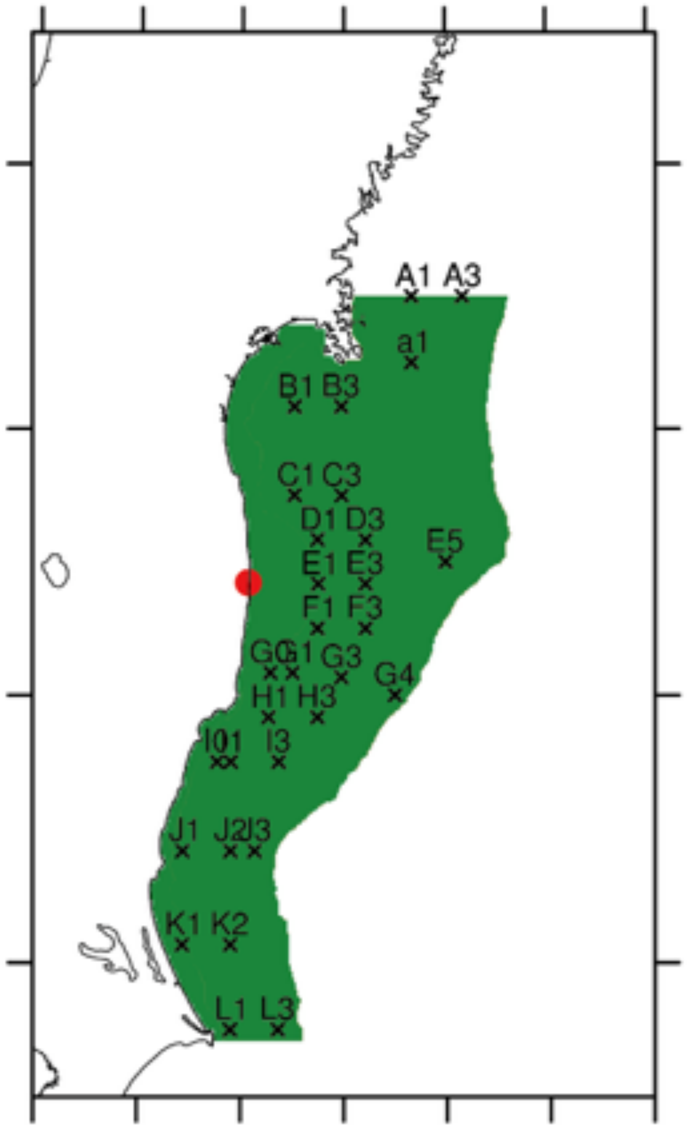


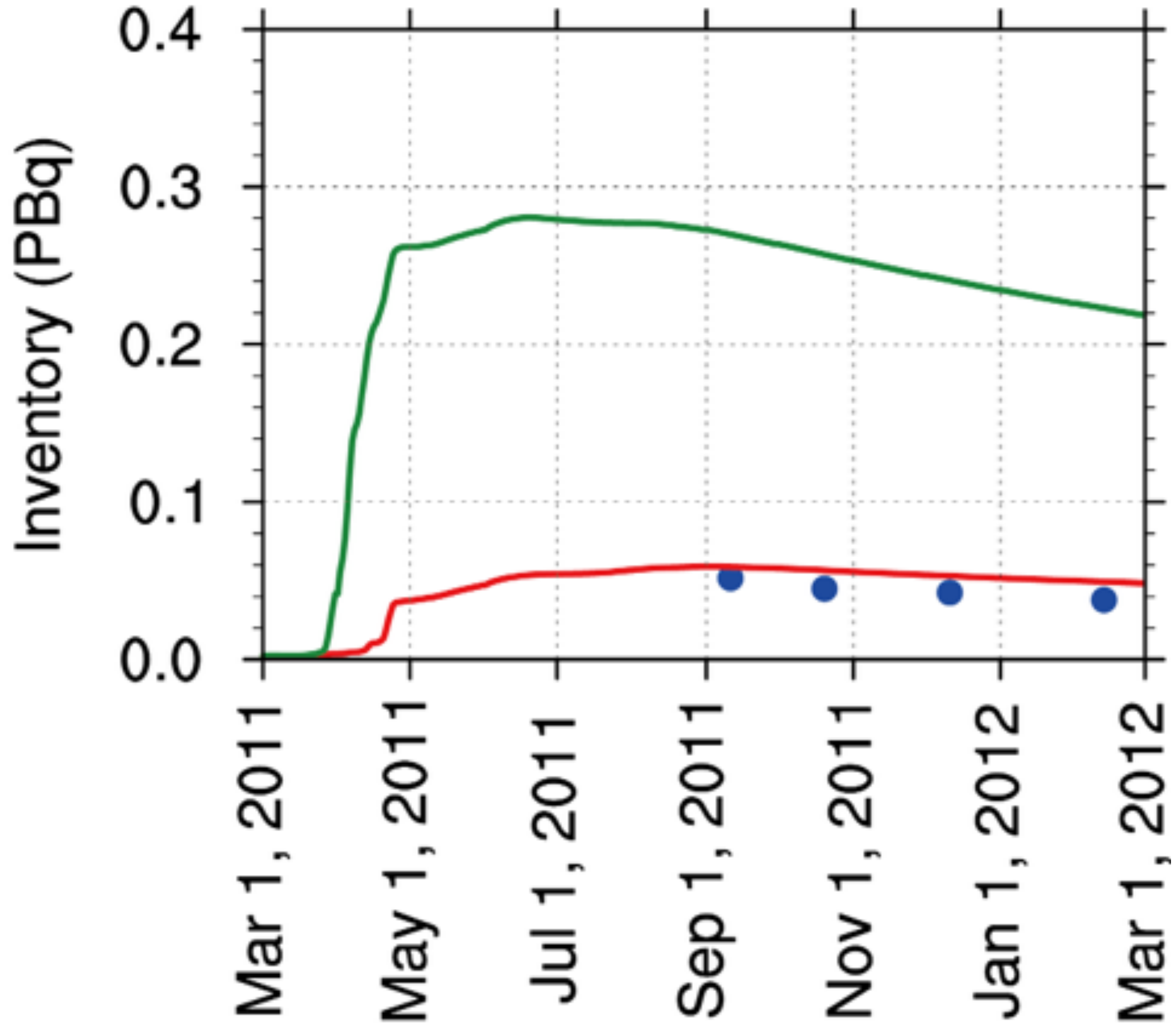


The total inventory of $^{137}Cs$ in sediments off the Fukushima coast is **O(0.1) PBq**.

# 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)