North Pacific distribution and budget of radiocesium released by the 2011 Fukushima nuclear accident

Michio Aoyama,[1] Mizuo Kajino,[1] Taichu Y. Tanaka,[1] Tsuyoshi Thomas Sekiyama,[1] Daisuke Tsumune,[2] Takaki Tsubono,[2] Yasunori Hamajima,[3] Toshitaka Gamo,[4] Mitsuo Uematsu,[4] Takeshi Kawano,[5] Akihiko Murata,[5] Yuichiro Kumamoto,[5] Masao Fukasawa,[5] Chino Masamichi[6]

1.Meteorological Research Institute

2.Environmental Science Research Laboratory, Central Research Institute of Electric Power Industry

3.Kanazawa University

4.Atmosphere and Ocean Research Institute , The University of Tokyo

5.Japan Agency for Marine-Earth Science and Technology

6.Japan Atomic Energy Agency

Objectives

- To reveal temporal and spatial distribution of radiocaesium released from Fukushima in the North Pacific Ocean
- To estimate total amount of radiocaesium released from Fukushima NPP accident including atmospheric release and direct discharge

我々の研究の特徴

北太平洋全域での観測結果から出発し、変動の大きい事故サイト周辺を除く北太平洋で積分した人工放射能総量を推定し使用した。また大気および海洋の輸送モデルも最先端のものを使用している。

外国の研究も含めて先行研究の弱点：複数のモデルや気象条件の解析から判っていることは、放出された人工放射能の2/3以上は北太平洋に降下したことである。しかし、大気への放出量を推定しているすべての研究は陸上（日本および諸外国）での観測値のみに依っている。従ってそれらの推定の不確かさが必然的に大きくなる。

得られた成果の自己評価：現時点で最も真実に近い数字を得た。

Temporal and spatial distribution of radiocaesium released from Fukushima in the North Pacific Ocean

Sampling summary and other data source

- NYK ships 7 cruises more than 150 samples, 79 samples done, 2 liters surface only until end of May 2011.
- NYK ships 10 cruieses from Aug. 2011-Now
- Tansei-maru, Hakuho-maru and Keifu-maru surface and vertical samples

放射性セシウムの高精度分析と不確かさ

- **収率**99%**程度で安定した抽出** (Aoyama and Hirose 2008)**事実上の世界標準法**
- **金沢大学尾小屋地下測定室での測定：総量で**1mBq**以下まで測定可能**

- ^{137}Cs**は表面水すべての値を決定：核実験起源分と整合**
- ^{134}Cs**は**0.4mBq L^{-1}**以下を下限値以下：福島事故由来分を正しく評価できた**

Table S2. Radiocaesium activity in the North Pacific Ocean in April/May 2011

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

Example of results

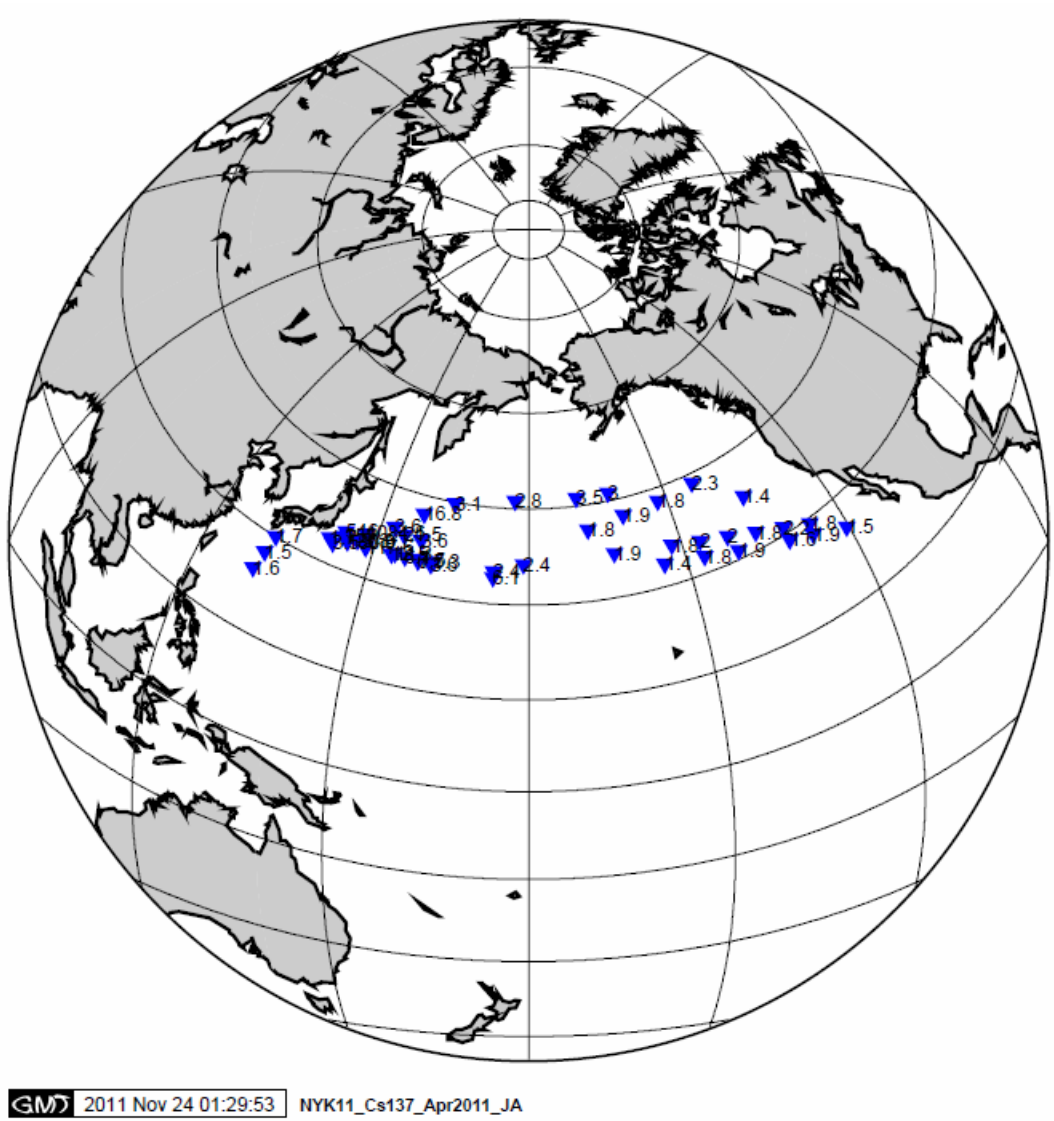
Latitude	Longitude	Date	^{134}Cs Bq m^{-3}	^{137}Cs Bq m^{-3}
36.60ºN	147.60ºE	20110401	1000 ± 71	1080 ± 60
36.35ºN	178.99ºE	20110406	1.1 ± 0.6	2.4 ± 0.4
41.12ºN	167.75ºW	20110407	ND	1.8 ± 0.2

Fuksuhima Fukushima+ bomb

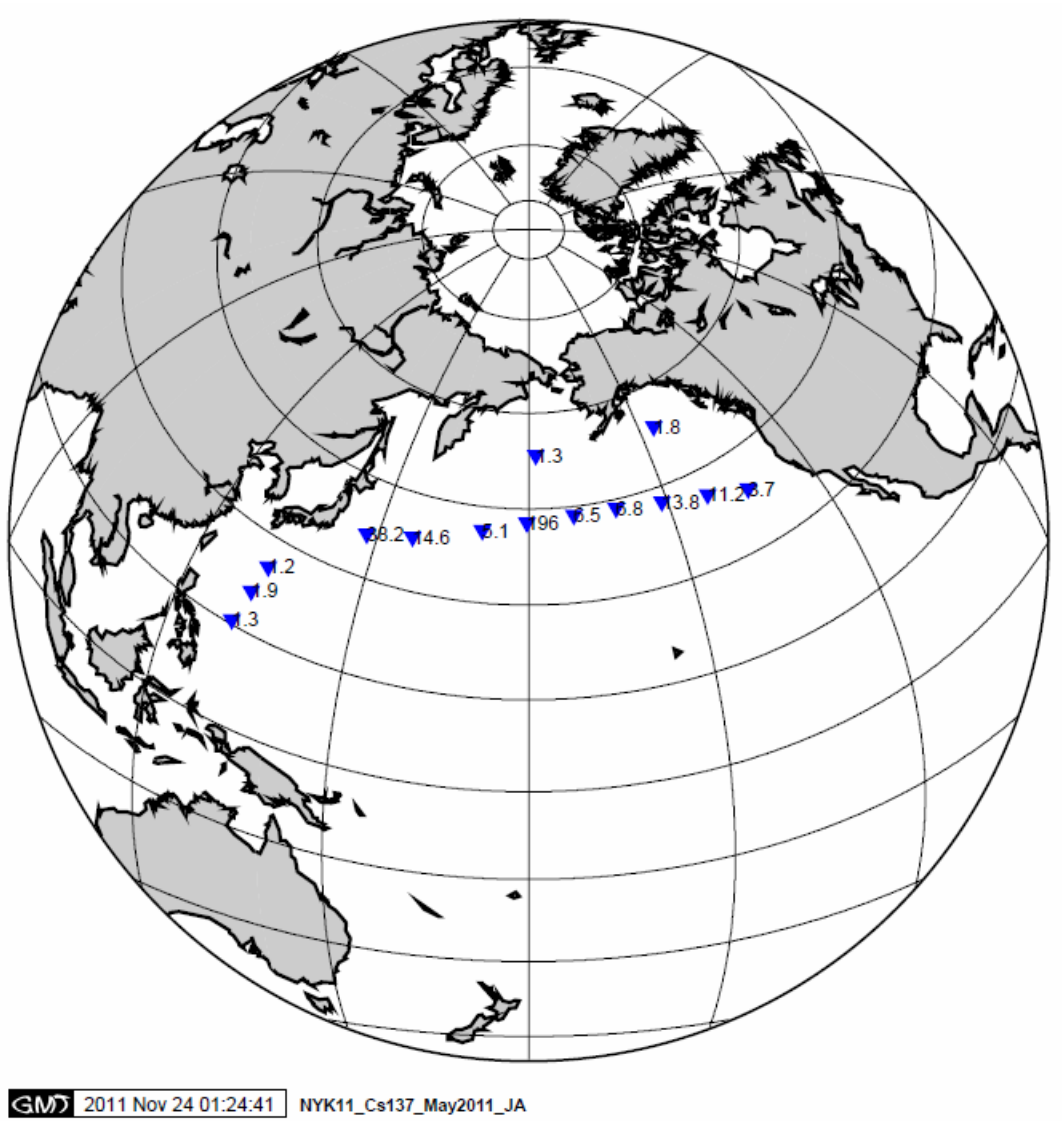
134Cs:137Cs activity ratio of Fukushima radioactivity

0.99 +- 0.02
Buesseller et al., 2011

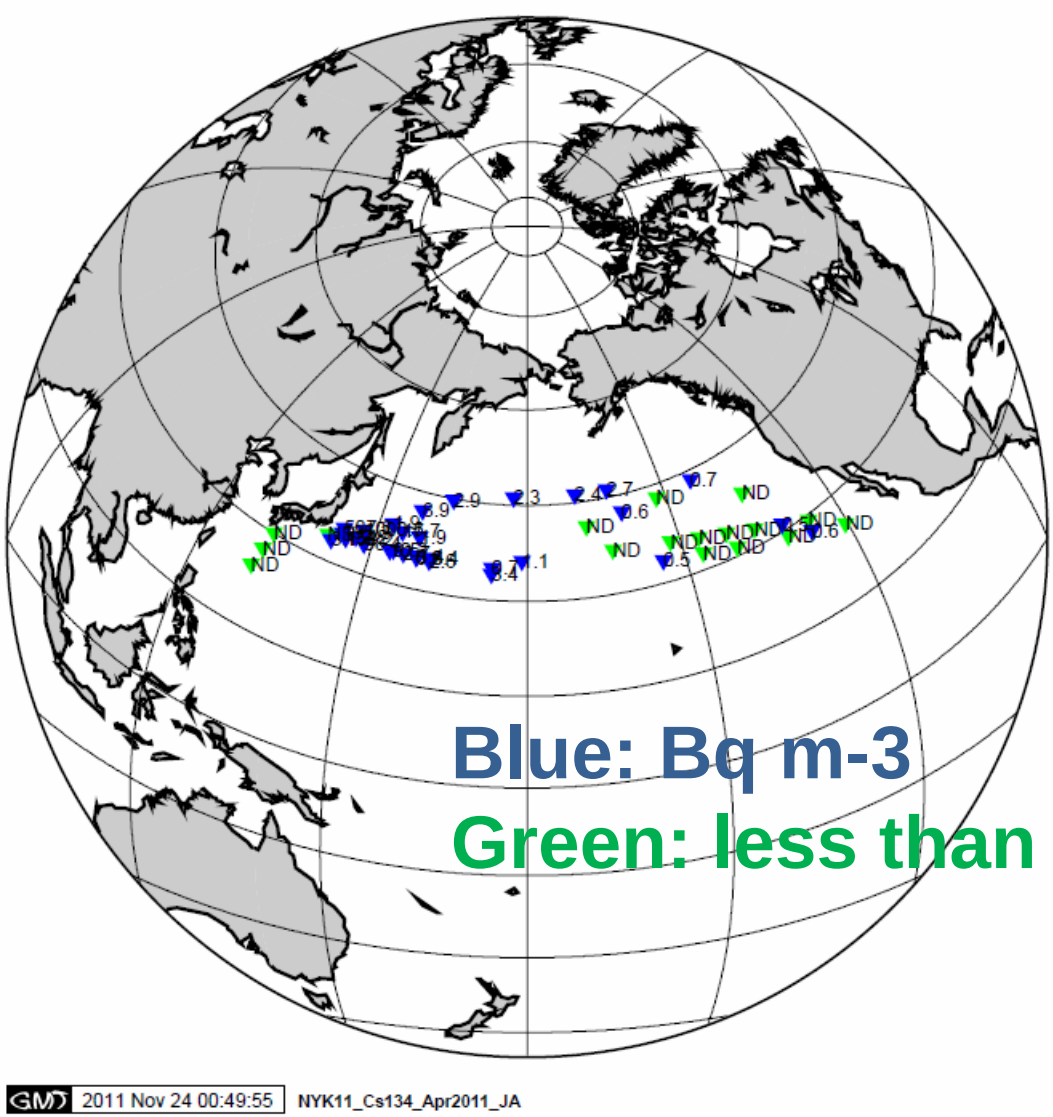
NYK11 ^{137}Cs April 2011



NYK11 ^{137}Cs May 2011



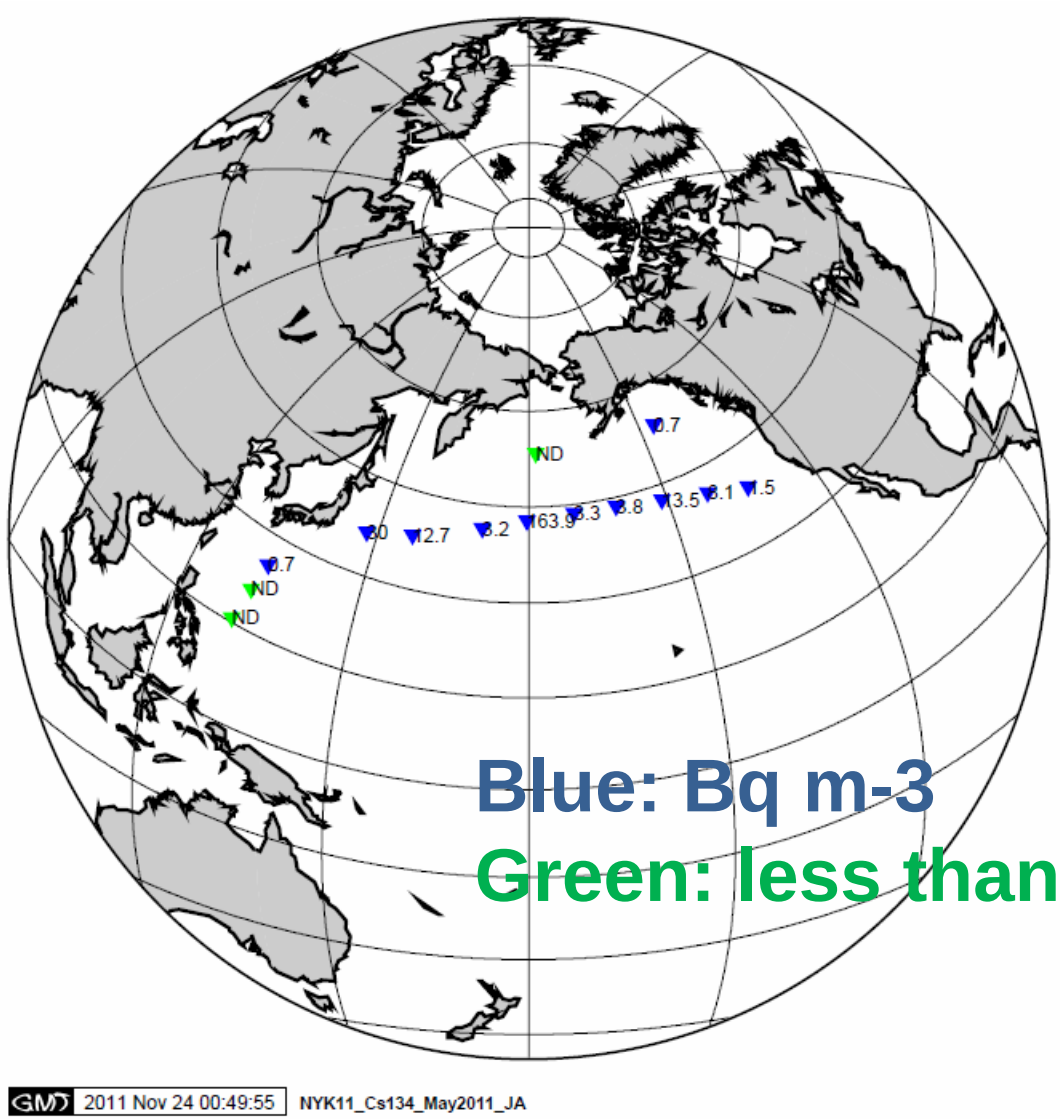
NYK11 ^{134}Cs April 2011



Blue: Bq m-3

Green: less than 0.4 Bq m-3

NYK11 ^{134}Cs May 2011



Blue: Bq m-3

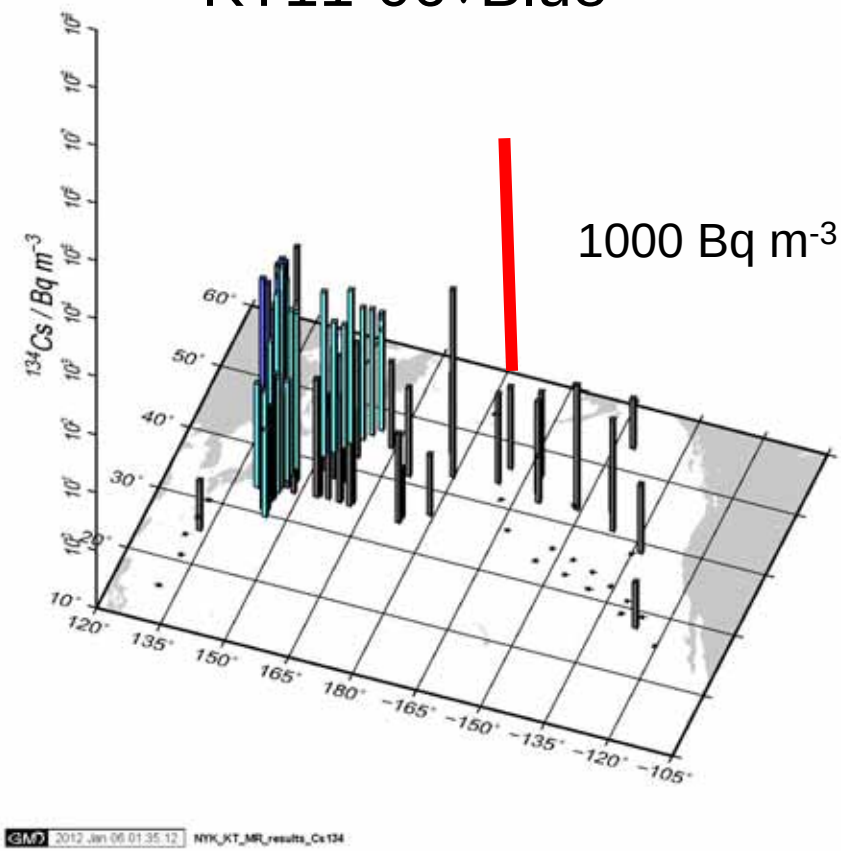
Green: less than 0.4 Bq m-3

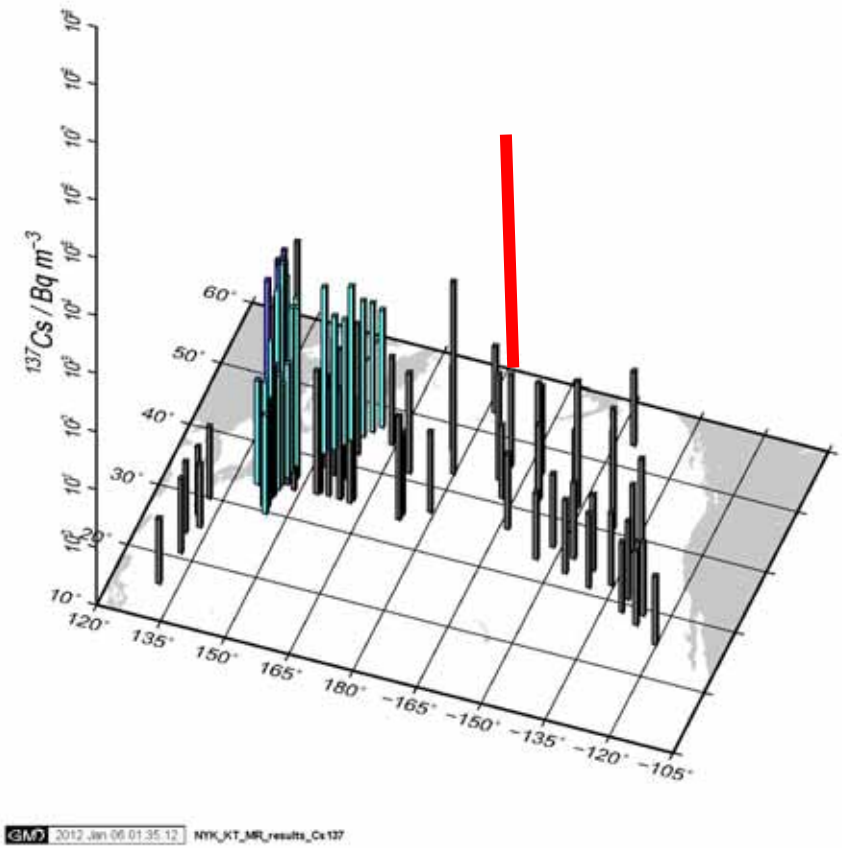
^{134}Cs (left) and ^{137}Cs(right) in April-May 2011

NYK ships : Brown

MR11-03: light blue , Honda et al., 2011(11:00 today)

KT11-06：Blue





^{137}Cs distribution before Fukushima

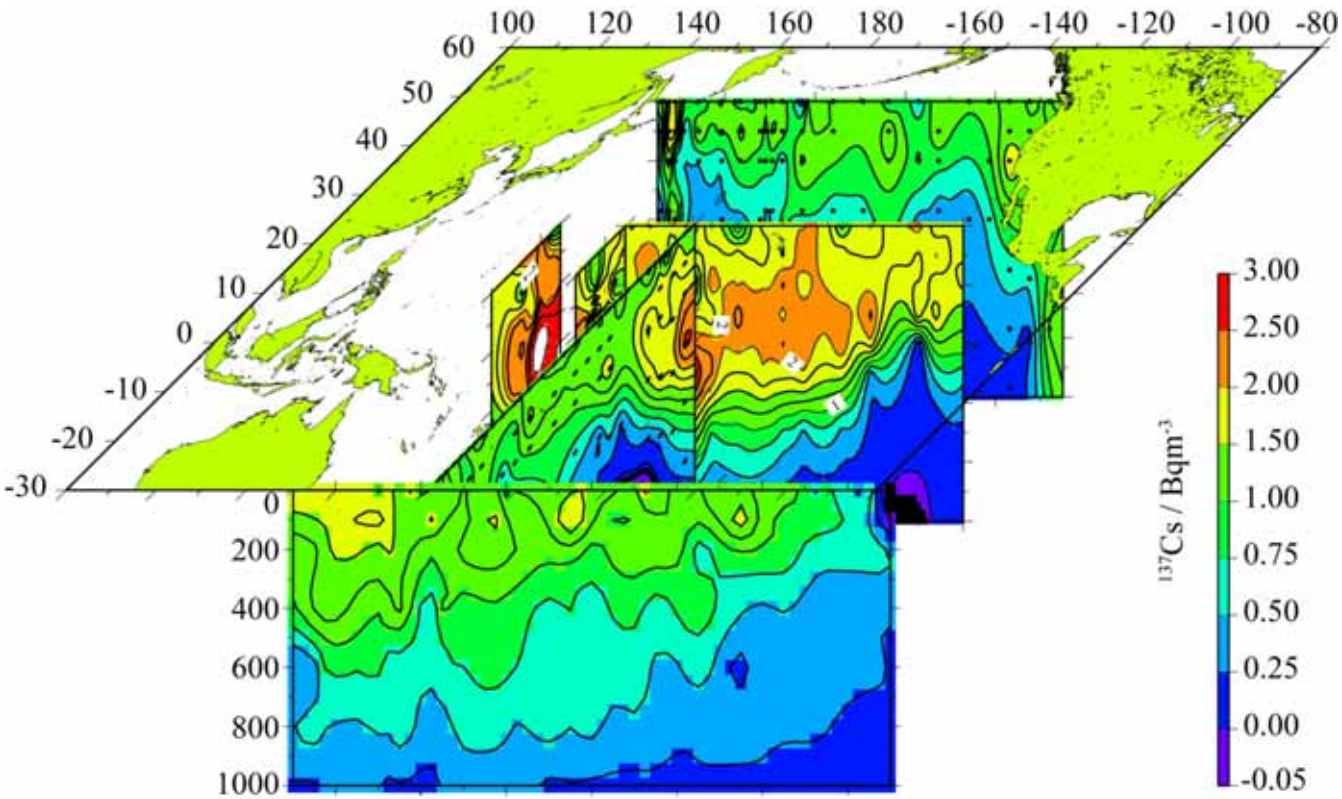
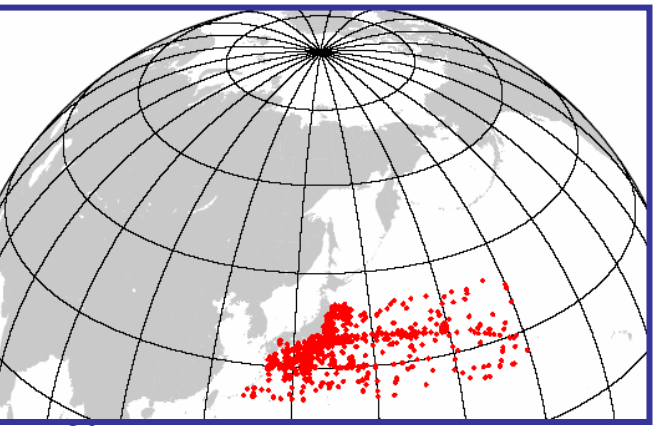
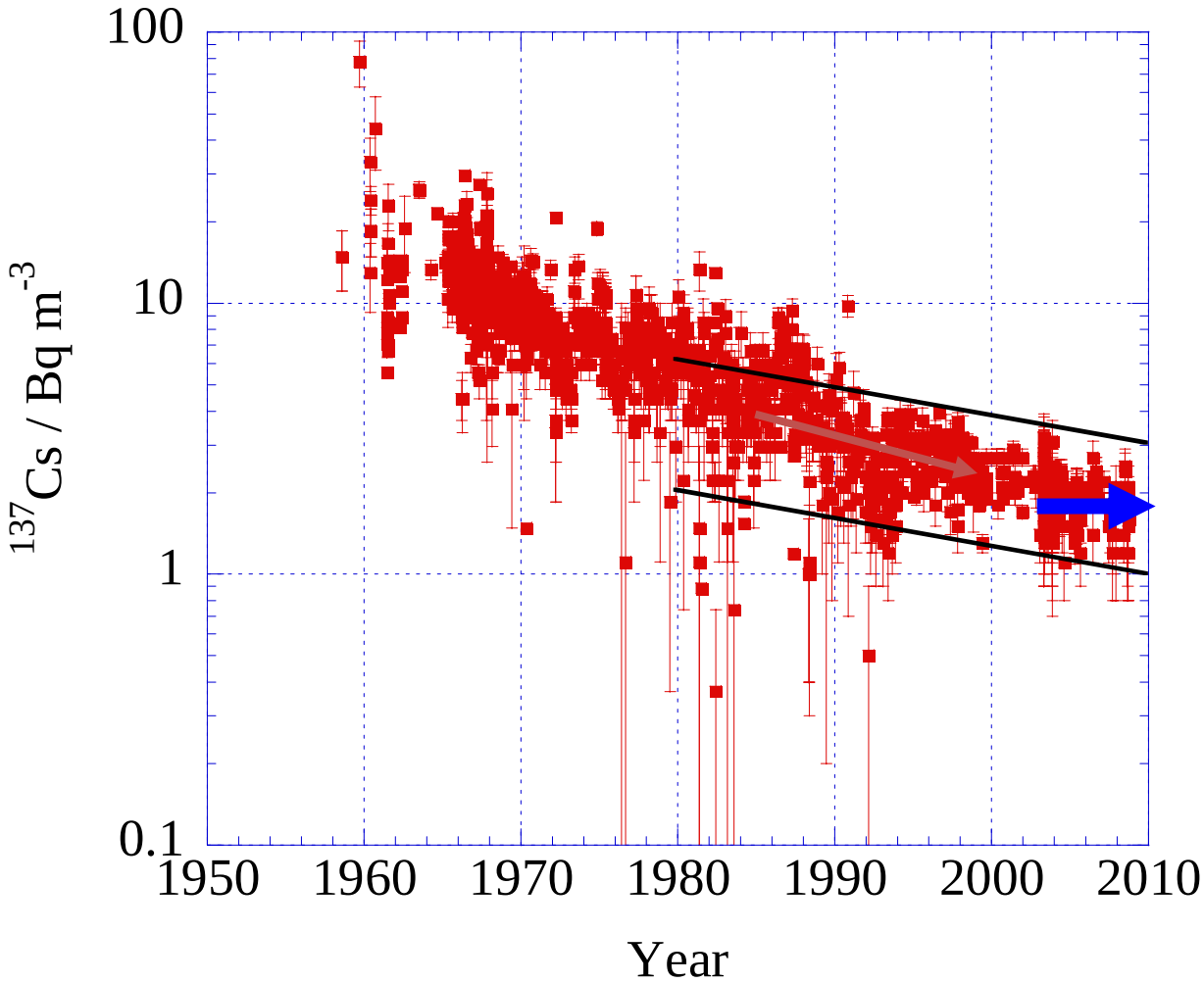


Fig. S1. 3-D ^{137}Cs in the Pacific Ocean before Fukushima accident in 2011





^{137}Cs trend in the subtropical gyre in the western North Pacific Ocean.(Aoyama, M., Hirose, K. , *TheScientificWorldJOURNAL*, **4**, 200-215, 2004 and update)

Past and present

TEPCO: Tokyo Electric Power Company, TEPCO News Press Releases 2011
http://www.tepco.co.jp/en/press/corp-com/release/

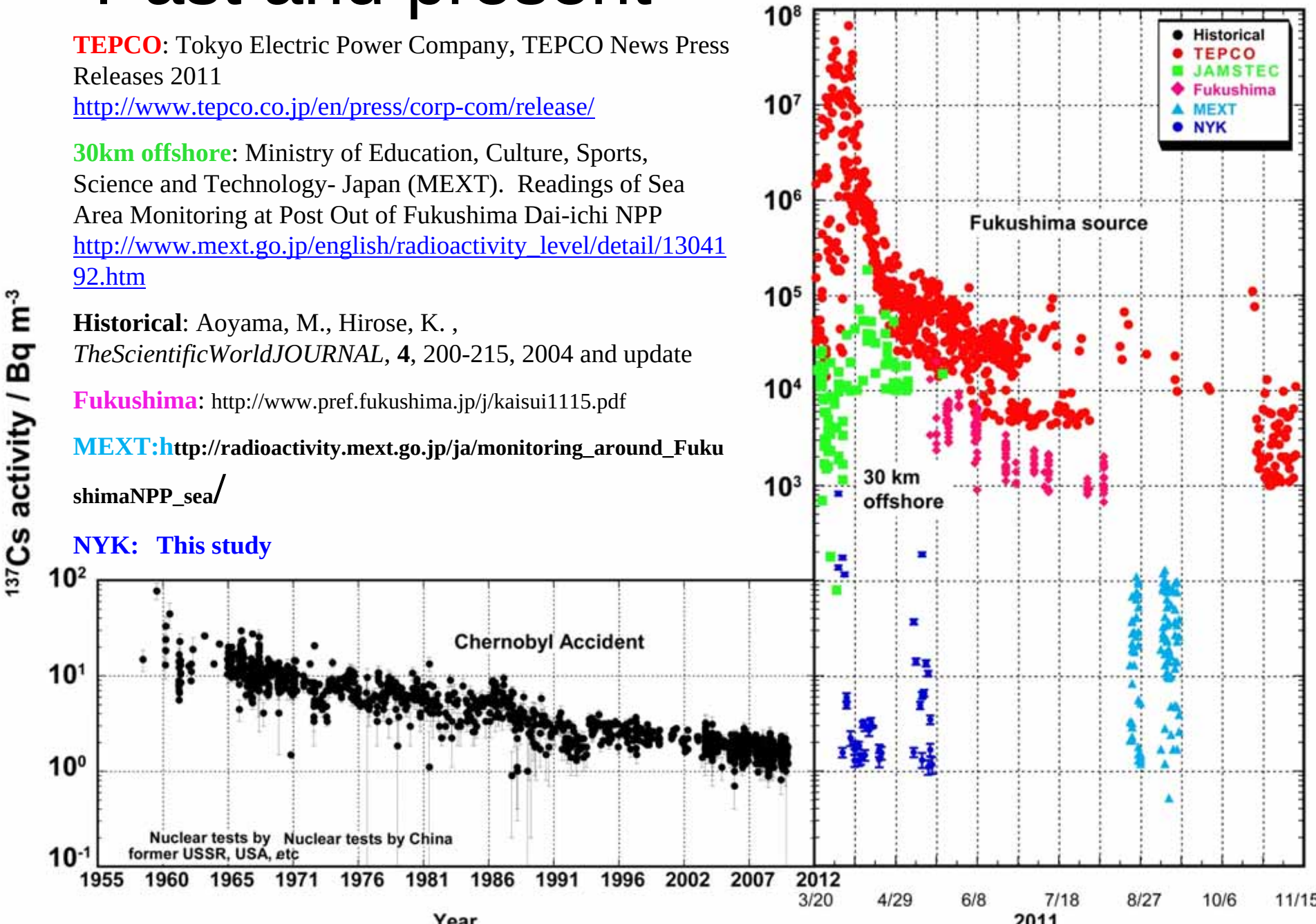
30km offshore: Ministry of Education, Culture, Sports, Science and Technology- Japan (MEXT). Readings of Sea Area Monitoring at Post Out of Fukushima Dai-ichi NPP
http://www.mext.go.jp/english/radioactivity_level/detail/1304192.htm

Historical: Aoyama, M., Hirose, K. , *TheScientificWorldJOURNAL*, **4**, 200-215, 2004 and update

Fukushima: http://www.pref.fukushima.jp/j/kaisui1115.pdf

MEXT:http://radioactivity.mext.go.jp/ja/monitoring_around_FukushimaNPP_sea/

NYK: This study



Radiocaesium activity in 4 regions

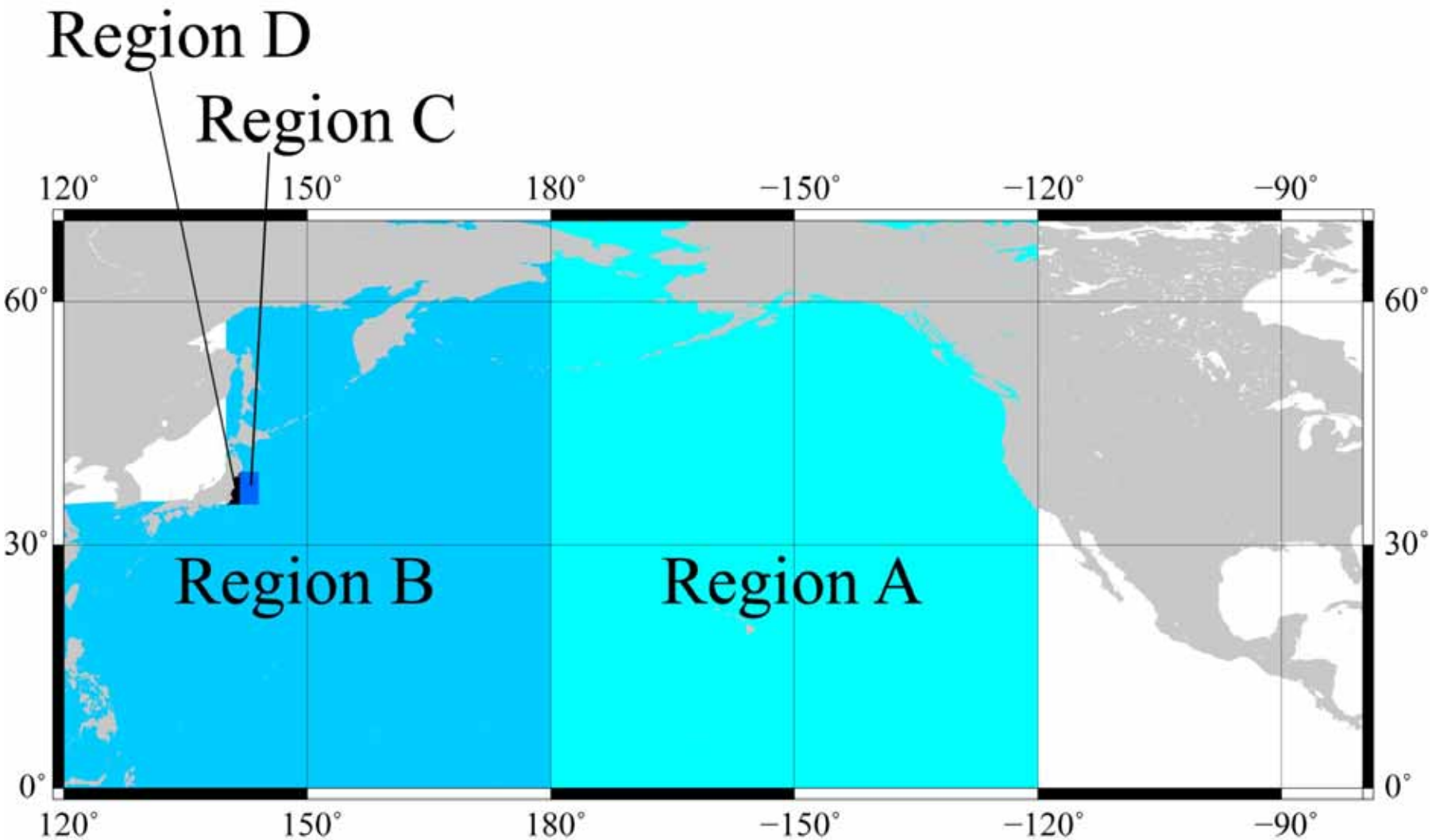
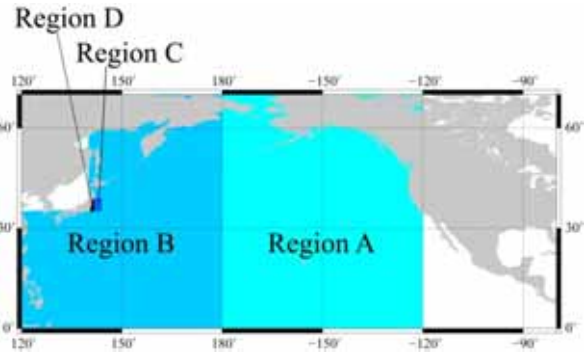


Fig. S3 Region of interest A, B, C and D



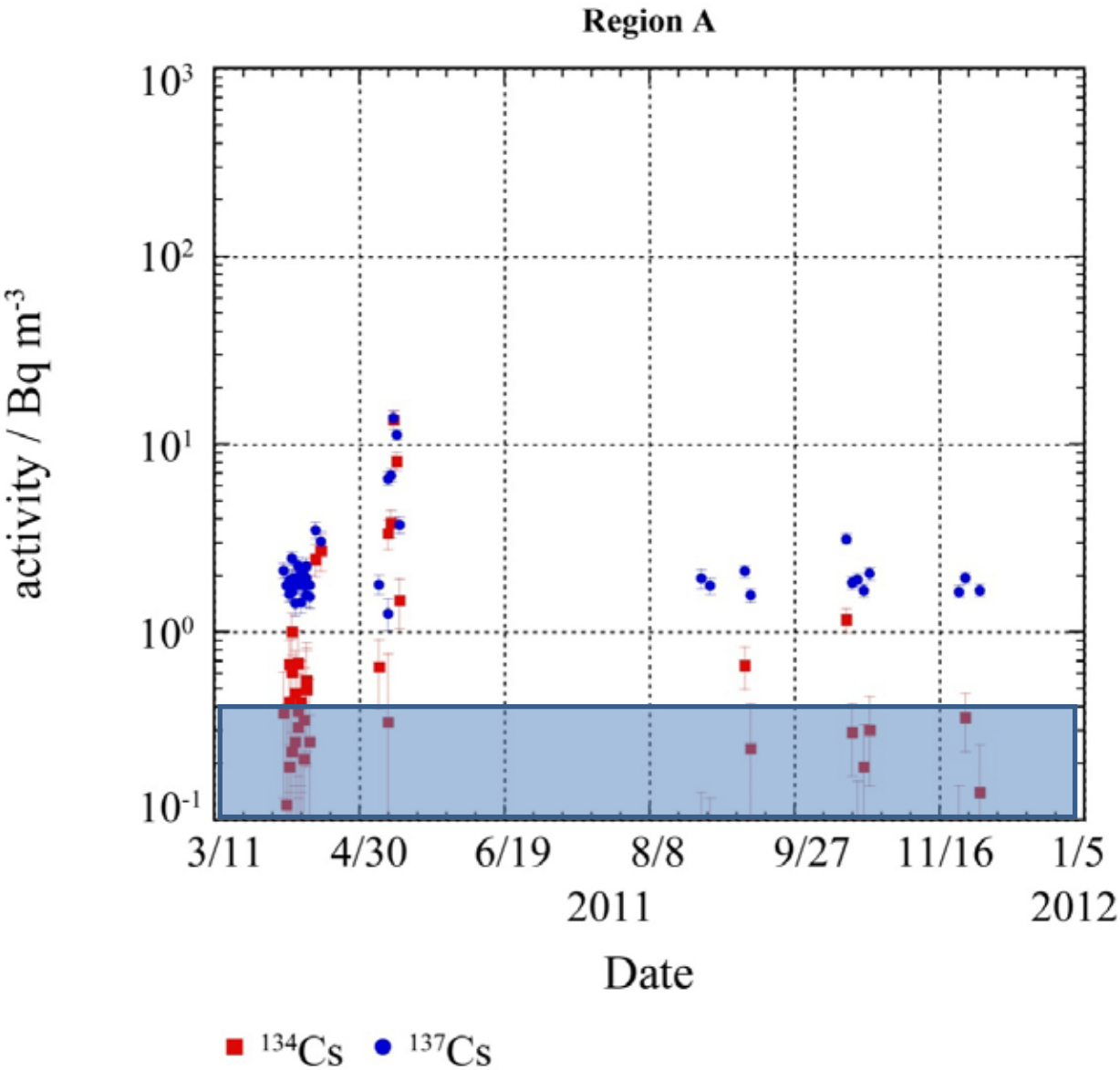
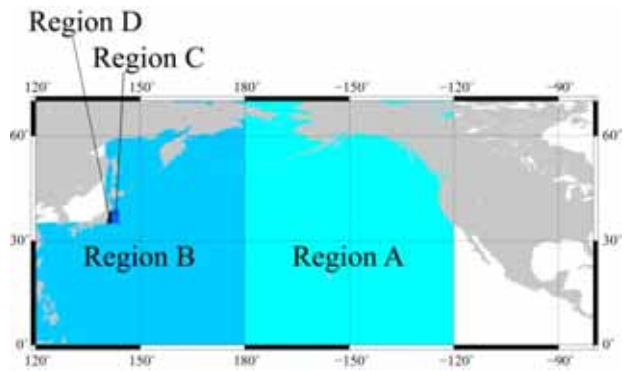


Fig S4. ^{137}Cs and ^{134}Cs activity in region A: eastern North Pacific Ocean



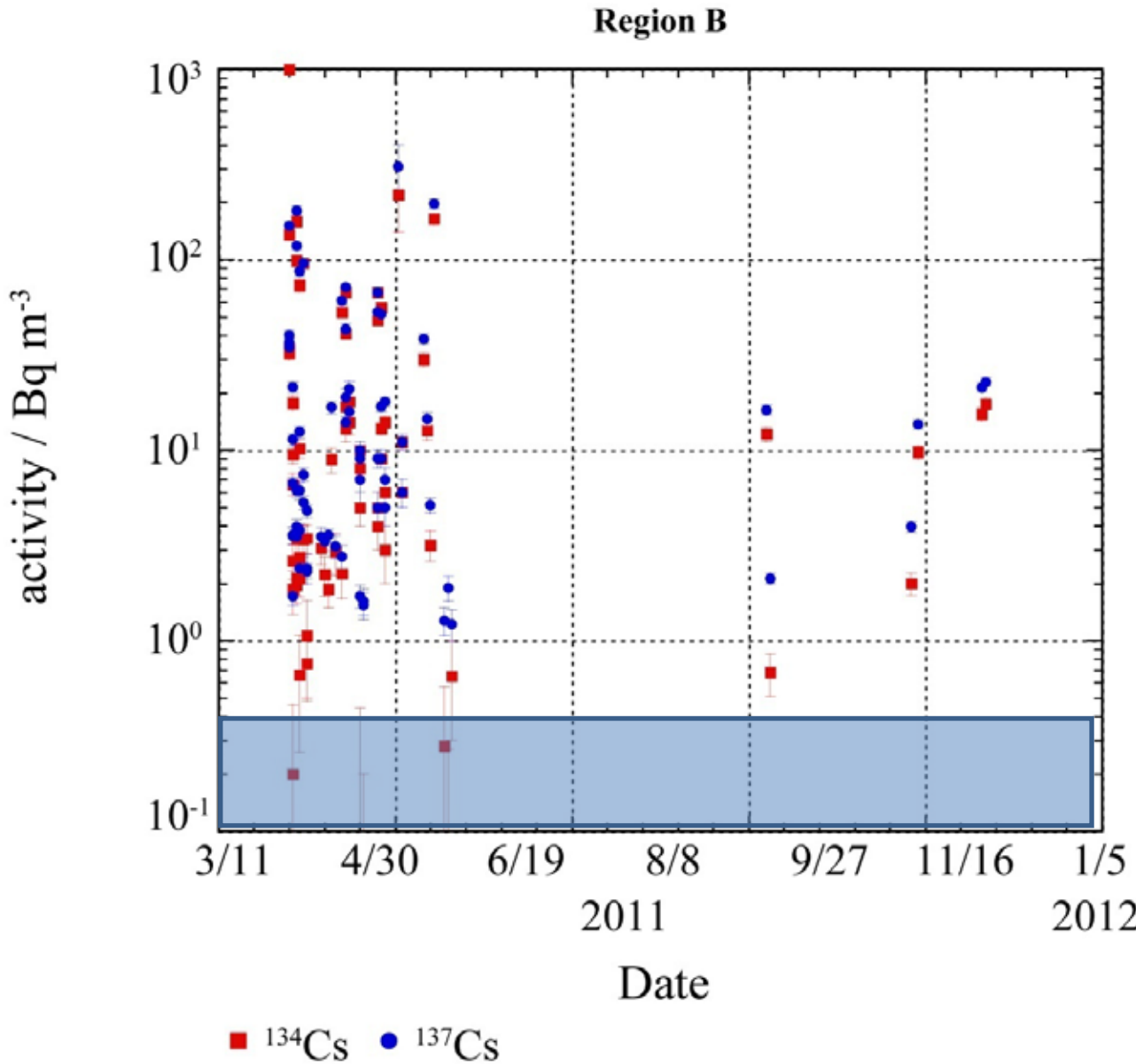


Fig S5. ^{137}Cs and ^{134}Cs activity in region B: western North Pacific Ocean

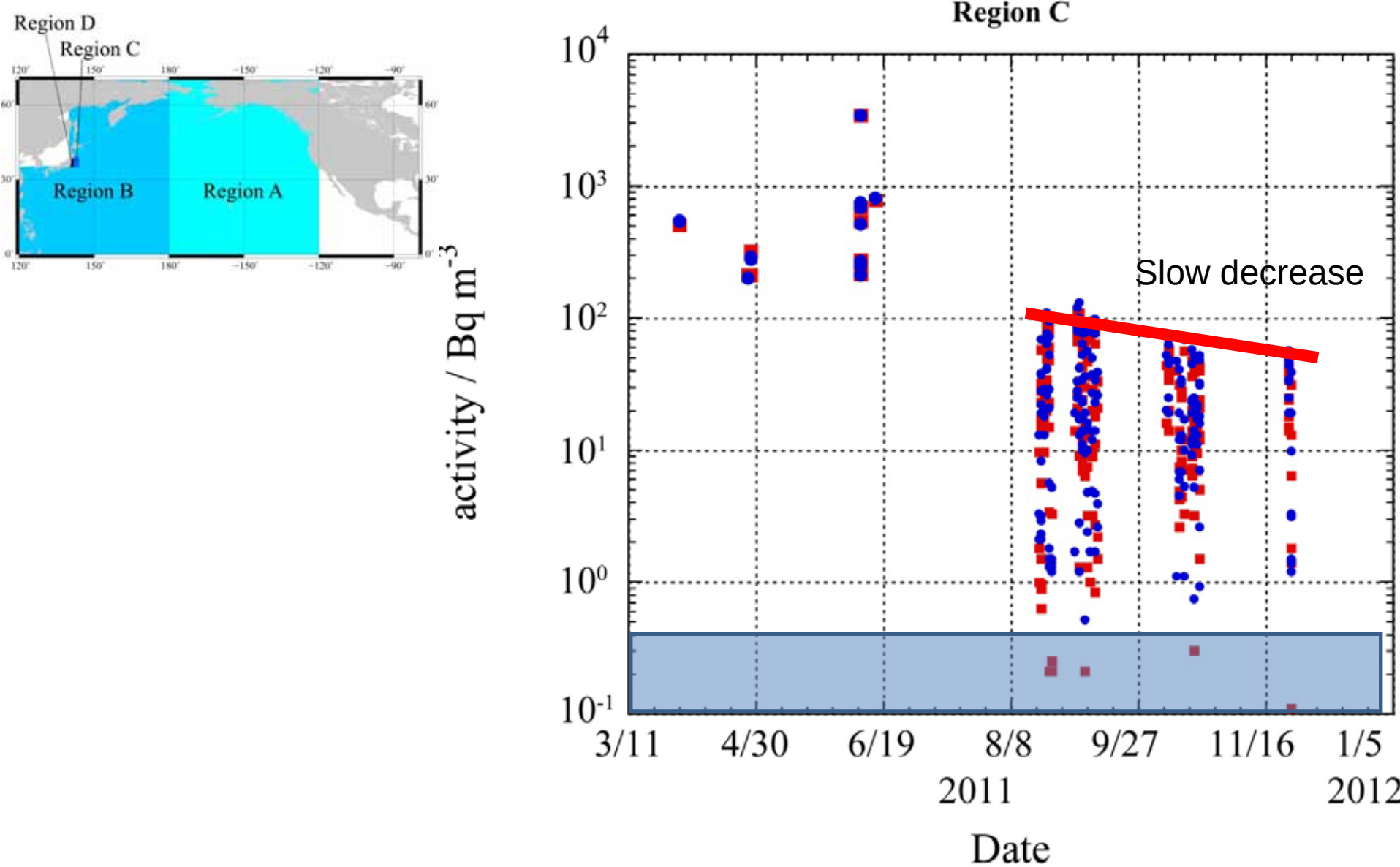


Fig S6. ^{137}Cs and ^{134}Cs activity in region C 35°N—39°N, 140.7°E—144°E

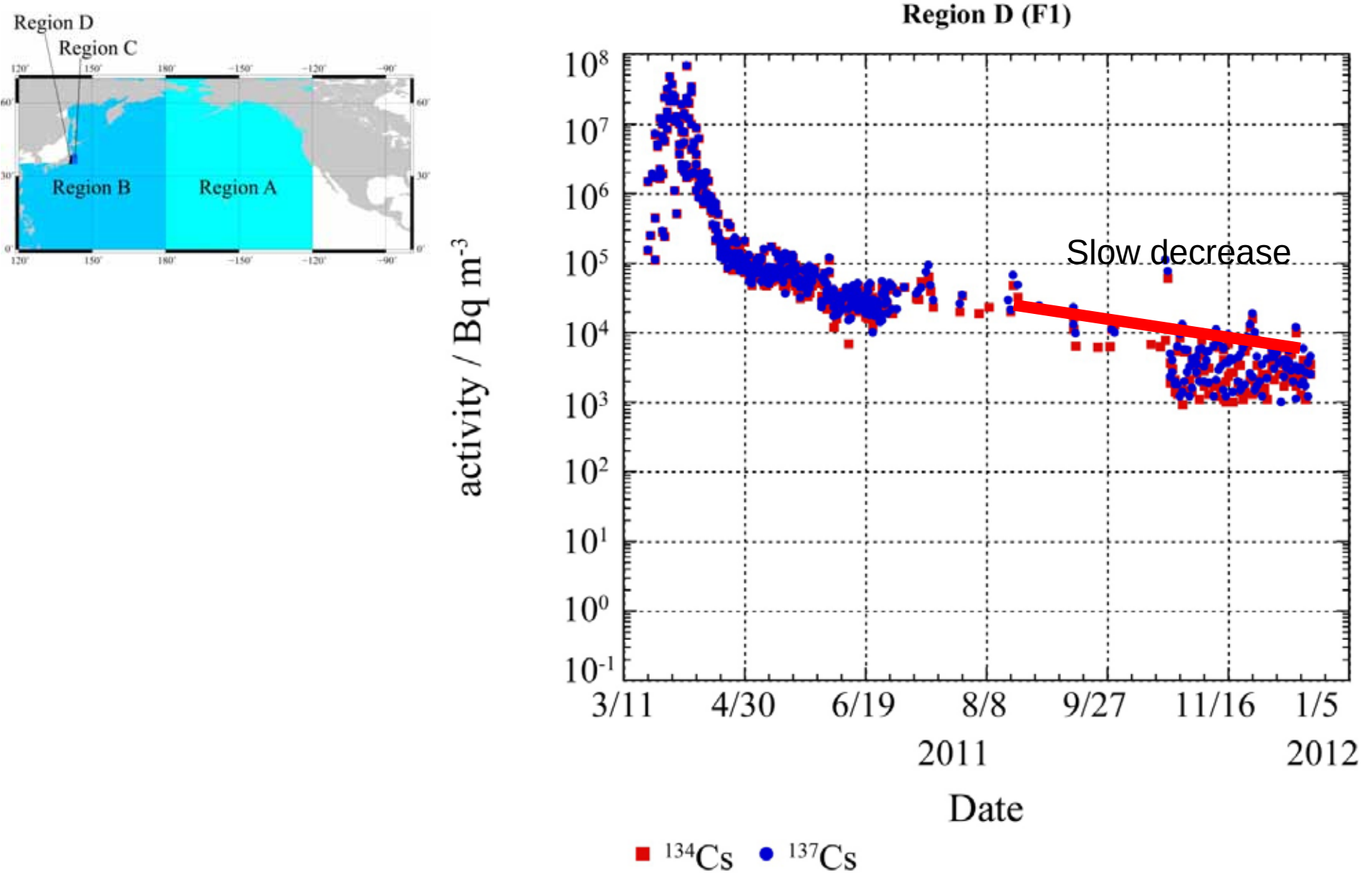


Fig S7. ^{137}Cs and ^{134}Cs activity in region D: close to the FNPP1 site

Summary of temporal and spatial distribution of Fukushima radiocaesium

- Fukushima radiocaesium deposited on wide area in the North Pacific Ocean, especially in western part of subarctic gyre and subtropical gyre.
- In the eastern North Pacific Ocean, maximum ^{134}Cs activity was ca. 10 Bq m^{-3} in April/May 2011.
- Detected ^{134}Cs was Fukushima origin and ^{137}Cs was Fukushima+ pre-existing bomb

8 steps to estimate total amount of released radiocaesium from Fukushima NPP accident

We already have direct discharge estimation. (3.5±0.7 PBq, Tsumune et al., 2011, presentation 14:45 today)

Step 1: prepare first guess of source term scenario of atmospheric release. (8.8 PBq)

Step 2: Three atmospheric transport models to simulate daily deposition

Step 3: Pass daily deposition to an ocean model in the North Pacific Ocean.

Step 4: simulate radiocaesium activity in the sea

Step 5: Compare simulated activities and observed activities to evaluate model simulations.

Step 6: Calculate inventory based on the ocean observations (8.1±2.8 PBq) and in the models.

Step 7: Compare observed inventory and model simulated inventories to have correction factors of the first guess of the released scenario.(factors were 1.7-2.3)

Step 8: Evaluate land portions and ocean

Step 5

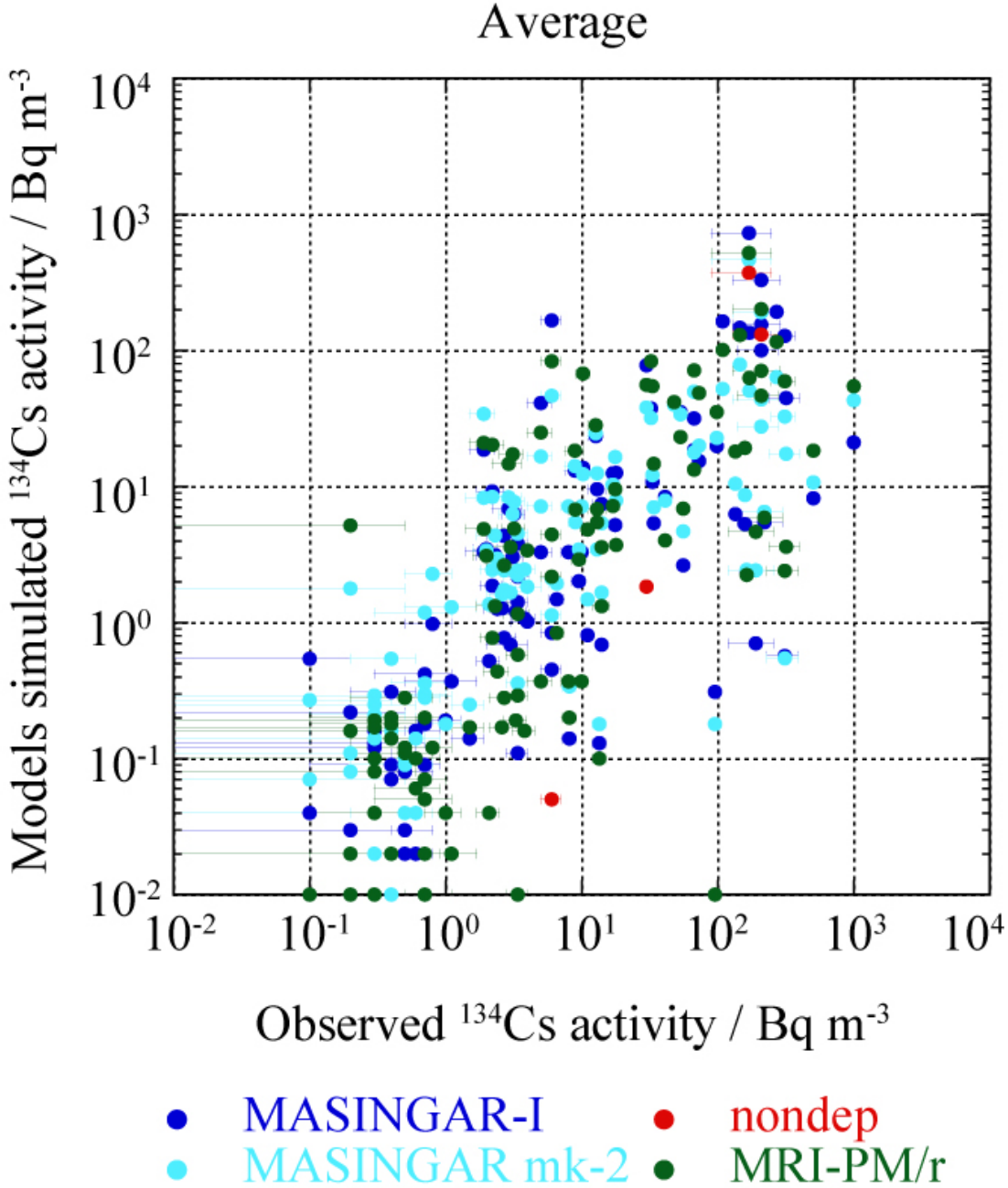


Figure 3 Model results vs. observation results comparis

Step 6 calculate inventory in the ocean

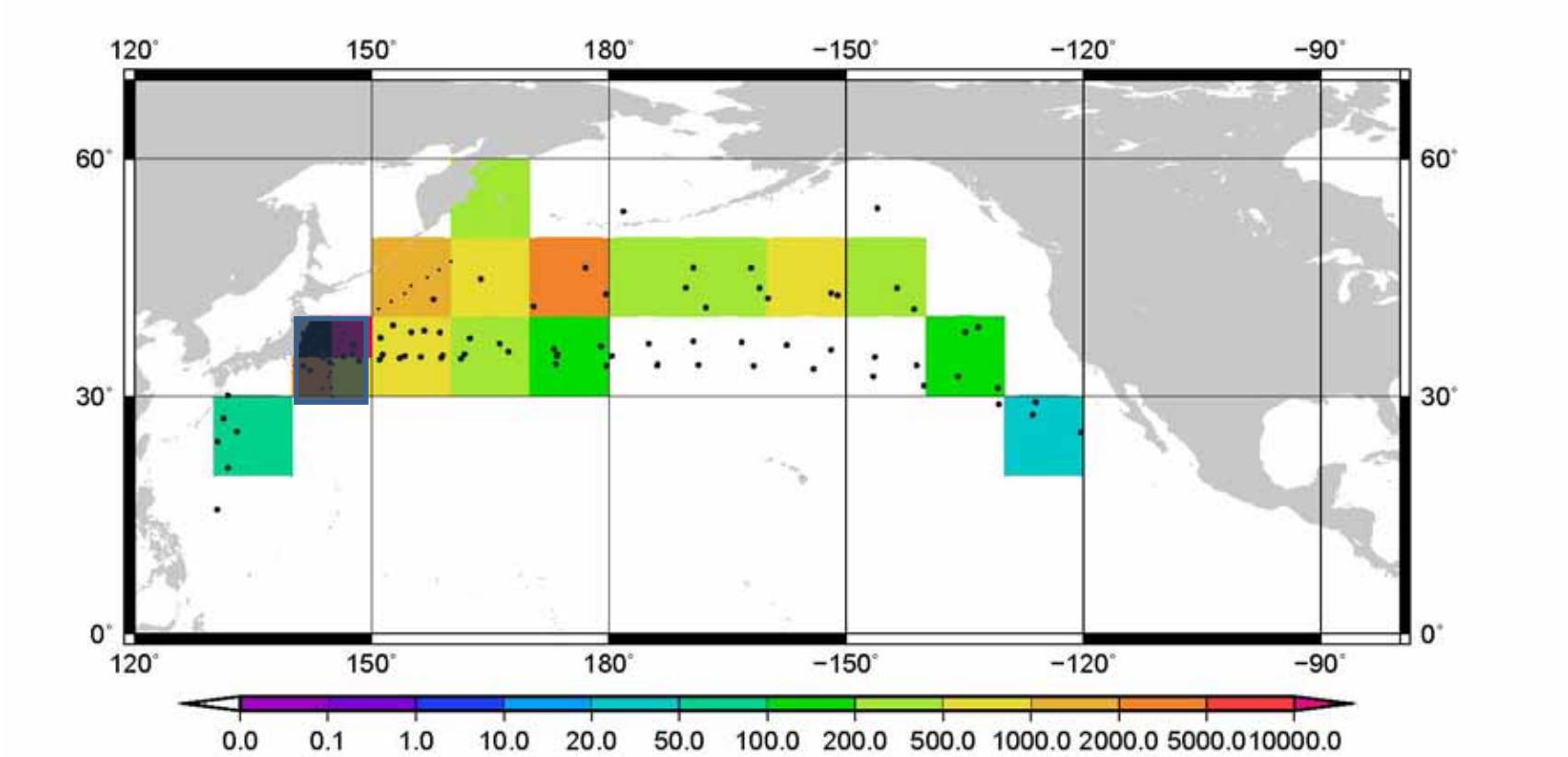
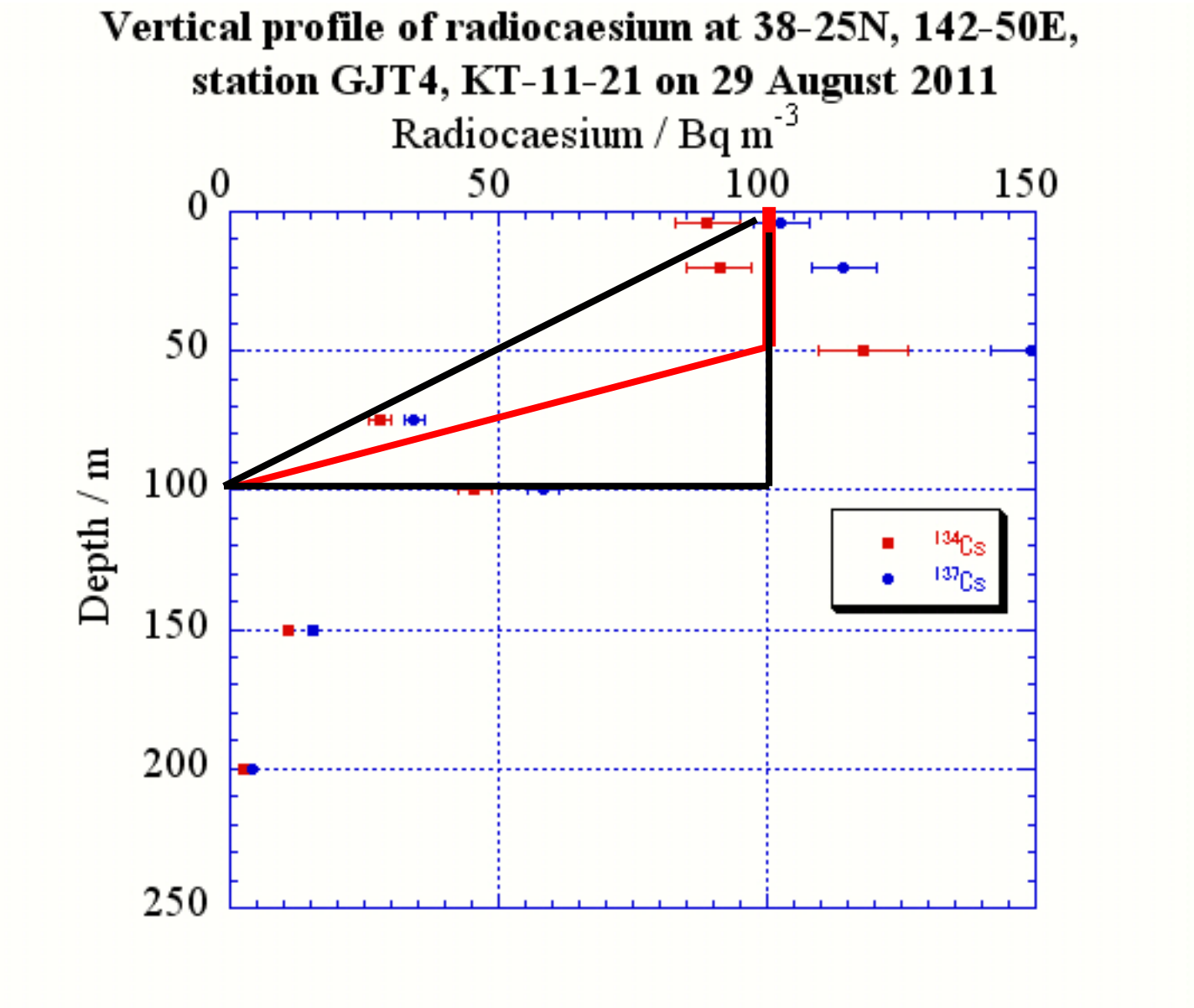


Fig S10. 10 deg mesh for integration of radiocaesium in Bq m^{-2}

Black dots show observation location.

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



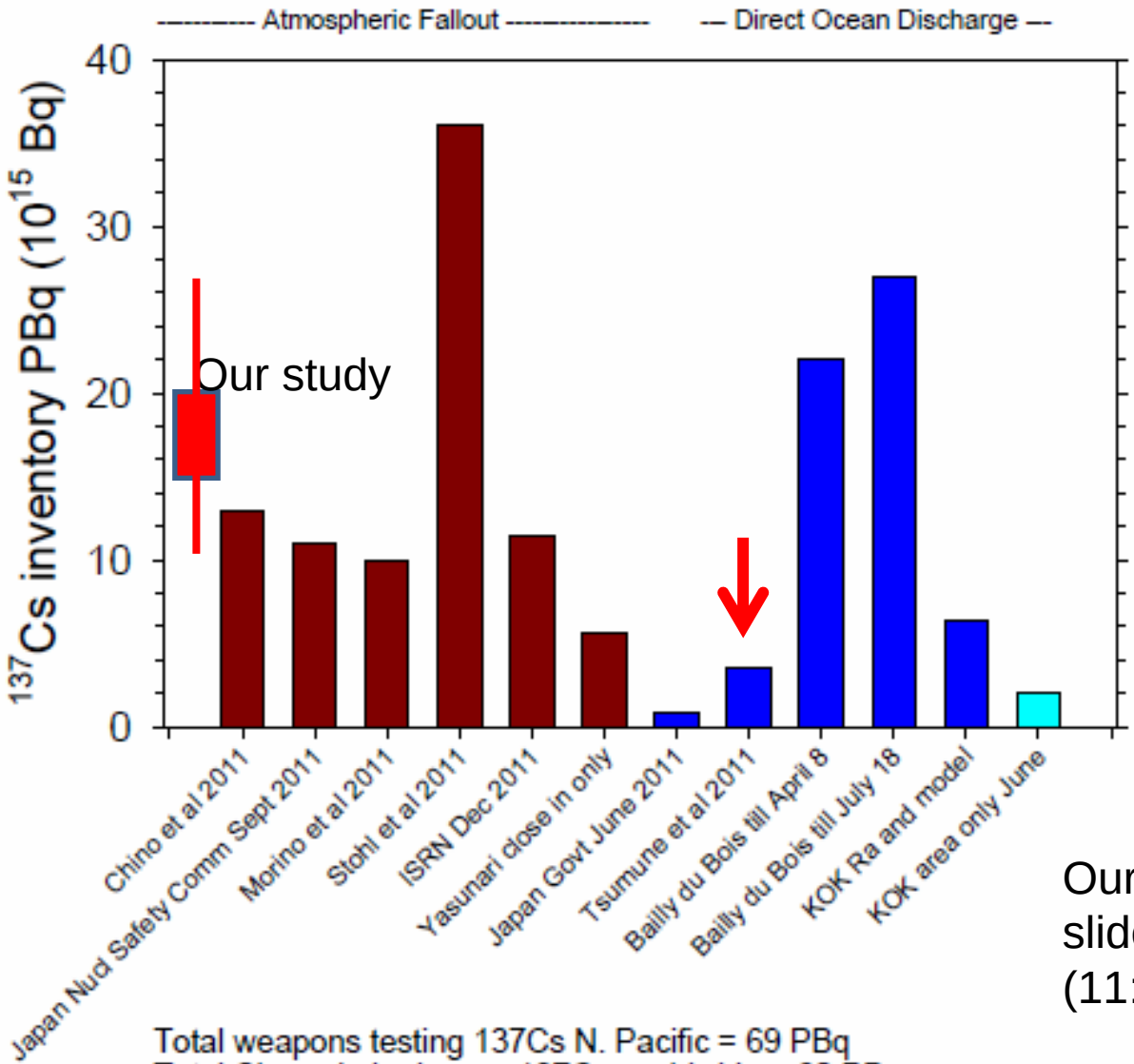
Our assumption to estimate inventory

Summary of budget of ^{137}Cs

- Global fallout as of 1970 290 ± 30PBq [a]
- Observed inventory as of 2002 85 PBq [b]
- Estimated inventory as of 2011 69 PBq [b]
- **Fukushima direct discharge to the North Pacific Ocean 3.5 ±0.7 PBq [c]**
- **Fukushima atmospheric release 15 - 20 PBq [d]**
- **Fukushima deposition on land 3.8 – 6.6 PBq [d]**
- **Total release from Fukushima ca. 19 – 24 PBq [d]**
- (Chernobyl global release in 1986 85 PBq [e])

a: Aoyama, M., Hirose, K., Igarashi, Y., *J. ENVIRON. MONITOR.*, **8**, 431-438, 2006
b: Aoyama unpublished data estimeted 3-D dostribution of ^{137}Cs
c: Tsumune et al., 2011,
d: this study
e: IAEA, Proceeding of an International Conference, Vienna, 8-12 Apr. 1996

Estimates of total releases from Fukushima



Total weapons testing 137Cs N. Pacific = 69 PBq
Total Chernobyl releases 137Cs worldwide = 60 PBq
Total Chernobyl releases 137Cs to ocean worldwide = 15-20 PBq
Total Fukushima releases- 137Cs atmospheric <10 to >35 PBq
- 137Cs direct ocean discharge <1 to >27 PBq

Our results are added to Ken's slide from his presentation (11:30 today)

Conclusions

1. Temporal and spatial distributions of radiocaesium from Fukushima were clearly observed in the North Pacific Ocean and coupled atmospheric/ocean models simulate the activity of radiocaesium well.

2. Total amount of the atmospheric deposition in the North Pacific Ocean from Fukushima was **12 – 15 PBq** for both ^{134}Cs and ^{137}Cs. Newly added **12 – 15 PBq** by atmospheric deposition and **3.5 ± 0.7 PBq** of direct discharge made the **22-27 %** increase of total ^{137}Cs inventory in the North Pacific Ocean.

3. Our study also gives us that total amount of released radiocaesium from the Fukushima NPP1 accident to the air was about **15 – 20 PBq** for both ^{134}Cs and ^{137}Cs. Total deposition on land might be around **3.4 – 6.2 PBq** which corresponds to **23 -33%** of total amount to the air.

Acknowledgements

Seawater sampling: Nippon Yusen Kaisha, the NYK Group's corporate social responsibility ,

Captains and crew of NYK ships

Sample treatments: Mr. Tomita at KANSO , Japan

Ocean model: Ms. Taguchi at DCC, Japan

possible pathway of radiocaesium

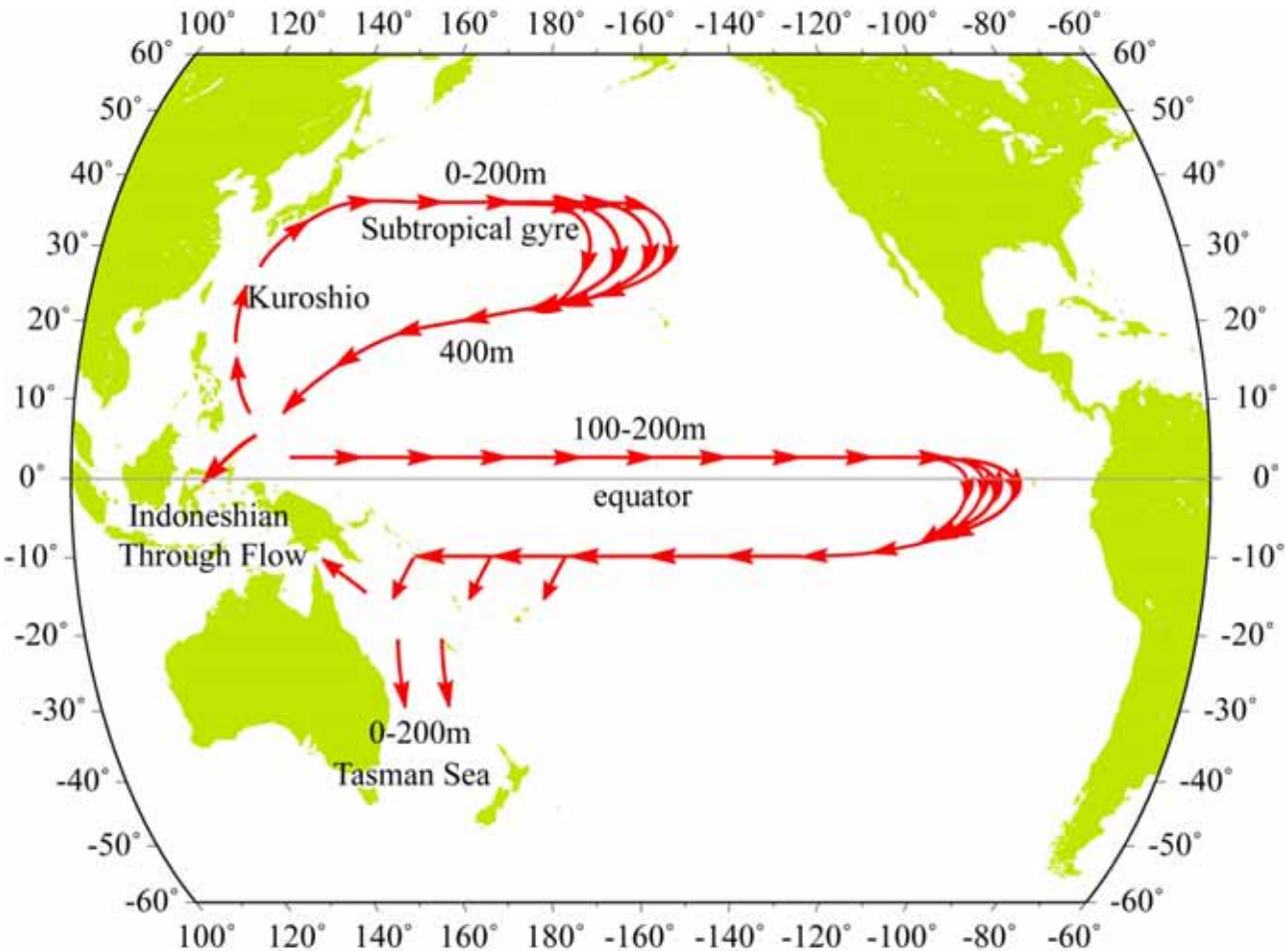


Fig. S2 Possible pathway of ^{137}Cs in the Pacific Ocean