^{134}Cs and ^{137}Cs in the North Pacific Ocean derived from the TEPCO Fukushima Dai-ichi Nuclear Power Plant accident, Japan in March 2011: Transport processes and estimation of ^{134}Cs and ^{137}Cs inventories

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Research team

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Objectives

- To describe long term behavior of TEPCO FNPP1 released radiocaesium in the coastal region and the North Pacific Ocean based on the observations and model simulations during the period from just after the accident to July 2015.
- To estimate total amount of radiocaesium and other radionuclides released from TEPCO Fukushima NPP1 accident including atmospheric release and direct discharge to the ocean based on observations on land and ocean and model simulations. The obtained numbers should be verified by the facts.

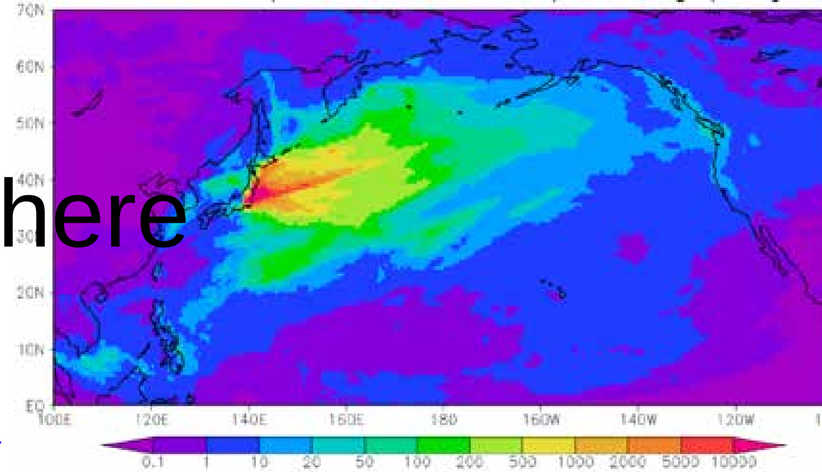
Talk outlines

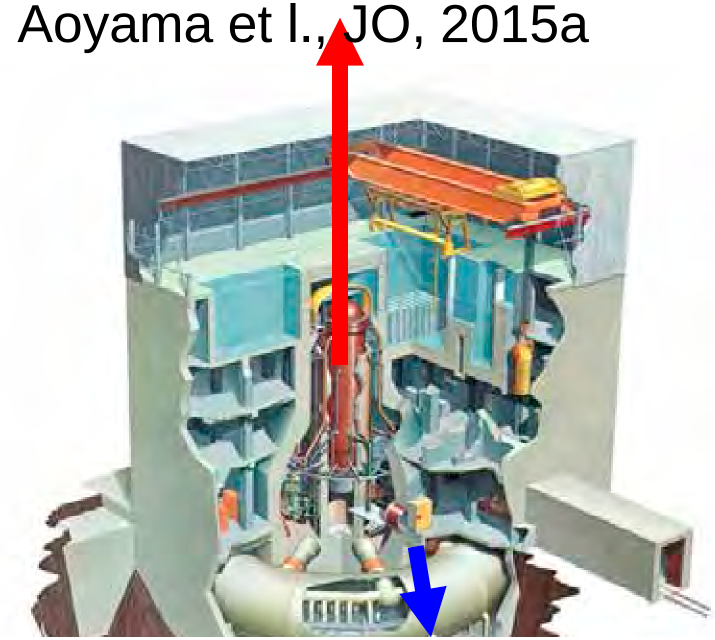
- Ultra low background measurement
- Fallout history since 1945 and 3-D distribution of ^{137}Cs before Fukushima accident in the Pacific Ocean
- Distribution of Fukushima radiocaesium by observations and model simulations
- Estimation of total amount of released radiocaesium to the atmosphere and the ocean
- Conclusions

^{137}Cs mass balance

14–17 PBq to the atmosphere

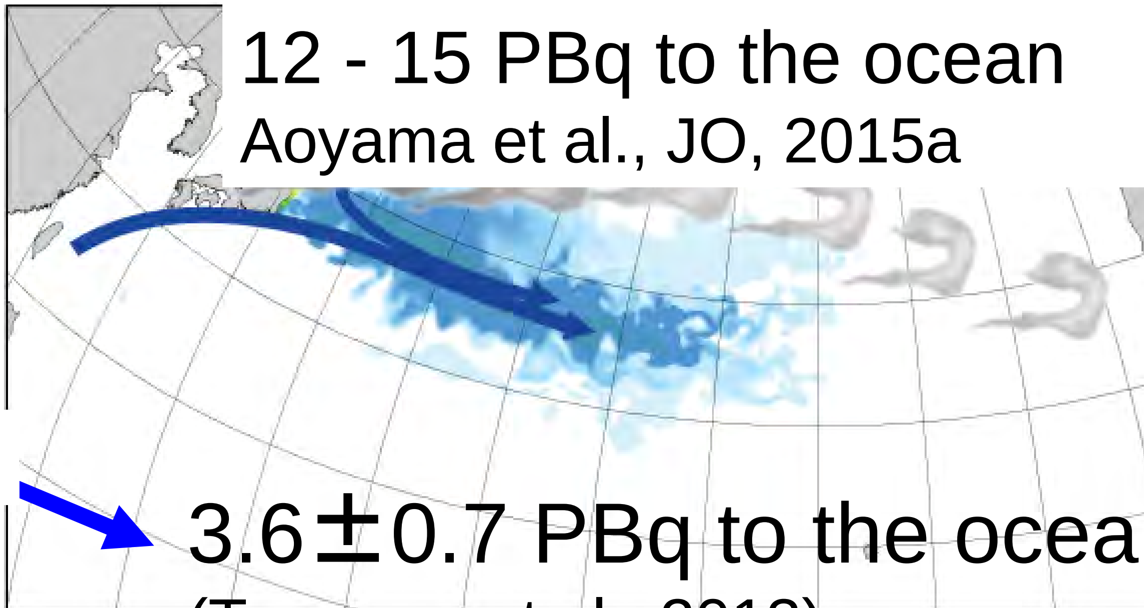
Aoyama et l., JO, 2015a





12 - 15 PBq to the ocean

Aoyama et al., JO, 2015a



140 PBq in stagnant water

Boiling Water Reactor Systems "Nuclear Reactor Concepts" Workshop Manual, U.S. NRC

3.6±0.7 PBq to the ocea

(Tsumune et al., 2013)

700 PBq was in the three core

(Nishihara et al.,, 2011)

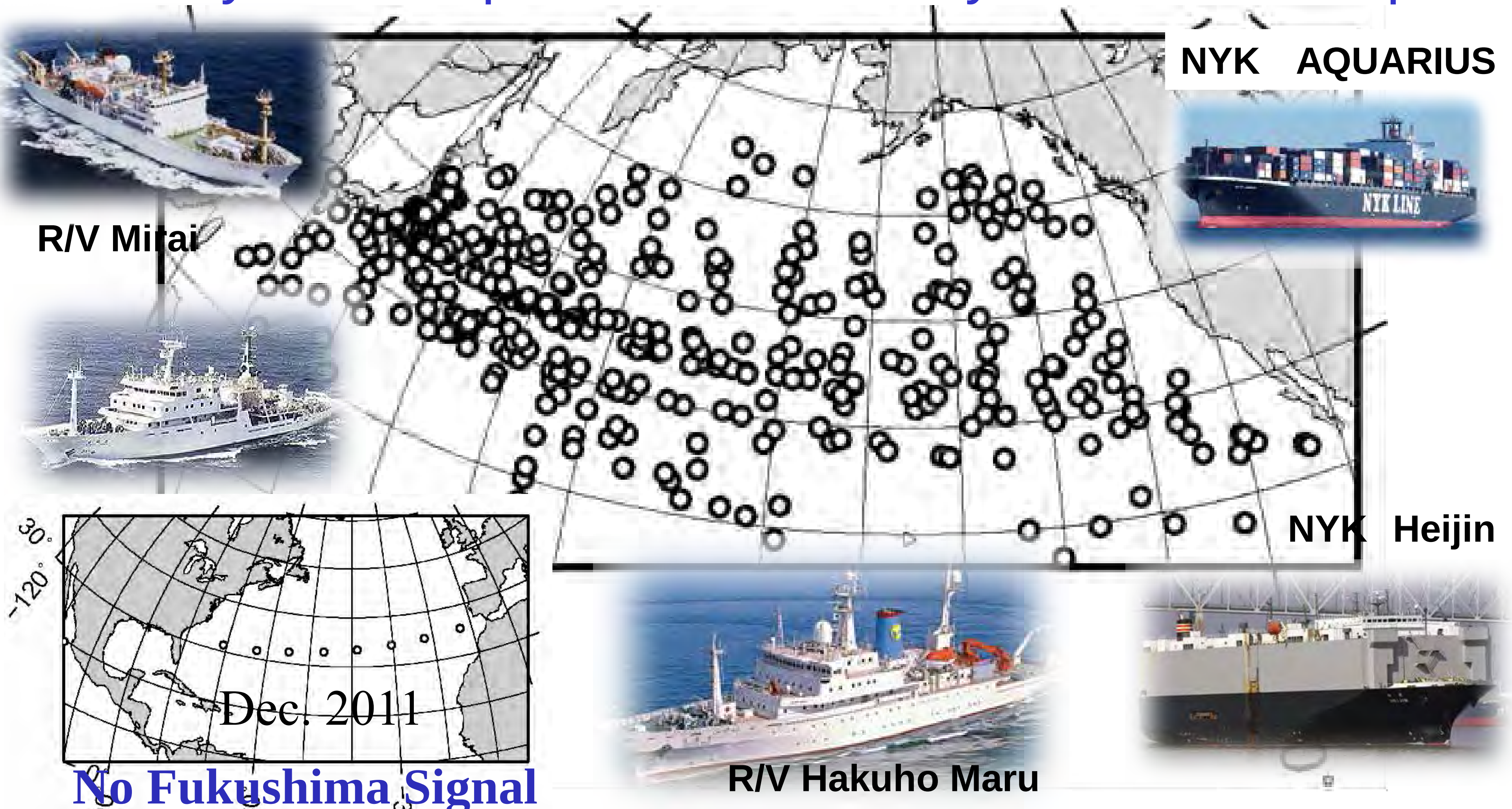
230 PBq recovered

TEPCO unpublished data

440 Sampling locations during the period from March 2011 to Dec 2012 for surface water. 2 liter samples => (1 mBq in the sample) low level techniques necessary because

Area 13×10^6 km^2、depth100 m, volume 1.3×10^{15} m^3

If activity is 0.5 Bq m^{-3}, total inventory will be 0.7 PBq



Two underground laboratories No. 1 in Japan

Ogoya underground laboratory
(Kanazawa University)
Y. Hahajima

11 of 18 Ge detectors were used

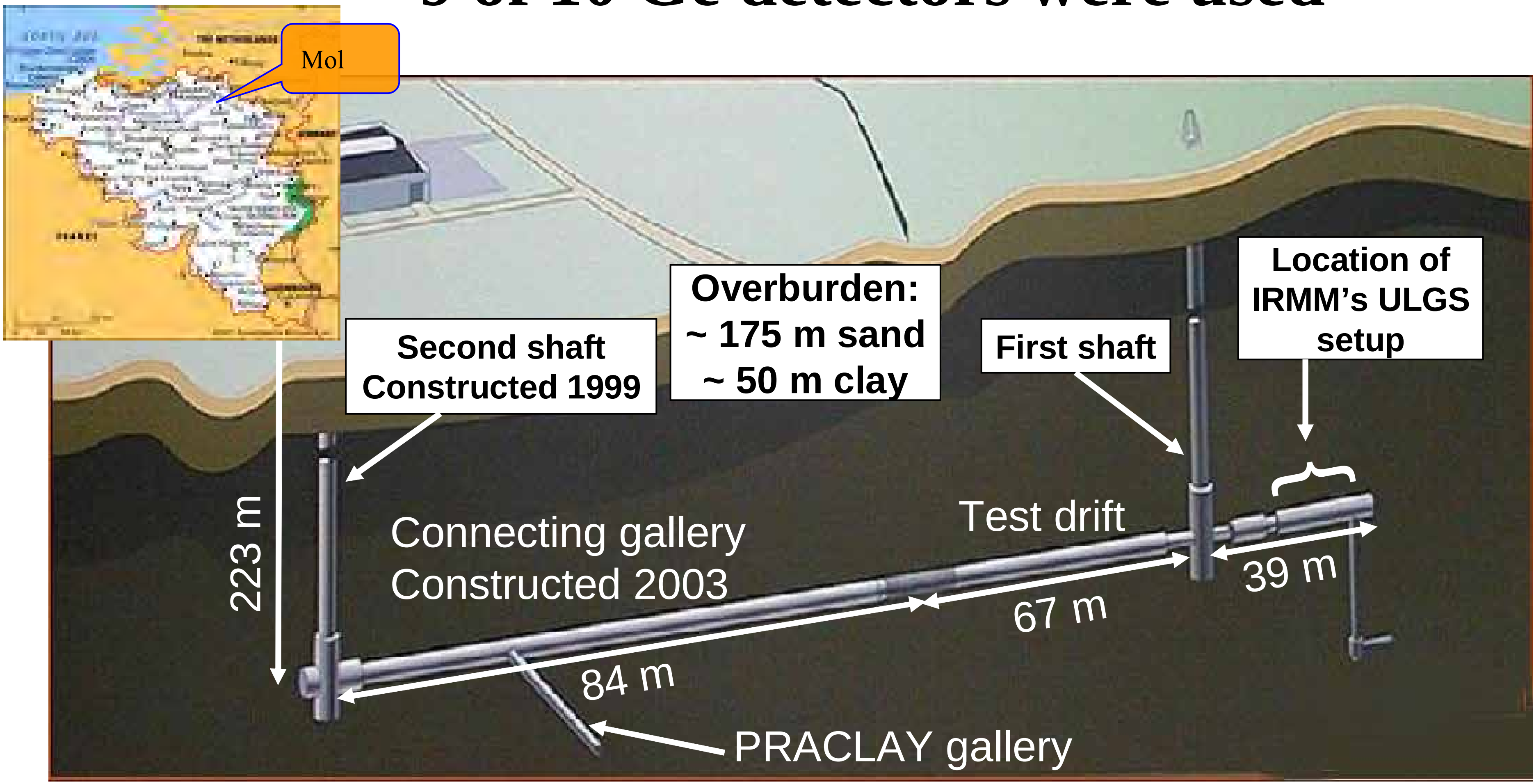
Located inside a tunnel – a former Cu-mine
Covered by 135 m rock

Shields from old lead from Kanazawa castle

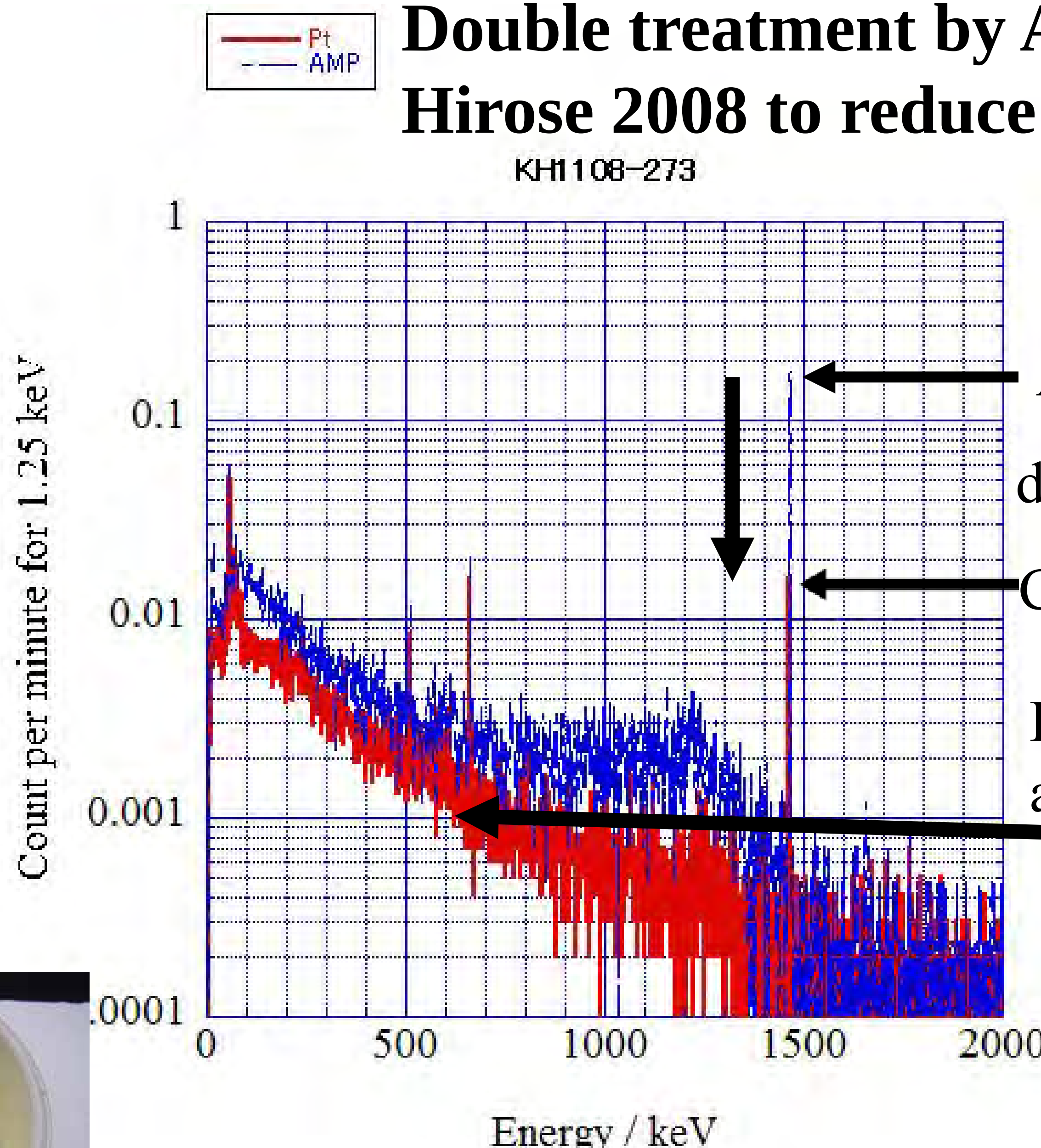
Two underground laboratories No. 2 in the EU

HADES underground laboratory
(EC-JRC-IRMM, located at the premises of SCK in Mol, Belgium)
M. Hult

9 of 10 Ge detectors were used



Double treatment by Aoyama and Hirose 2008 to reduce ^{40}K

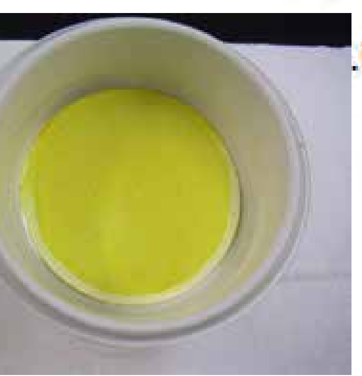


AMP/Cs compound

decrease 40K content

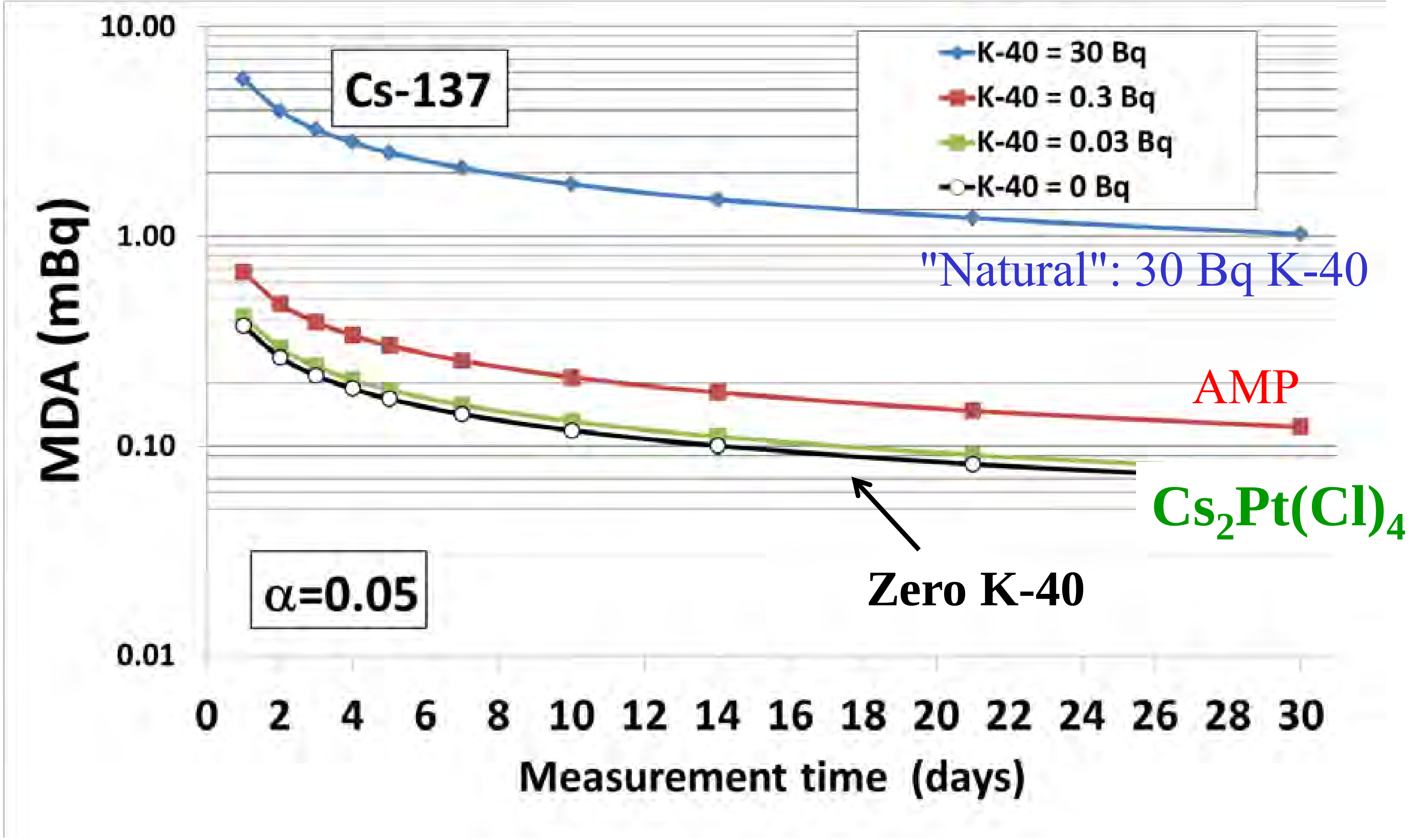
Cs2Pt(Cl)4 precipitate

Decrease compton as expected



<- AMP/Cs compound

$Cs_2Pt(Cl)_4$ precipitate ->



Detection limits (MDA) for ^{137}Cs in a **<u>4-g sea water precipitate sample</u>,** measured in a 2-kg well-detector (Ge-12 in HADES), as a function of measurement time for different activities of ^{40}K in the sample.

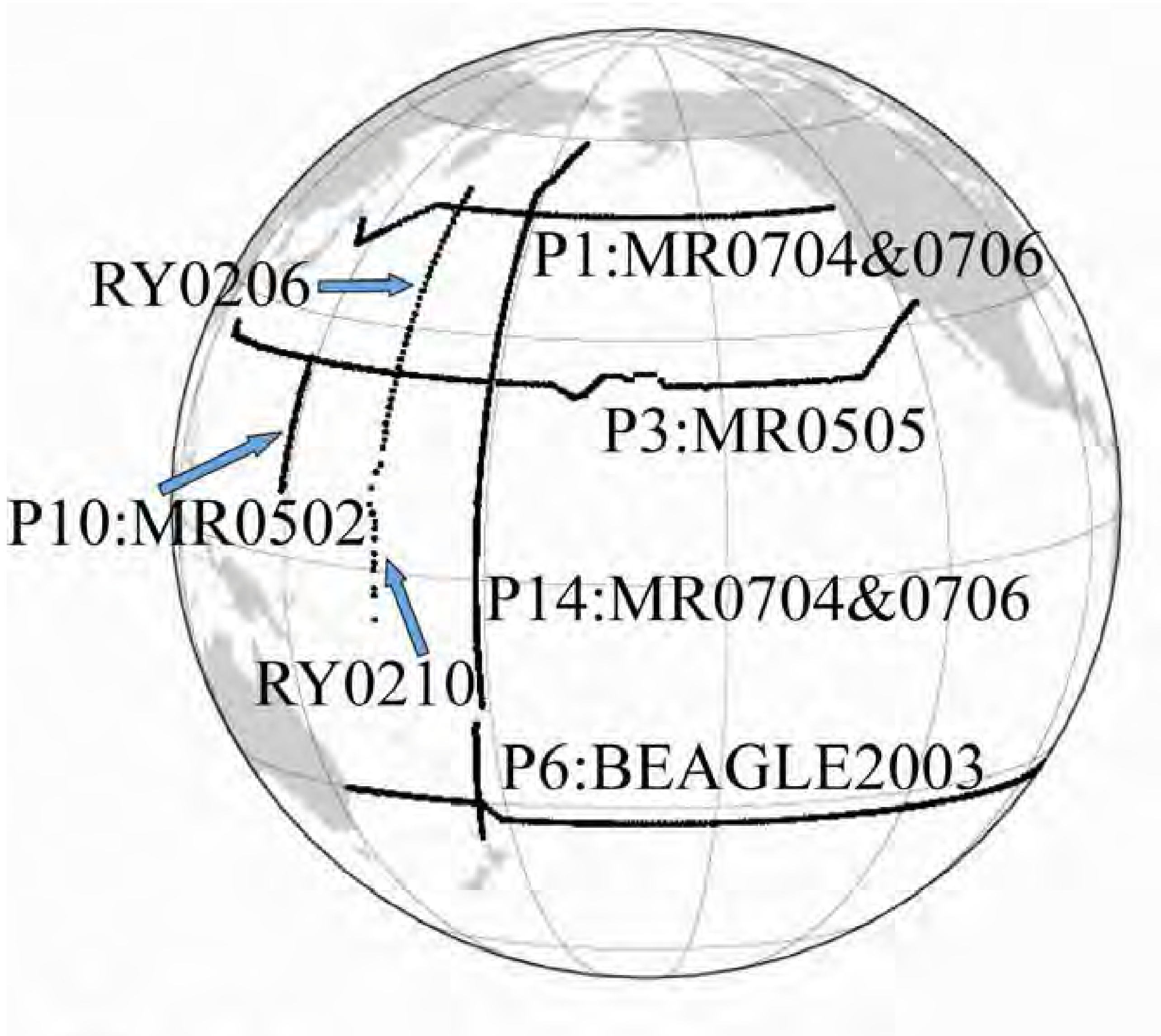
Ca. 0.1 mBq of ^{137}Cs can be measured

Lutter et al., NUKLEONIKA 2015

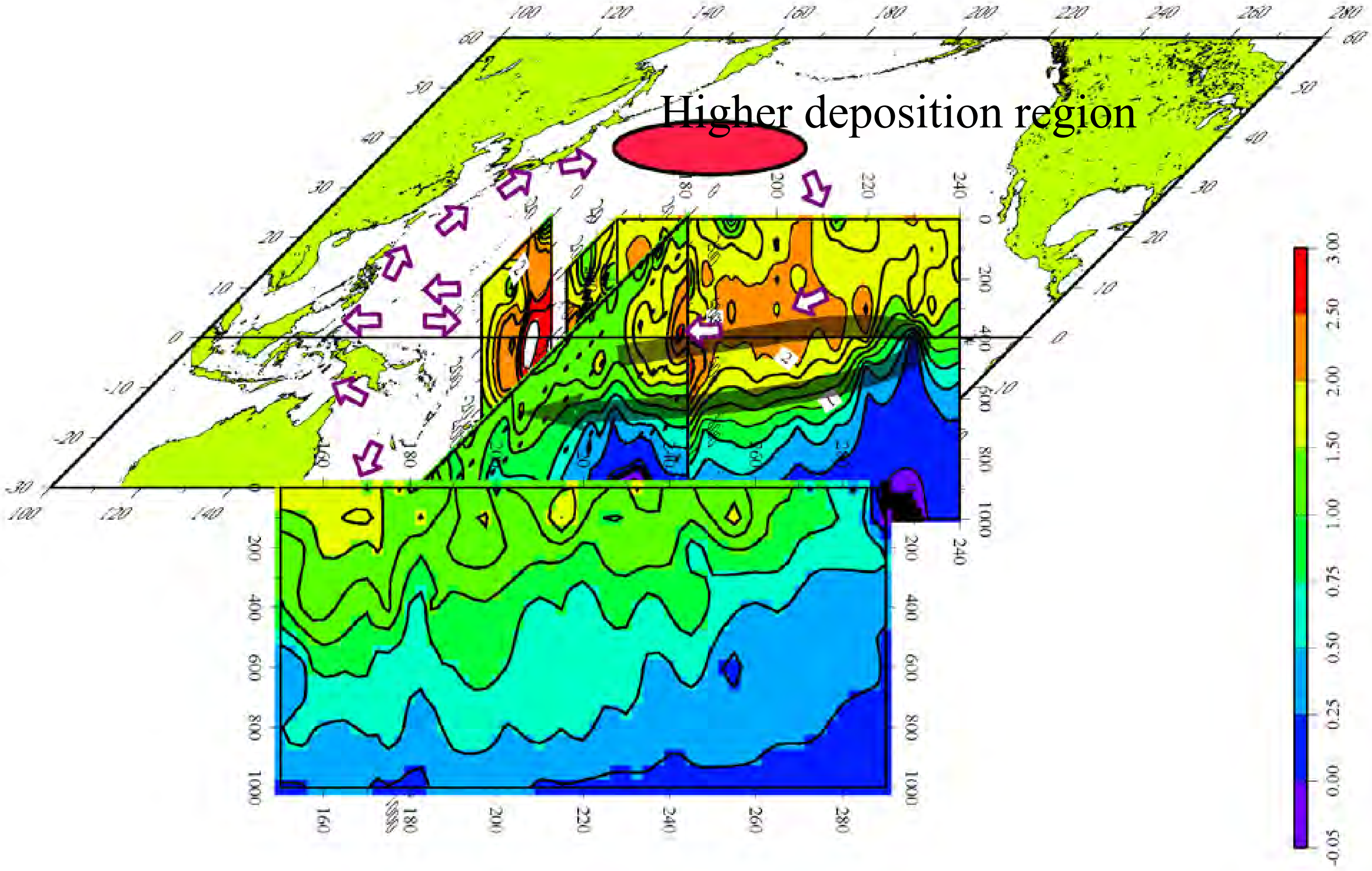
samples and range of ^{137}Cs activities

- Surface seawater 2 liters 1 mBq 1 Bq
- Subsurface seawater 10 liters 1 mBq 0.1 Bq
- Deep seawater 100-200 liters 1 mBq 5 mBq
- Particles 10 mg 100 mg 0.1 mBq 5 mBq
- Contents in the stomach of fish 0.1 mBq 1 mBq

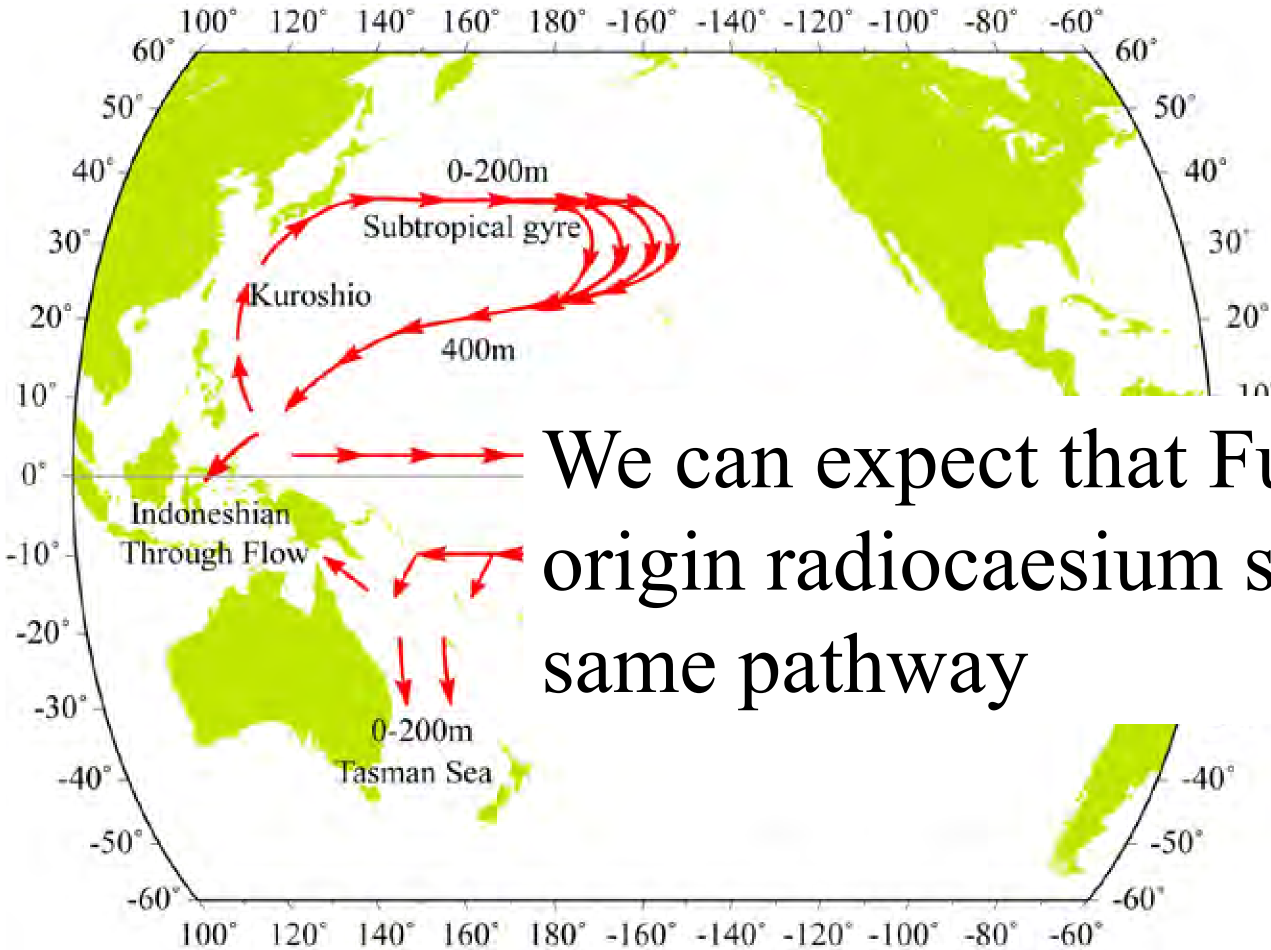
Observations in the Pacific Ocean from 2002 to 2007



3D distribution of ^{137}Cs in the Pacific Ocean based on 6 sections in 2000s: with movements



A pathway of weapons tests derived ^{137}Cs in the North Pacific Ocean, tracer of sea water movement

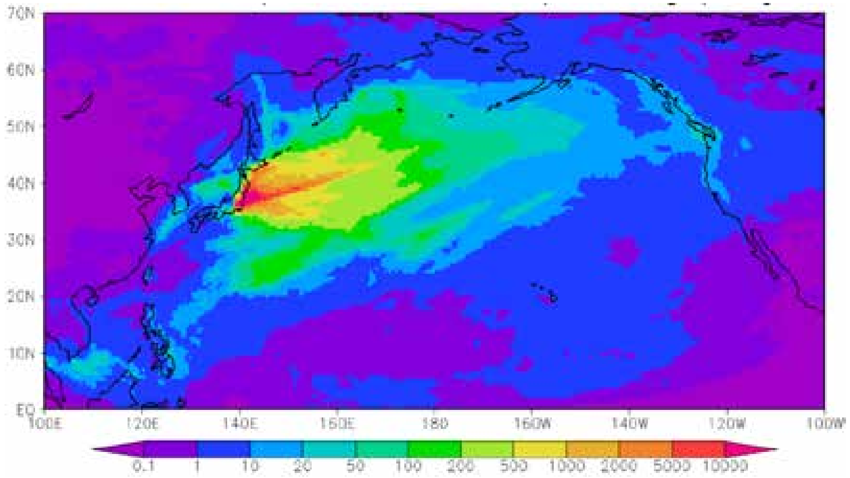


We can expect that Fukushima origin radiocaesium should go same pathway

Fig. S2 Possible pathway of ^{137}Cs in the Pacific Ocean based on 3-D observations of ^{137}Cs in 2000s (Aoyama et al., 2013)

Possible pathways to the Ocean

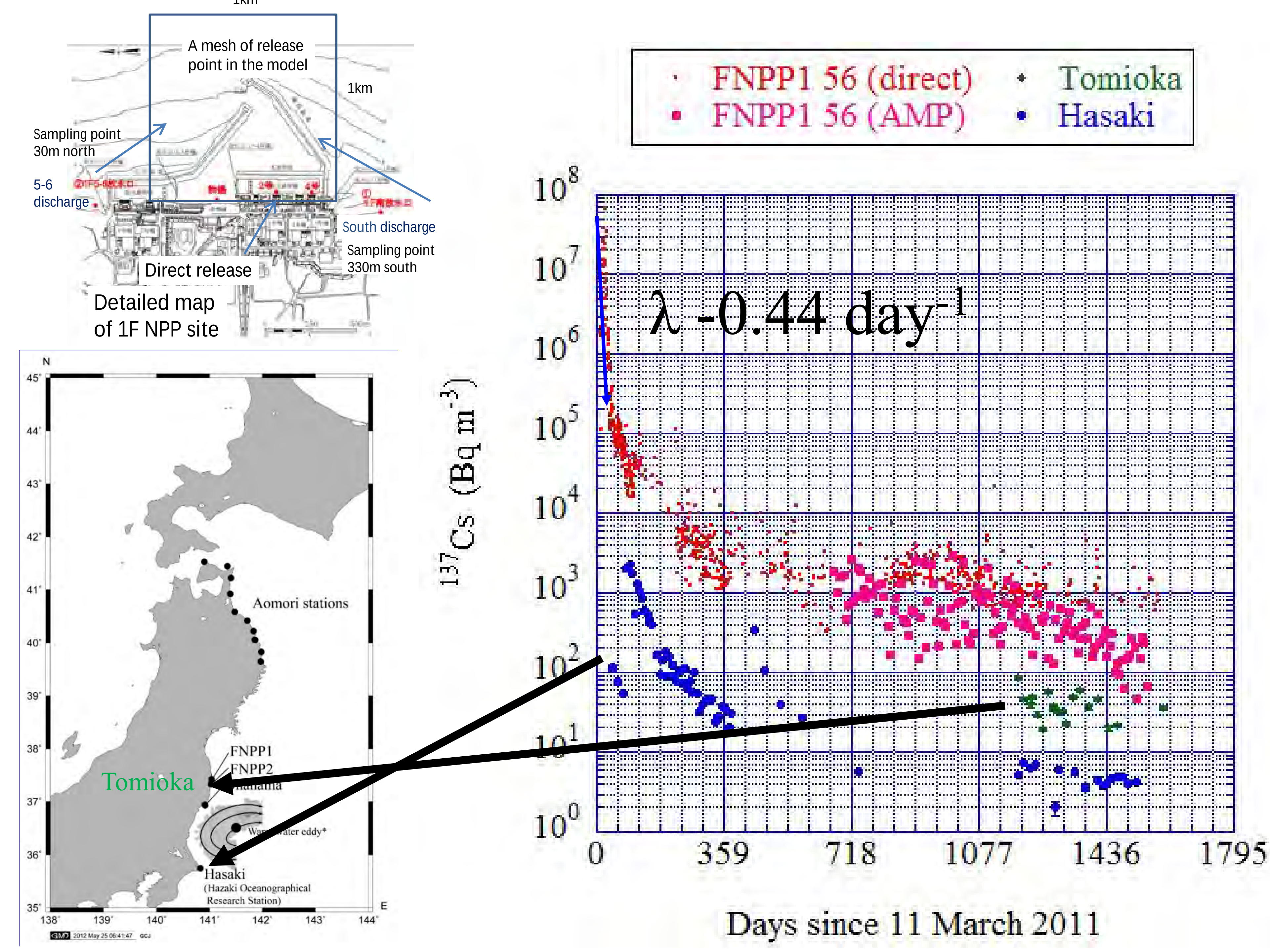
- Atmospheric deposition
- Direct release
- Groundwater discharge
- Freshwater runoff from the 1F NPP site
- River runoff (initial stage)
- Planned release of low-level waste water

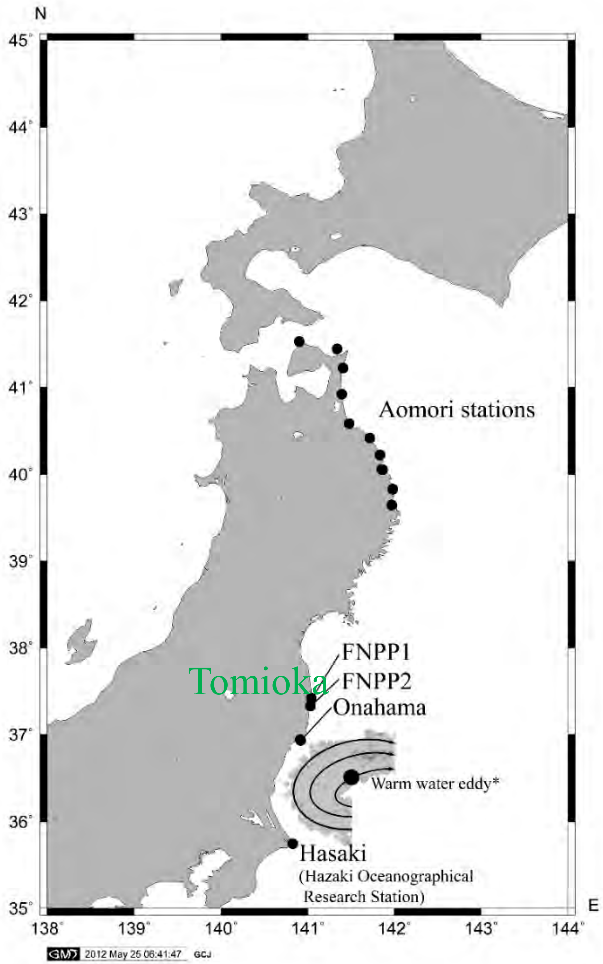


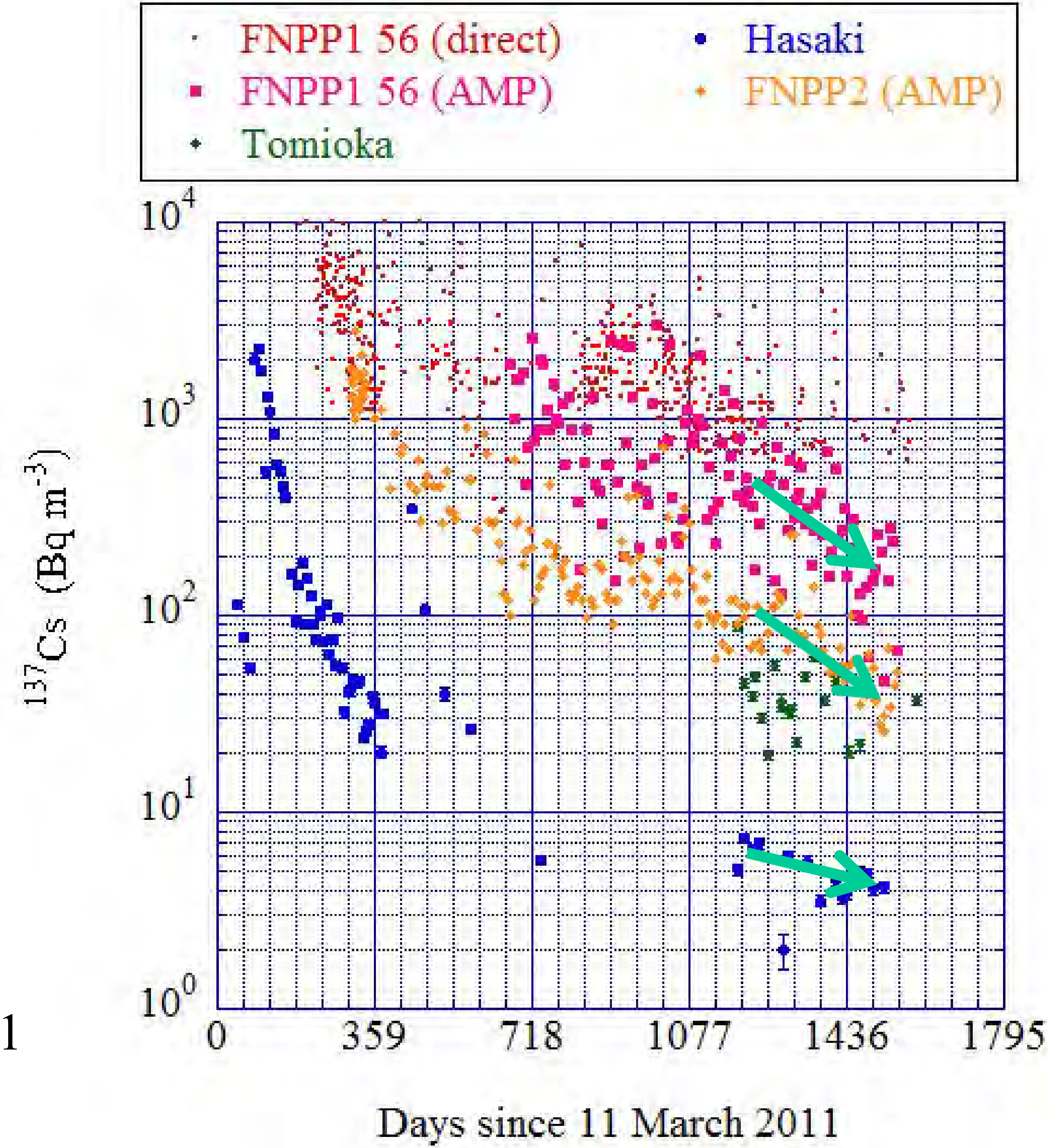
Simulated atmospheric deposition of ^{137}Cs ($Bq\ m^{-2}$) (by Masingar II of MRI) (Aoyama et al., JO, 2015a)

^{137}Cs : 1.8E+12 Bq/m^3

TEPCO Press release


1km
A mesh of release point in the model
1km
Sampling point 30m north
5-6 discharge
South discharge
Sampling point 330m south
Direct release
Detailed map of 1F NPP site
Aomori stations
FNPP1
FNPP2
Tomioka
Hasaki
(Hazaki Oceanographical Research Station)
FNPP1 56 (direct)
FNPP1 56 (AMP)
Tomioka
Hasaki
λ -0.44 day-1
137Cs (Bq m-3)
Days since 11 March 2011





Flux from FNPP1
2013 30 GBq day-1
2014 10 GBq day-1
2015 a few GBq day-1

Radiocaesium in surface water in April-May 2011

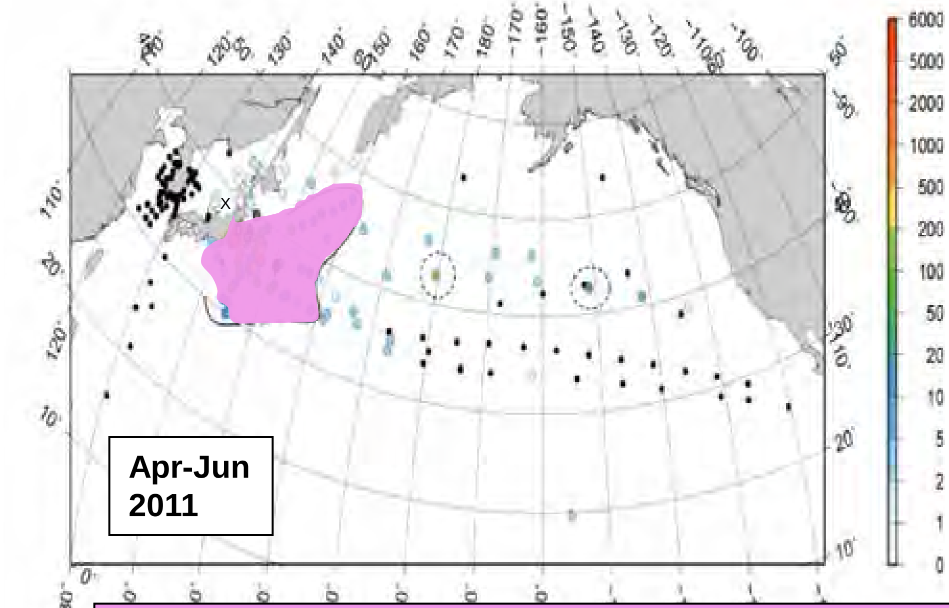
Station	Depth dbar	Latitude	Longitude	Date	^{134}Cs Bq m^{-3}	^{137}Cs Bq m^{-3}
NYK11-043	0	34.95°N	143.86°E	20110331	135 ± 10	150 ± 8
NYK11-001	0	35.68°N	143.77°E	20110401	507 ± 33	546 ± 28
NYK11-003	0	36.60°N	147.60°E	20110401	1000 ± 71	1080 ± 60
NYK11-044	0	35.07°N	146.44°E	20110401	34 ± 2.6	36.8 ± 2.1
NYK11-007	0	38.18°N	154.97°E	20110402	17.7 ± 1.6	21.5 ± 1.3
NY						
NY						
NY						
NY						
NY						
NY						
NY						
NY						
NY						
NY						
NY						
NYK11-091						
NYK11-092	0	35.32°N	161.70°E	20110405	3.4 ± 0.6	5.3 ± 0.4
NYK11-095	0	36.35°N	178.99°E	20110406	1.1 ± 0.6	2.4 ± 0.4
NYK11-021	0	41.12°N	167.75°W	20110407	ND	1.8 ± 0.2
NYK11-023	0	42.33°N	159.88°W	20110408	0.6 ± 0.3	1.9 ± 0.2
NYK11-025	0	43.00°N	151.95°W	20110409	ND	1.8 ± 0.2
NYK11-055	0	33.46°N	154.15°W	20110409	ND	1.4 ± 0.2
NYK11-098	0	36.84°N	163.23°W	20110409	ND	1.9 ± 0.2
NYK11-027	0	43.62°N	143.57°W	20110410	0.7 ± 0.3	2.3 ± 0.2
NYK11-056	0	32.52°N	146.59°W	20110410	ND	1.8 ± 0.2
NYK11-100	0	35.88°N	151.92°W	20110410	ND	1.8 ± 0.2
NYK11-125	0	33.29°N	142.20°E	20110410	3.1 ± 0.6	3.5 ± 0.4
NYK11-029	0	38.18°N	134.97°W	20110411	ND	1.4 ± 0.2
NYK11-057	0	31.32°N	140.20°W	20110411	ND	1.9 ± 0.2
NYK11-101	0	34.97°N	146.43°W	20110411	ND	2 ± 0.2
NYK11-127	0	35.36°N	147.57°E	20110411	2.2 ± 0.5	3.3 ± 0.4
NYK11-102	0	33.92°N	141.12°W	20110412	ND	2 ± 0.2
NYK11-103	0	32.50°N	135.86°W	20110412	ND	1.8 ± 0.2
NYK11-129	0	39.01°N	152.70°E	20110412	1.9 ± 0.4	3.6 ± 0.3
NYK11-058	0	28.94°N	130.73°W	20110413	ND	1.6 ± 0.2

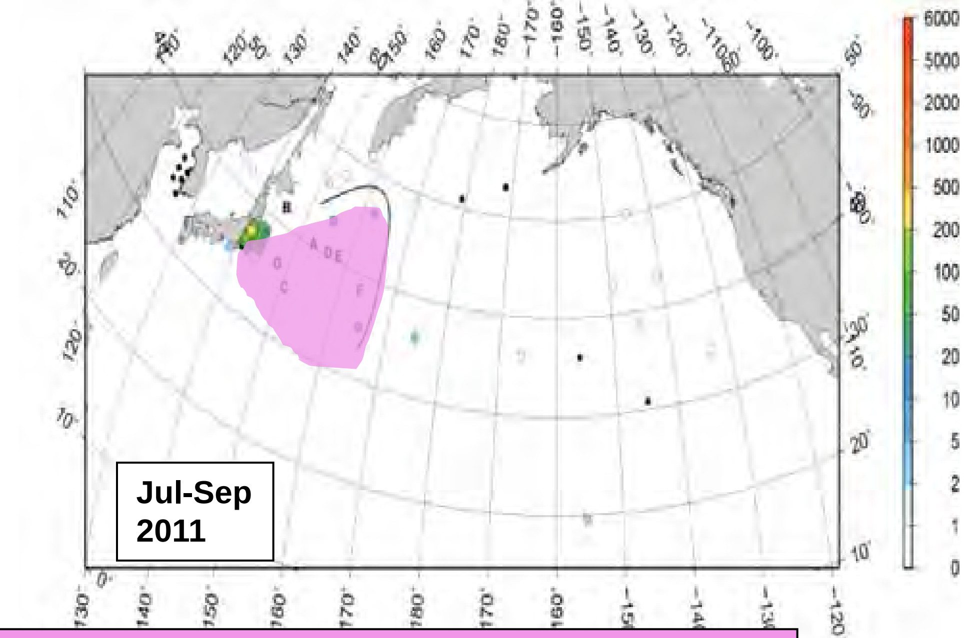
examples

Latitude	Longitude	Date	^{134}Cs Bq m^{-3}	^{137}Cs Bq m^{-3}
36.60°N	147.60°E	20110401	1000 ± 71	1080 ± 60
36.35°N	178.99°E	20110406	1.1 ± 0.6	2.4 ± 0.4
41.12°N	167.75°W	20110407	ND	1.8 ± 0.2

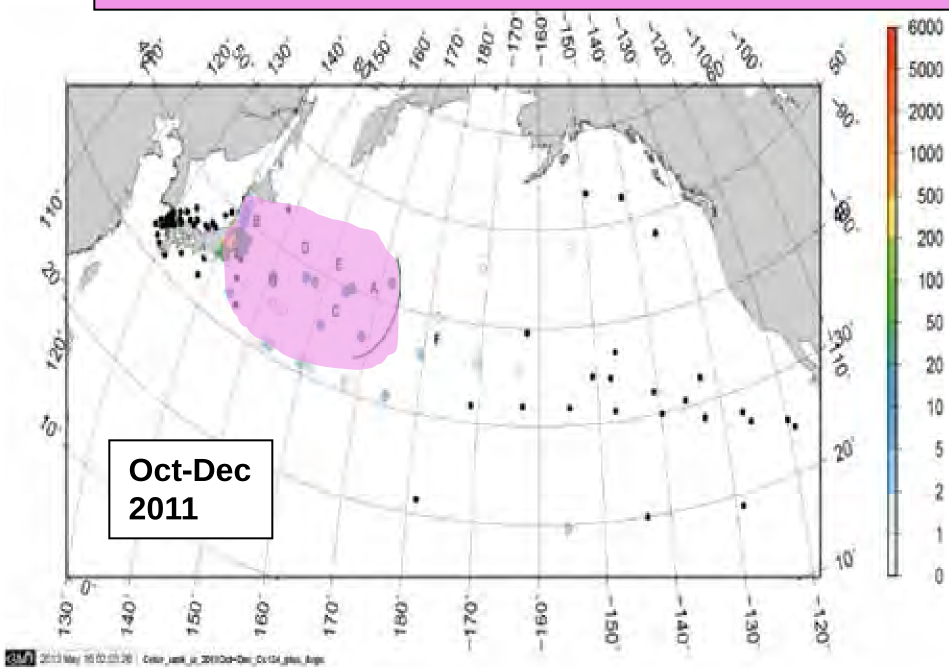
Fuksuhima Fukushima+ bomb

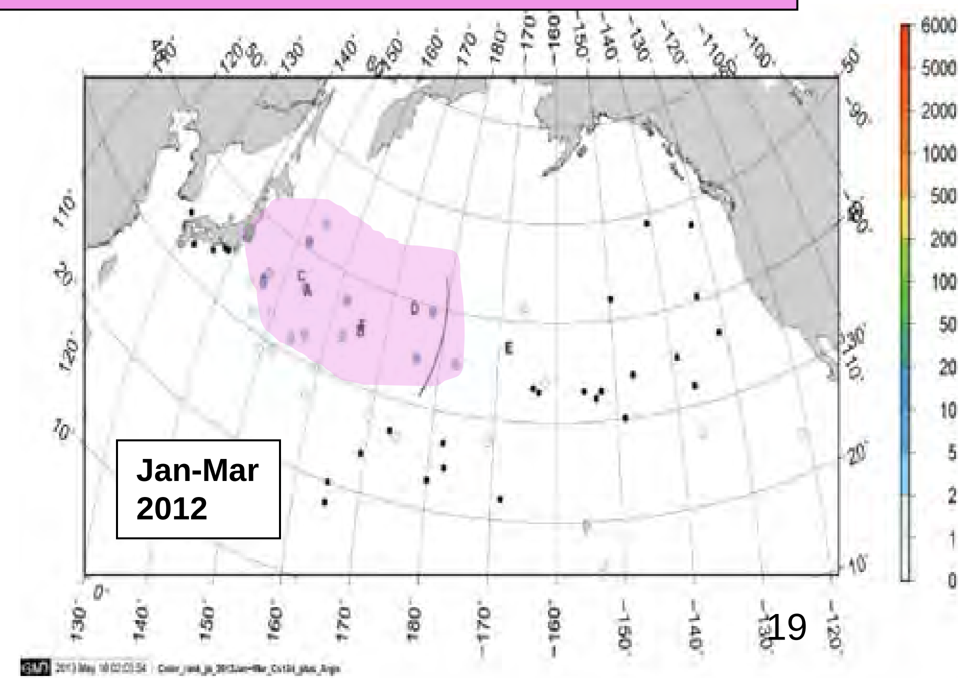
Aoyama et al., 2013 BG





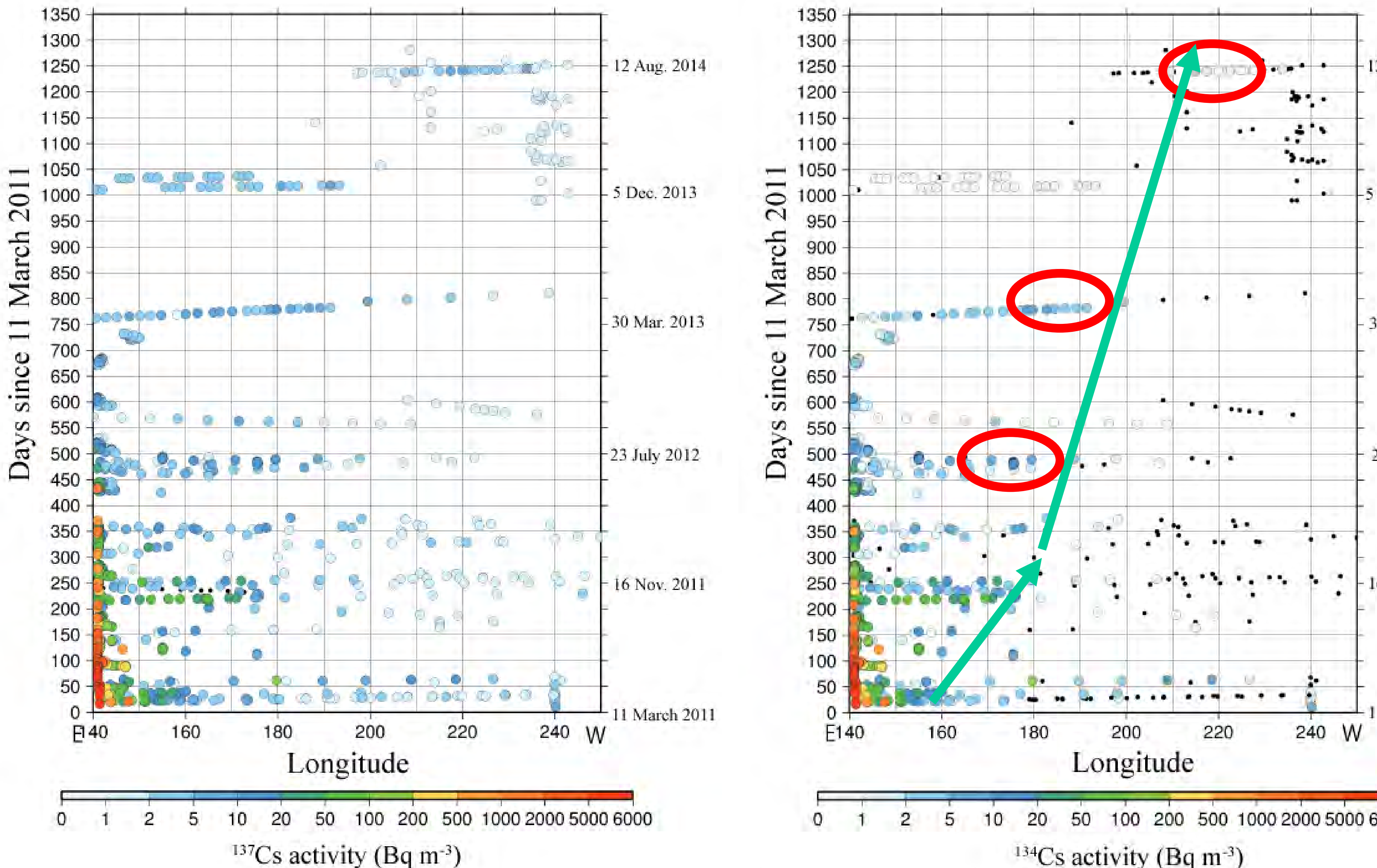
Surface speed of contaminated water ca. 7 km day^{-1}





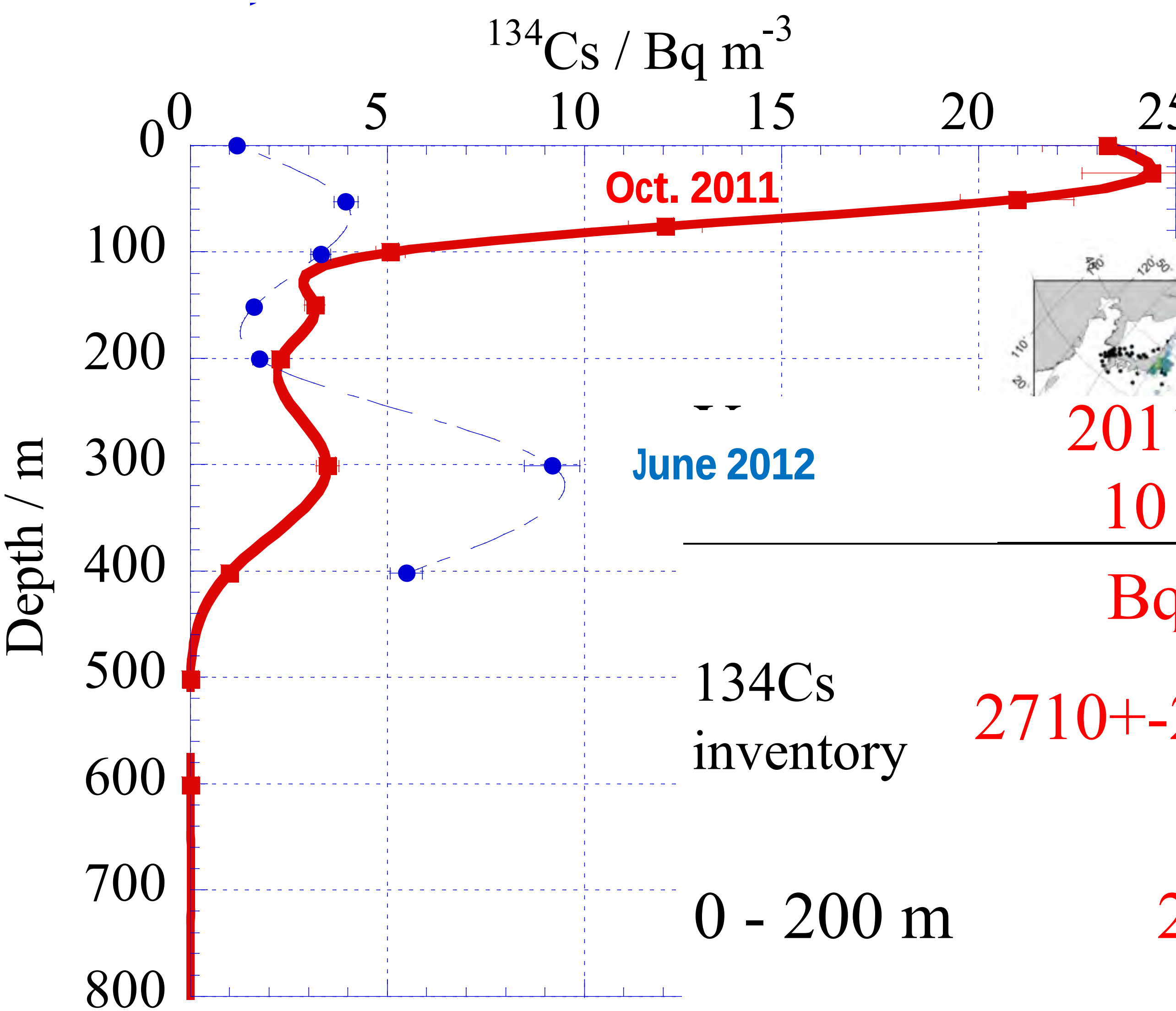
(Aoyama et al., BG 10 3067-3078, 2013)

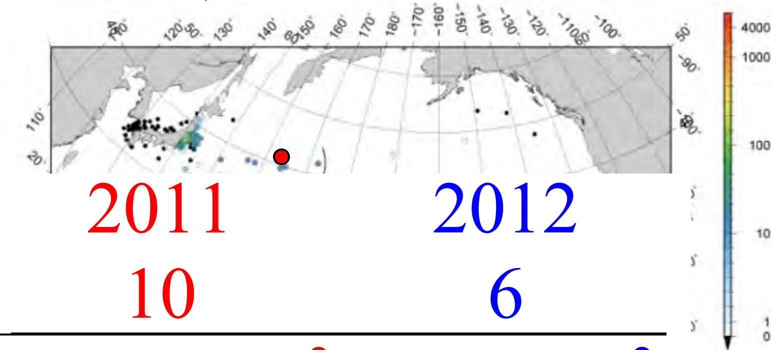
^{134}Cs actiity



Aoyama et al., JO, 2015b

Over time, Cs moves east and subducted in the ocean interior

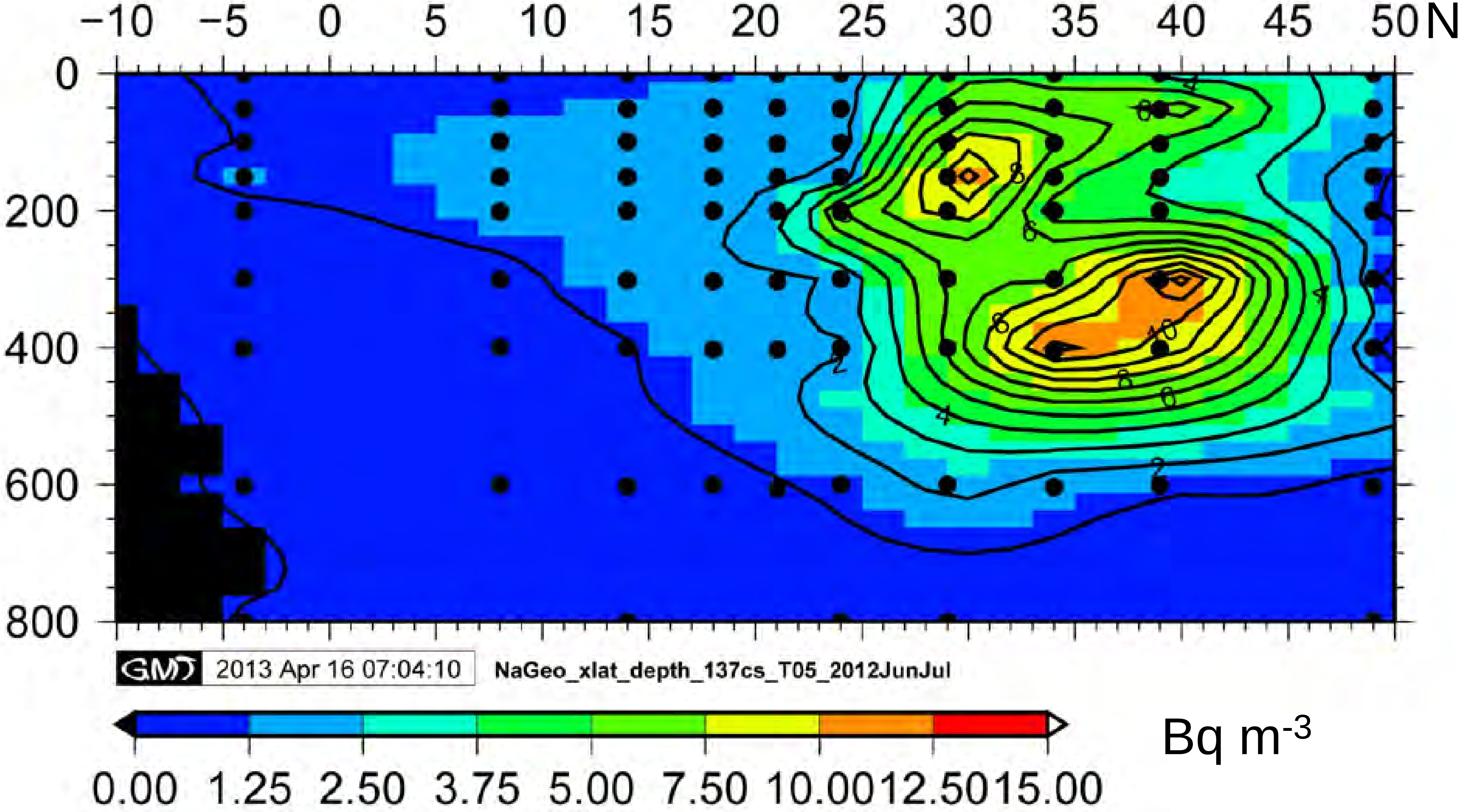




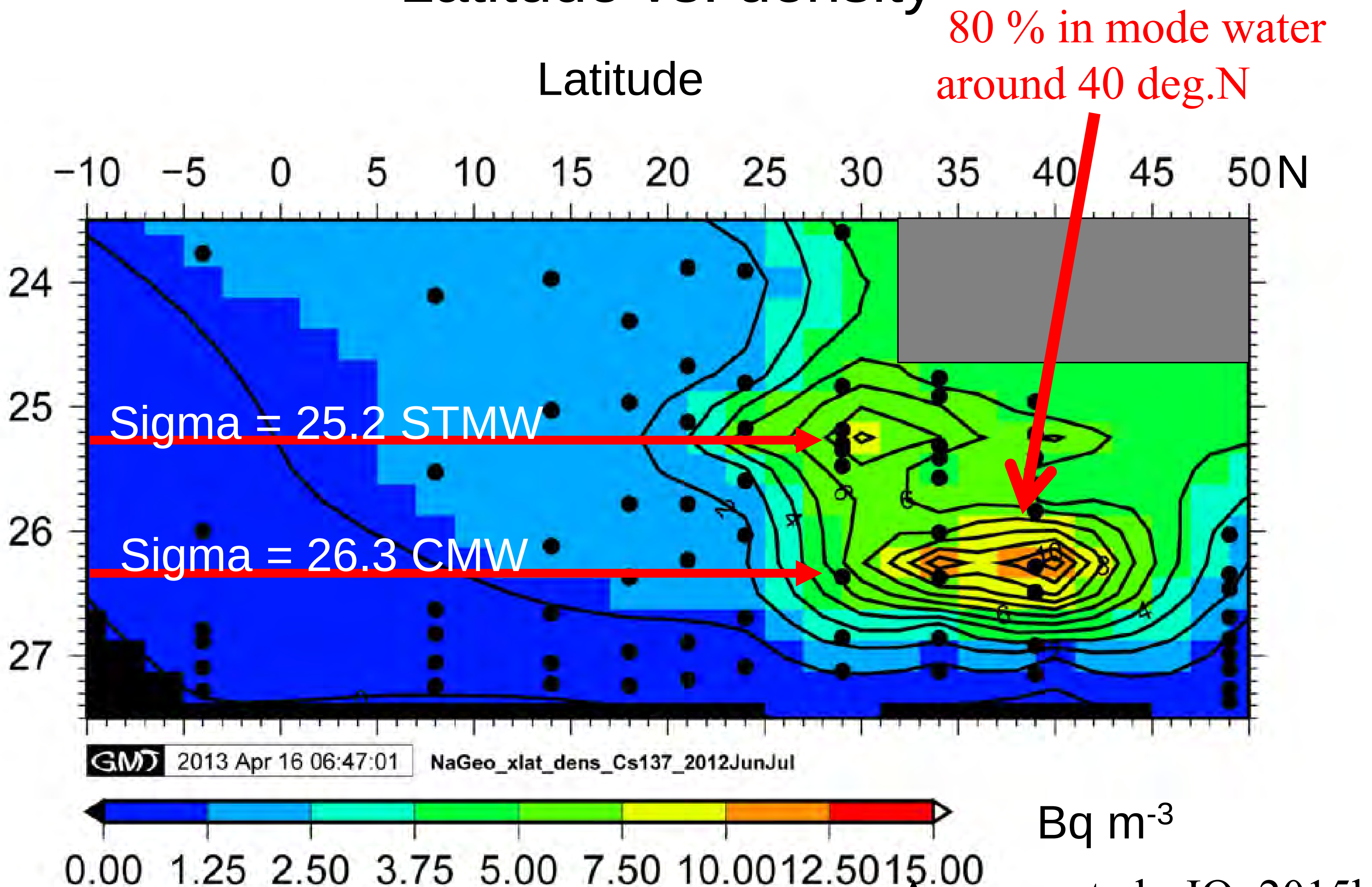
	2011 10	2012 6
	Bq m^{-2}	Bq m^{-2}
134Cs inventory	2710+-210	2350+-190
0 - 200 m	2150	520
Deeper than 200 m	520	1830

^{137}Cs cross section along 165 ºE in June 2012

Start of southward travel into ocean interior



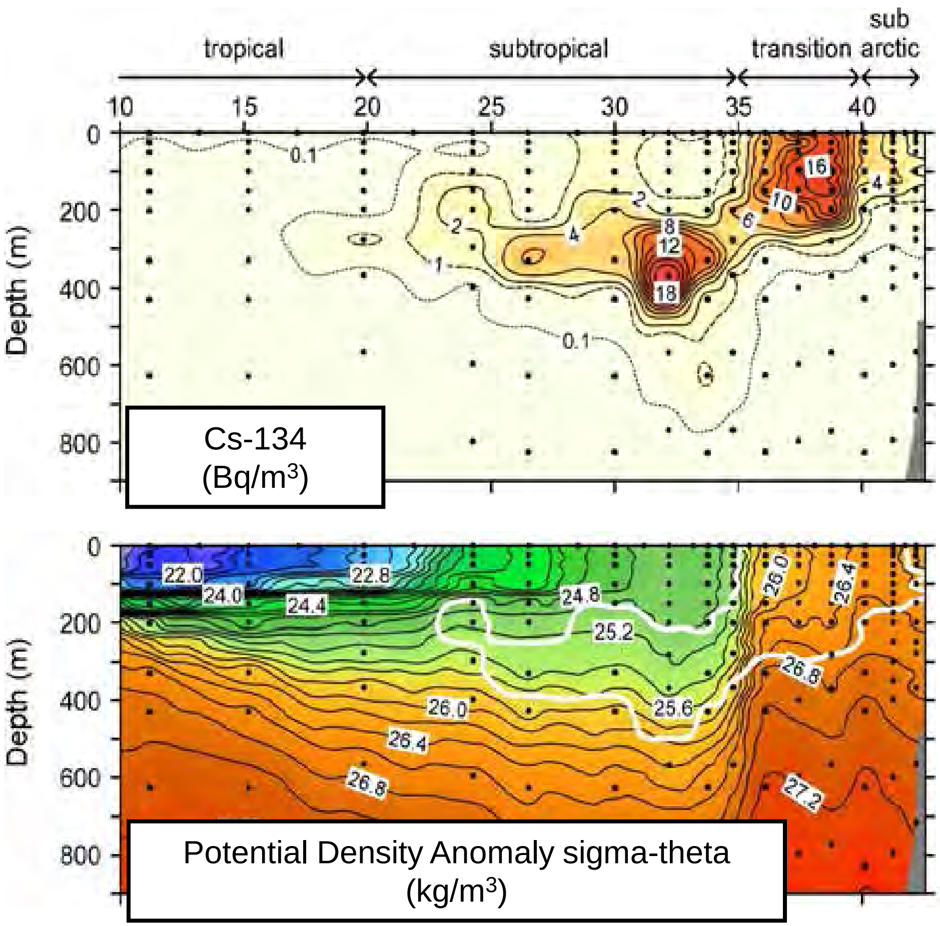
^{137}Cs cross section along 165 ºE in June 2012
Latitude vs. density

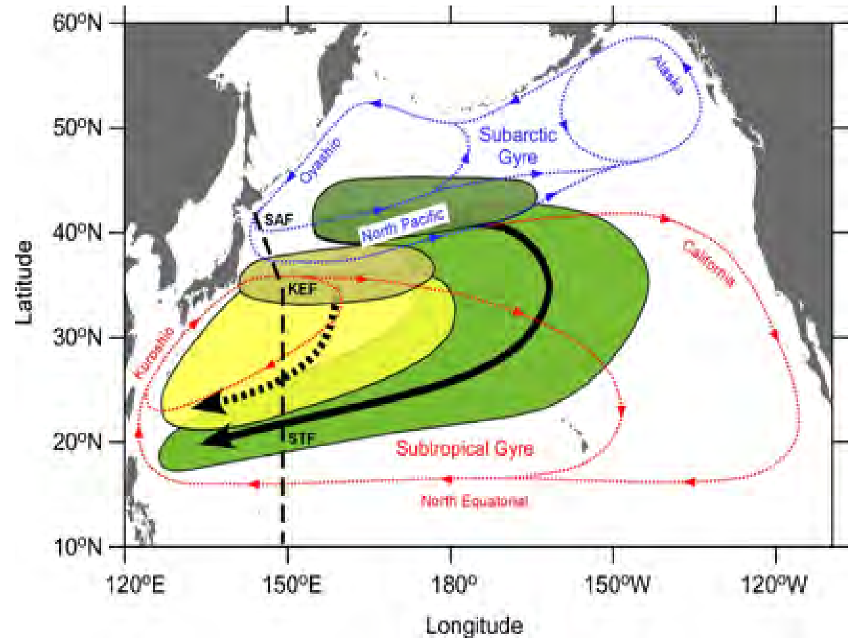


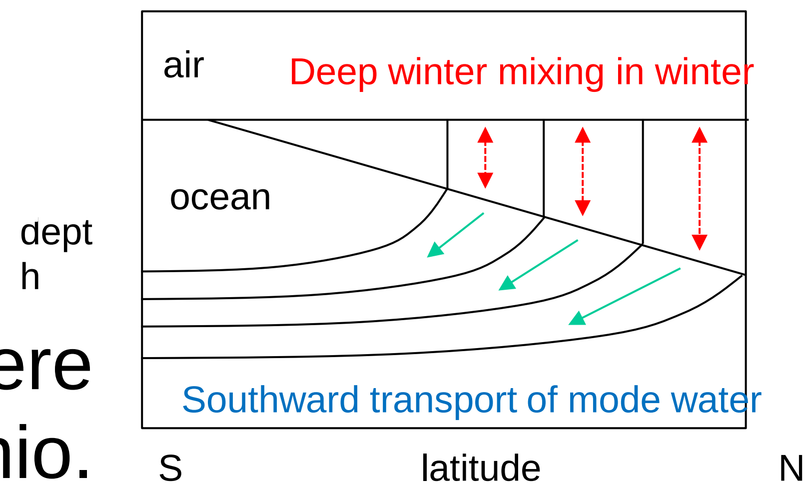
Aoyama et al., JO, 2015b

A ^{137}Cs section along 149 deg. E on Nov.-Dec. 2012

Kumamoto et al. Sci. Rep. (2014)

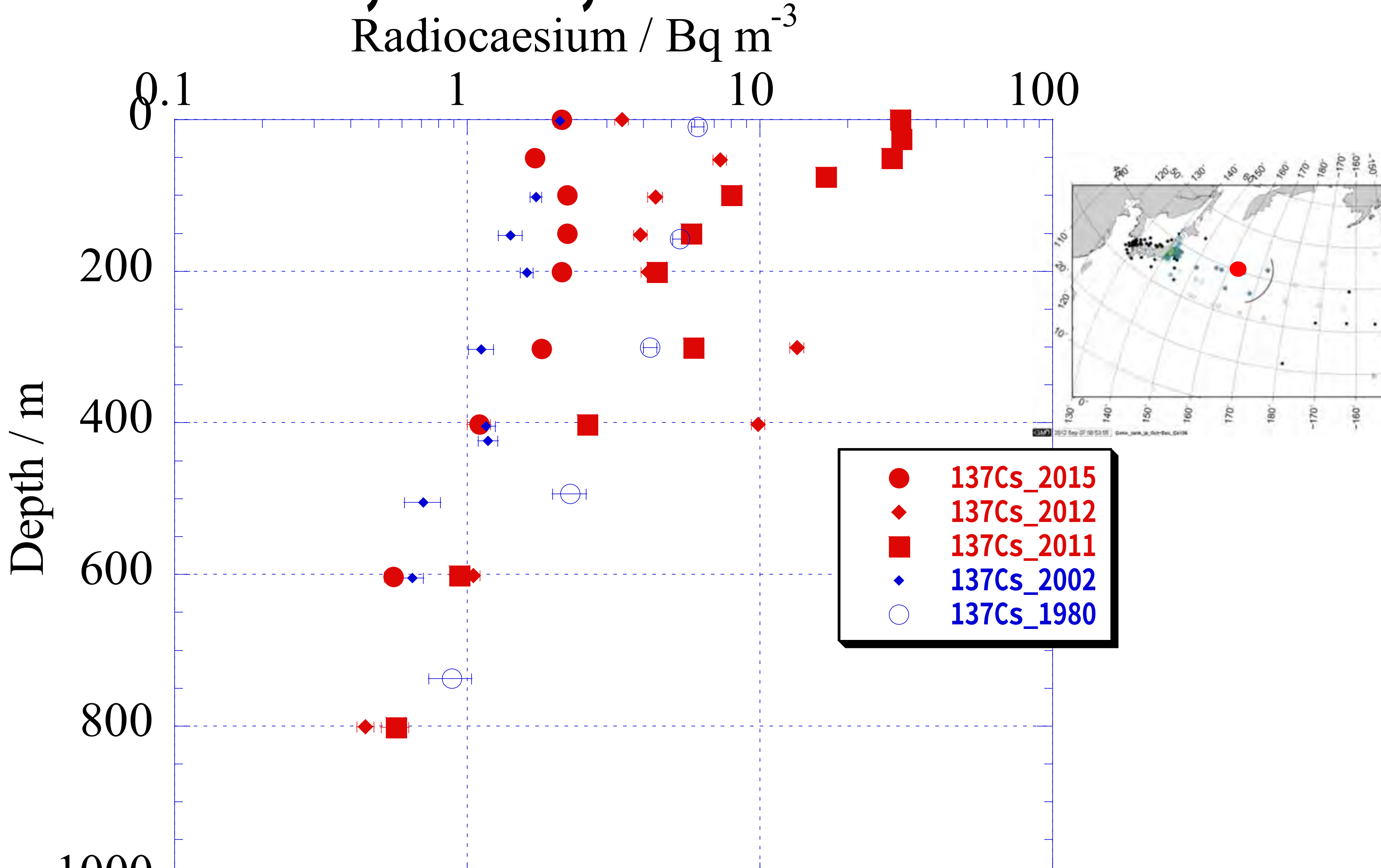






About 6 PBq of ^{137}Cs were transported south of Kuroshio. (40% of total amount in the sea)

Vertical profiles of 137Cs in 1980, 2002, 2011,2012 and 2015



A simple method by Aoyama et al.,JO, 2015a calculate inventory in the ocean

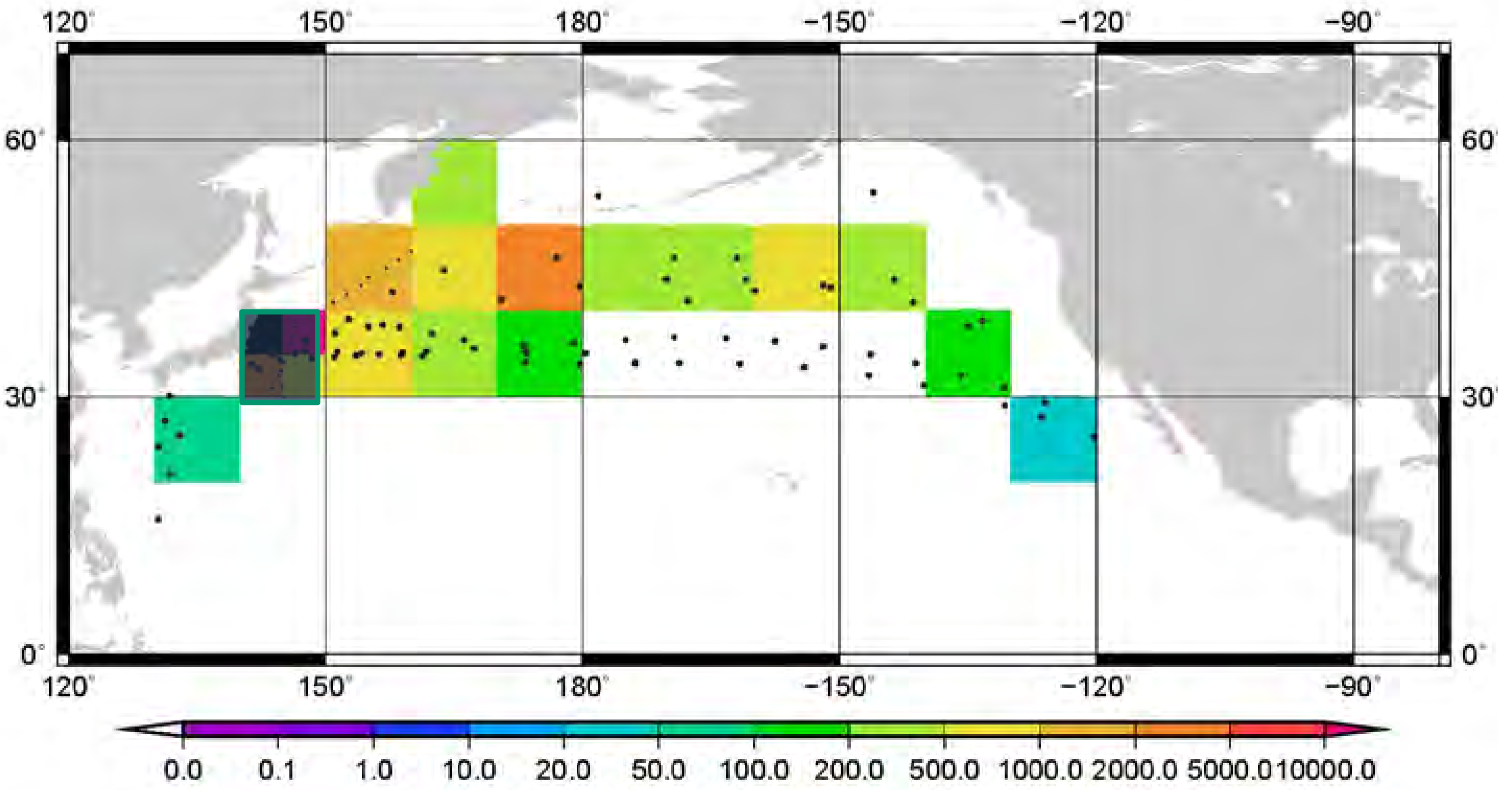
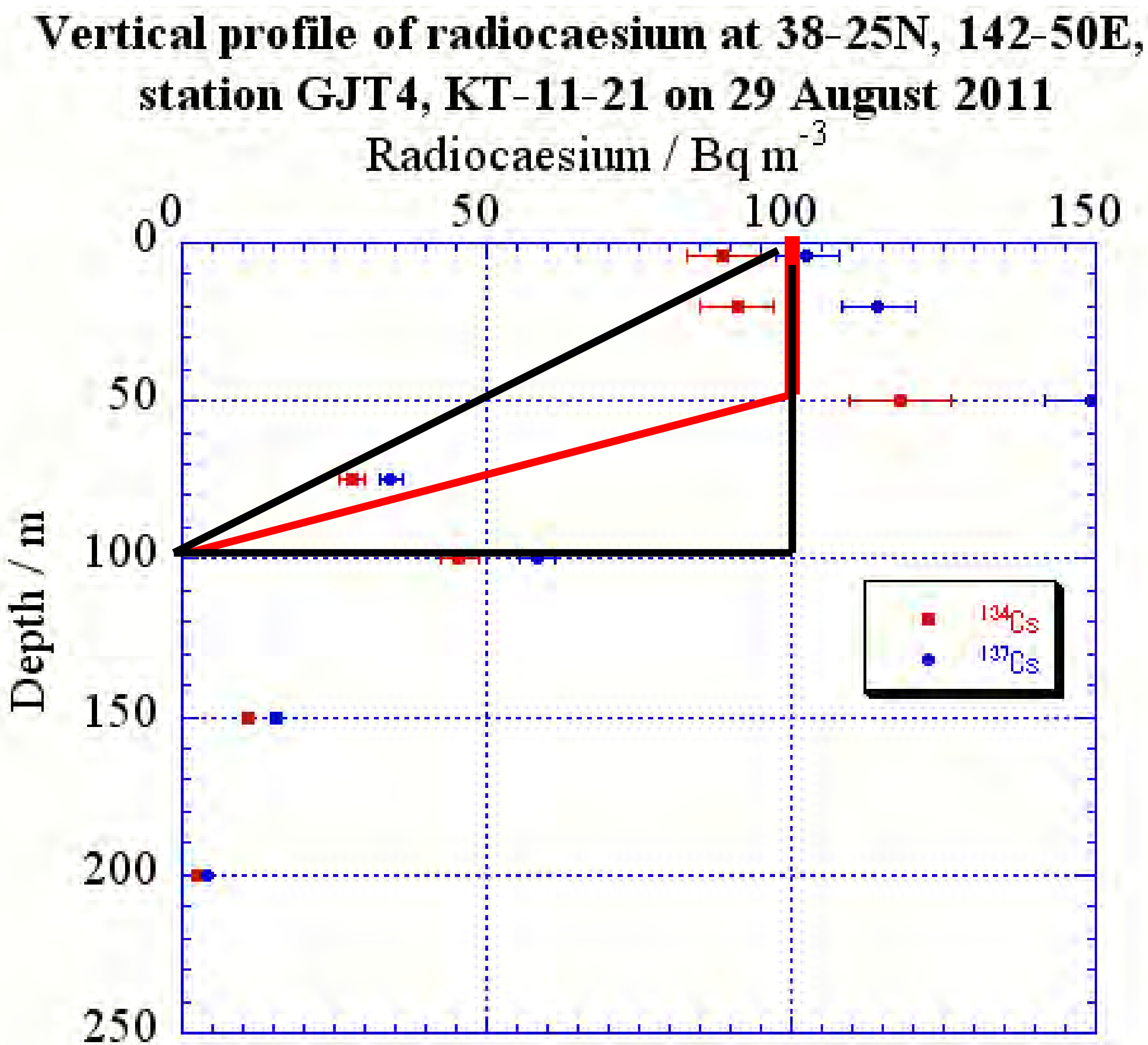


Fig S10. 10 deg mesh for integration of radiocaesium in Bq m-2
Black dots show observation location.



Our assumption to estimate inventory

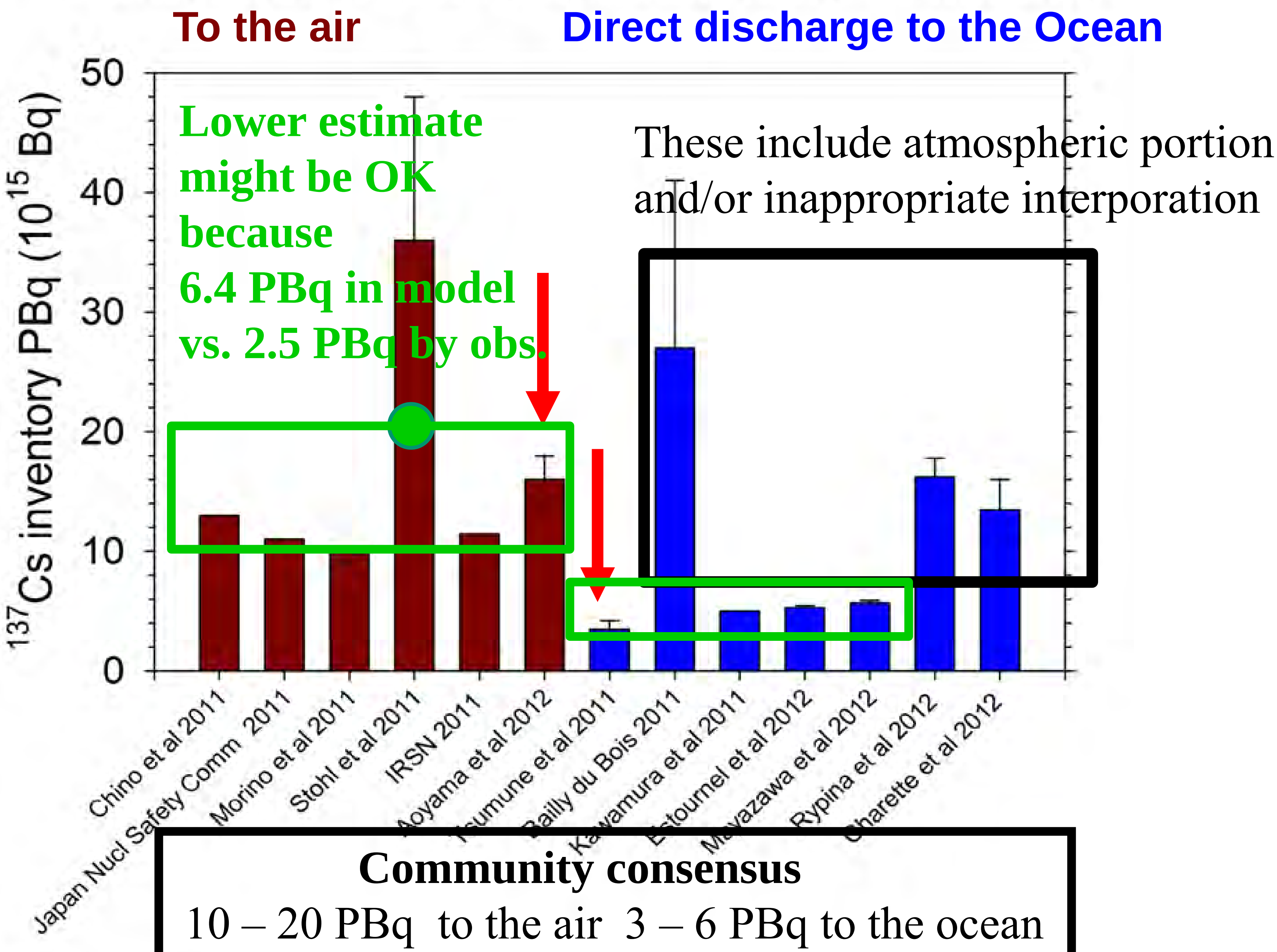
Table S7. Estimation of total amount in the North Pacific Ocean

Longitude	Latitude	Area km^2	^{134}Cs surface Bq m^{-3}	Inventory Bq m^{-2}	Total amount in a grid PBq
170	40	875218	57	4275	3.7
150	40	758595	25.5	1913	1.5
150	30	1011562	7.4	555	0.6
200	40	875223	7.05	529	0.5
160	40	875211	6.8	510	0.4
210	40	875223	4.4	330	0.3
160	30	1011562	3.4	255	0.3
180	40	875223	3.3	248	0.2
160	50	611243	3	225	0.1
190	40	875223	3	225	0.2
170	30	1011562	1.7	128	0.1
220	30	1011562	1.5	113	0.1
130	20	1116711	0.7	53	0.06
230	20	1116920	0.6	45	0.05
Total					8.1 +-2.8

Table 1. Summary of inventories in the ocean, source terms and land deposit

Parameters	Symbol	MASIN	MASIN	PM/r	uncerta	remarks
		PBq	PBq	PBq	PBq	
	Open Ocean in the North Pacific Ocean					
Observed inventory	a	8.1	8.1	8.1	2.8	This study
Modeled inventory	b	4.7	3.5	3.8		This study
Factor by source term correction	f=a/b	1.7	2.3	2.1		This study
	Source term correction					
First guess source term	s	8.8	8.8	8.8		This study
Corrected source term	s*f	15.2	20.4	18.8		This study
	North Pacific Ocean					
Total inventory in the model	g	10.3	9.9	9.4		This study
Direct discharge	d	3.5	3.5	3.5	0.7	Tsumune et al. 2011
Atmospheric portion in the model	g-d	6.8	6.4	5.9		This study
Corrected atmospheric portion	(g-d)*f	11.7	14.8	12.6		This study

Estimates of total releases from Fukushima



Aoyama et al., JO 2015a vs. UNSCEAR 2013

	Aoyama	UNSCEAR
Fukushima direct discharge to the North Pacific Ocean	**3.5 +- 0.7** PBq 3 – 6 PBq	3 - 6 PBq
Fukushima deposition in the North Pacific Ocean	**12ー15** PBq	5 – 8 PBq
Fukushima deposition on land	**2.5 - 3** PBq	no estimation (1 – 12 PBq??)
Total release to the air	**14-17** PBq 10 – 20 PBq	6 – 20 PBq

Huge inconsistency in UNSCEAR estimation

Conclusions

- After July 2012, the activities of ^{137}Cs in surface water at near FNPP1 site were still kept around 1000 Bq m^{-3} which corresponds flux of about 10 GBq day^{-1}. A zonal speed of FNPP1 derived radiocaesium in surface water at mid latitude in the North Pacific Ocean was 7 km day-1, 8 cm s-1 until March 2012 , however it after March 2012 till August 2014 was ca. 3 km day-1, 3.5 cm s-1. Then FNPP1 derived radiocaesium arrive at west coast of US continent as expected.

Conclusions-2

- Clear increase of ^{134}Cs due to STMW formation was observed as well as increase of ^{134}Cs due to CMW formation. These observations indicate that mode waters formation were most effective pathway to introduce Fukushima derived radiocaesium into ocean interior about one year time scale. More than 80 % of released radiocaesium might be in mode waters (sub surface layers) and NOT in surface region as expected, too.