Transport of Fukushima Radioactivity to North America

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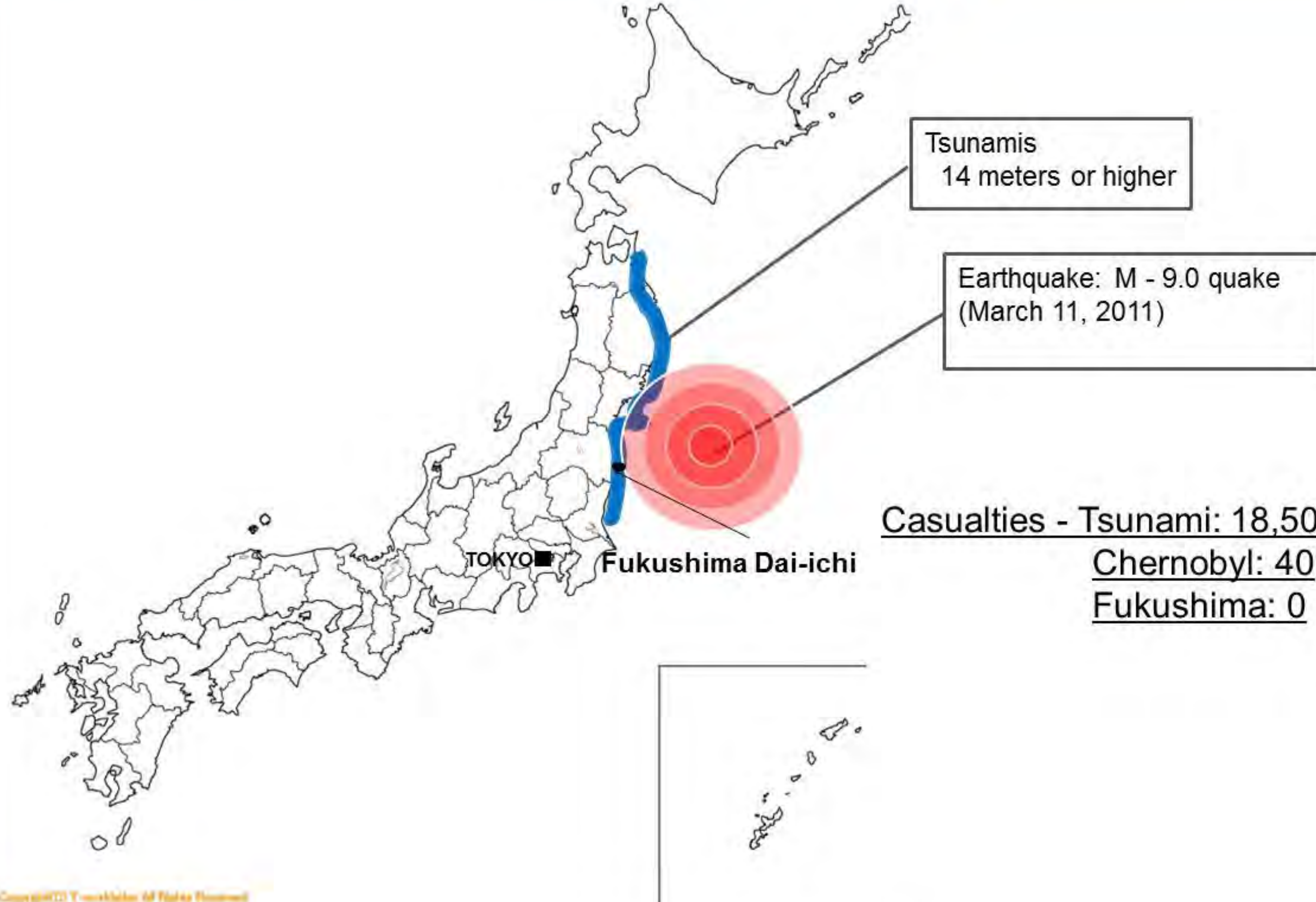
Earthquake ➡ Tsunami ➡ Nuclear Accident



Casualties - Tsunami: 18,500
Chernobyl: 40
Fukushima: 0

Devastating tsunami sweeps across northeastern Japan…

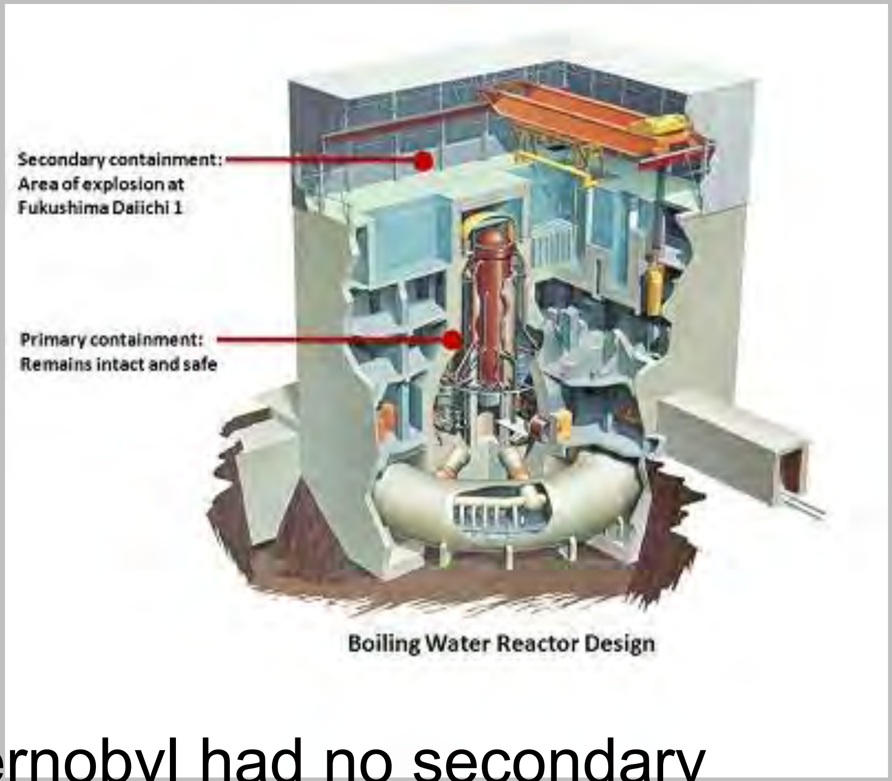
…approaches Fukushima Dai-ichi nuclear stations.

…tsunami swamps cooling pumps

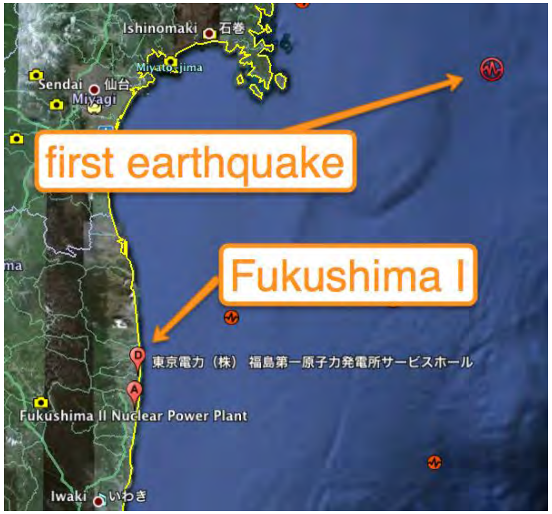
Why did the explosions occur?

Zirconium (Zr) in fuel assemblies reacts with steam (H_2O) at high temperatures to produce hydrogen. H_2 was vented from nuclear core when cooling systems failed, but then reacted with O_2 explosively in outer containment buildings.

Cores did not explode.

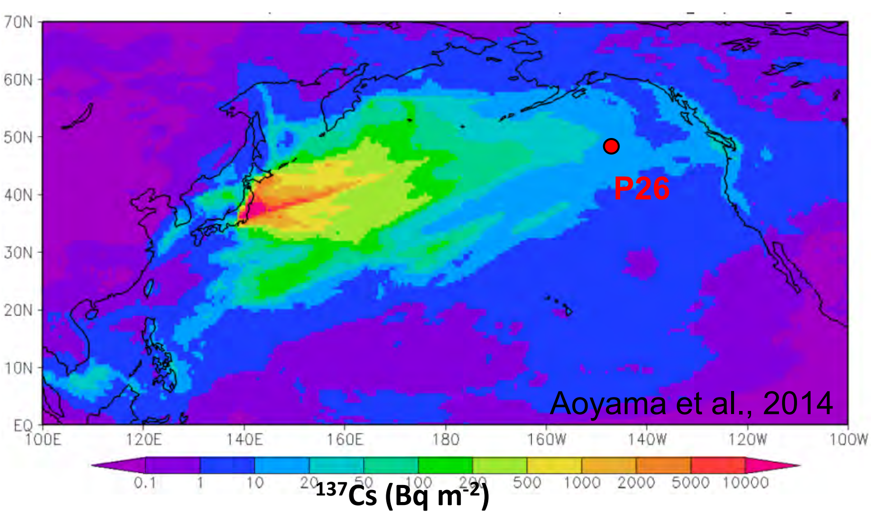


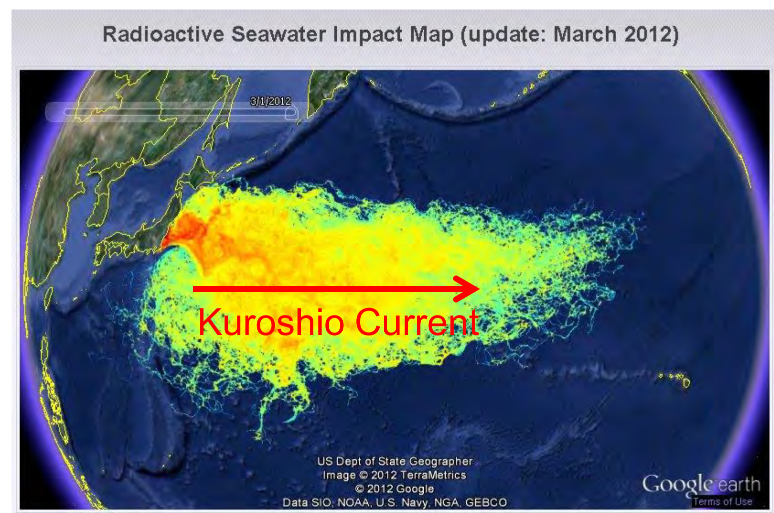
Chernobyl had no secondary containment!



The March 11, 2011 earthquake-triggered tsunami resulted in damage to four of the six Fukushima nuclear power reactors.

Note: Accident resulted in no immediate deaths…some projected long term health impacts in evacuation zone.





Atmospheric transport of radioactivity plume was directed farther northeastward compared to more eastward transport of water borne plume driven by Kuroshio Current.

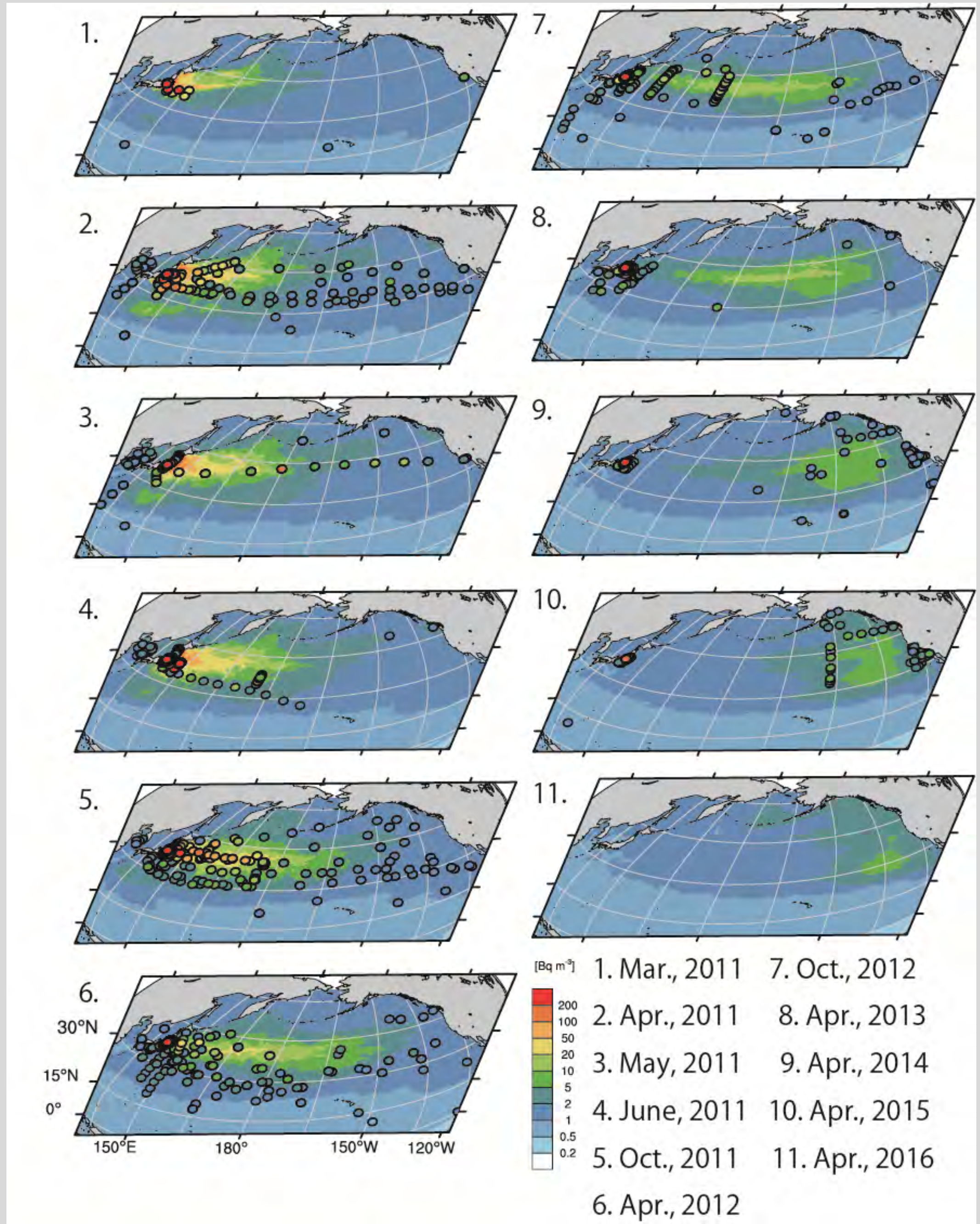


Figure 1. Time-series of measured ^{137}Cs in surface seawater overlain on model derived prediction (Tsubono et al., 2016). Color bar applies to both data and model (Bq m^{-3}). Observed data compiled from expanded MARIS database.

Fukushima Daiichi-derived radionuclides in the Ocean: transport, fate, and impacts

Ken Buesseler, Minhan Dai, Michio Aoyama, Claudia Benitez-Nelson, Sabine Charmasson, Kathryn Higley, Vladimir Maderich, Pere Masqué, Deborah Oughton and John N. Smith, 2017.

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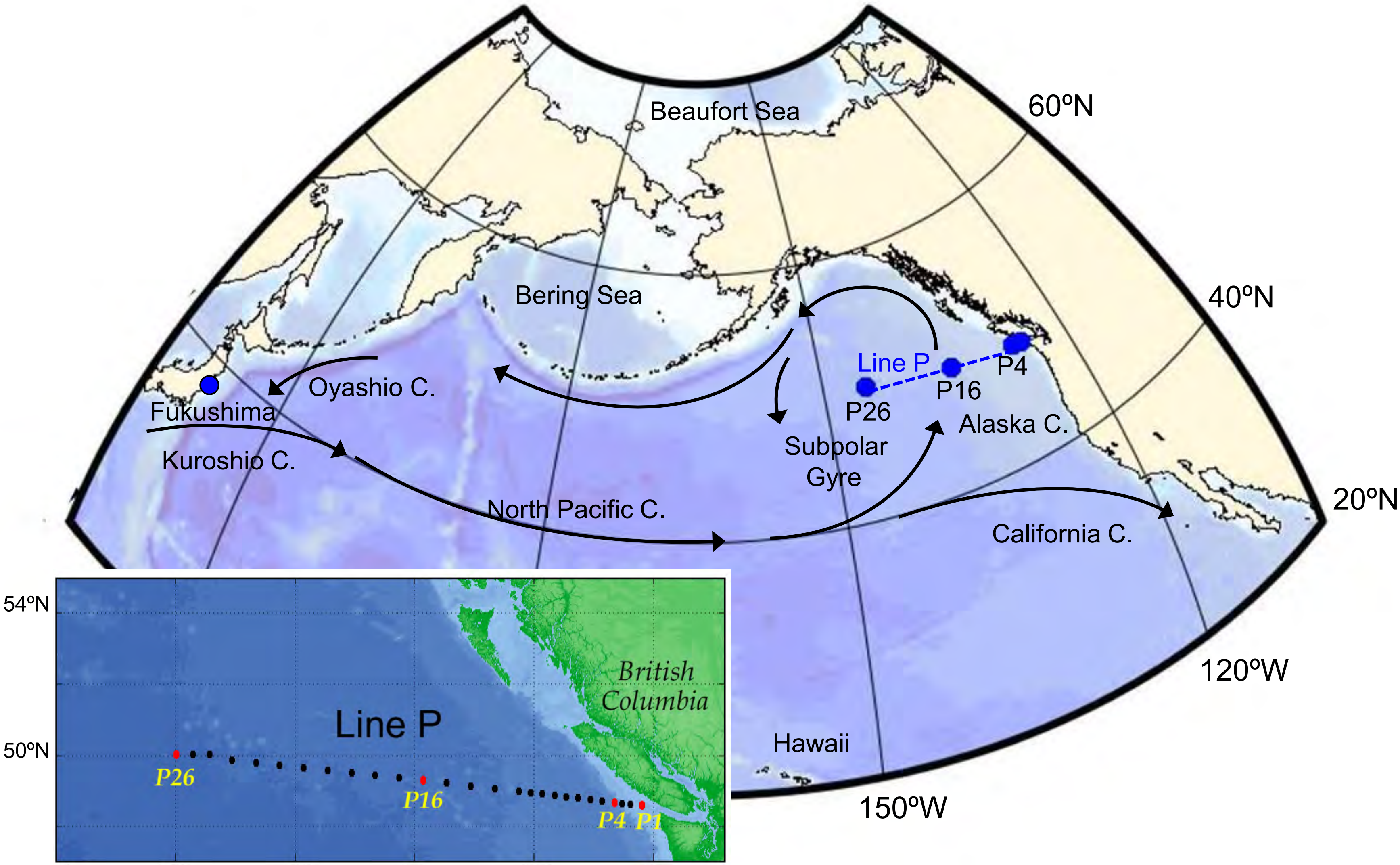
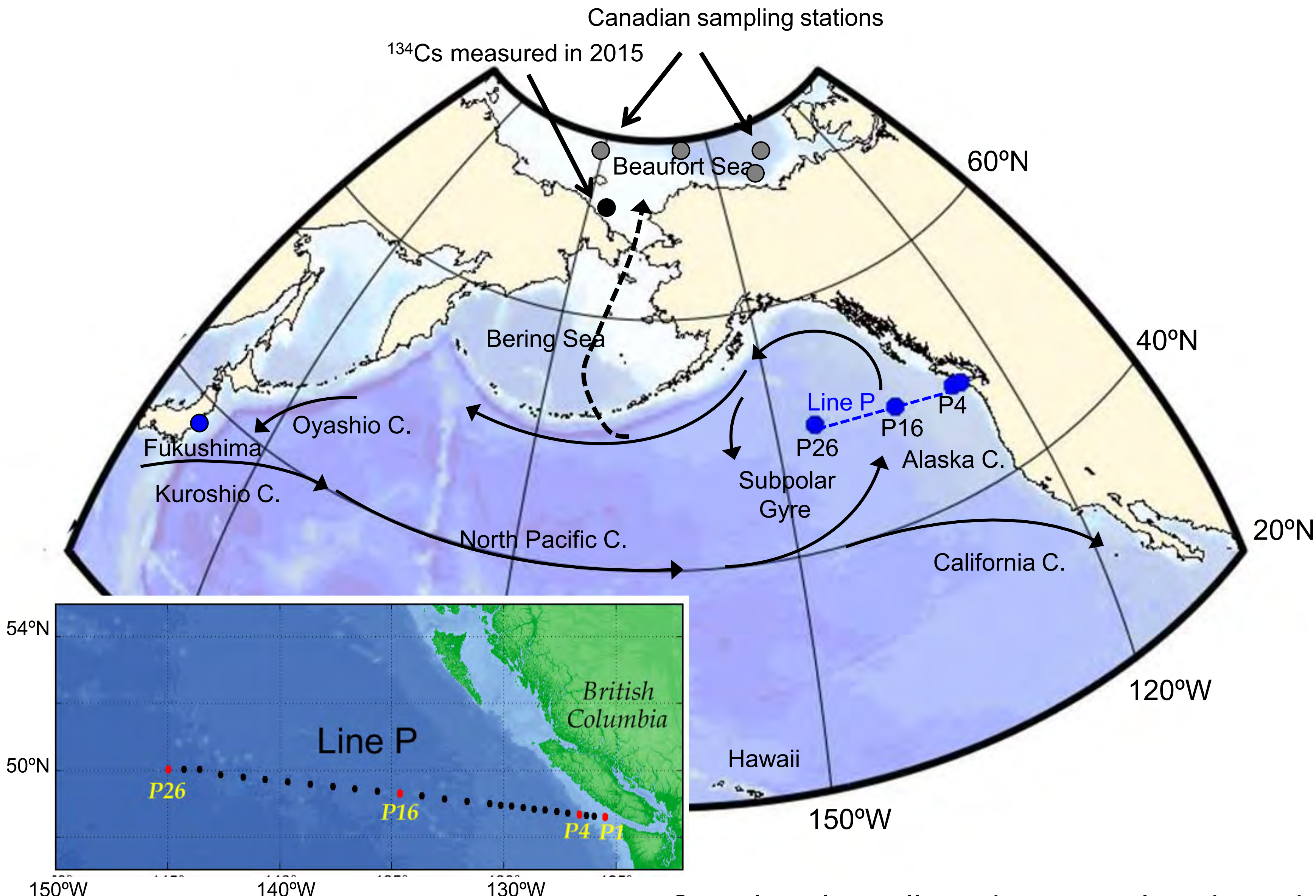
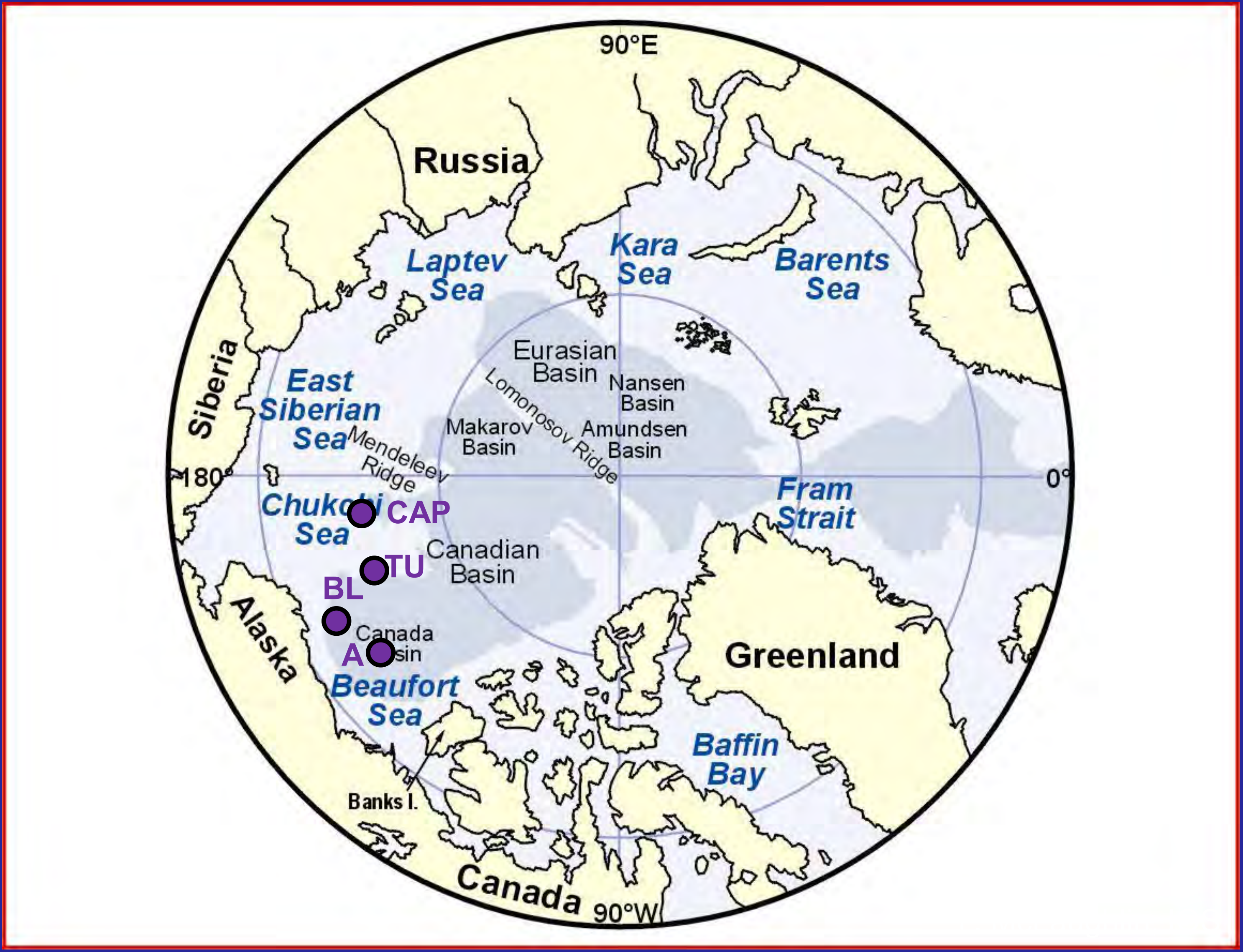


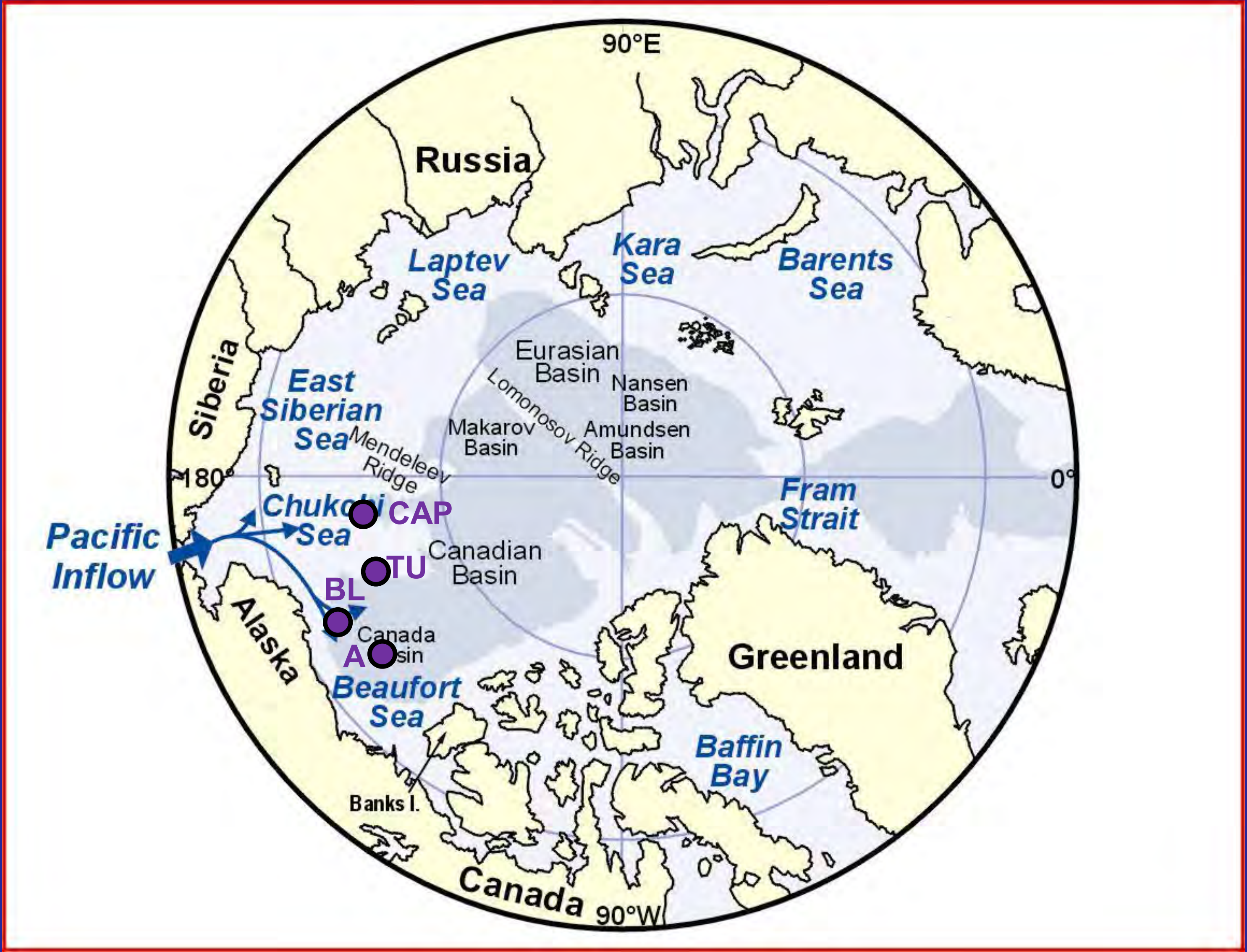
Fukushima radioactivity signal transported eastward in North Pacific Current which splits into northward flowing Alaska current and southward flowing California Current. Seawater samples (20-60 l) first collected at Stas. P4 and P26 on Line P in June 2011, 4 months after the accident.



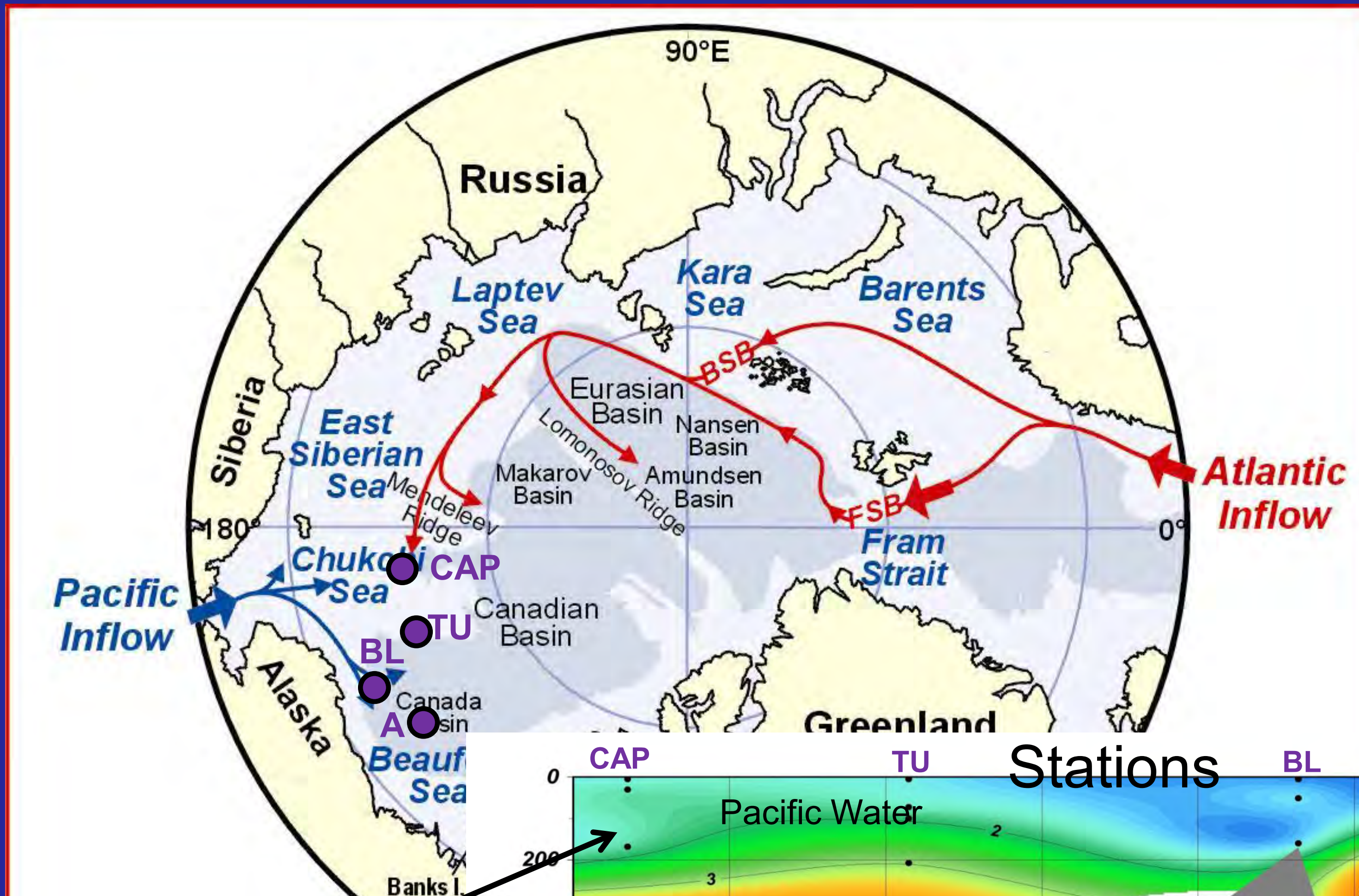
Samples also collected at several arctic stations to evaluate Pacific Water inflow of radioactivity to the Beaufort Sea.



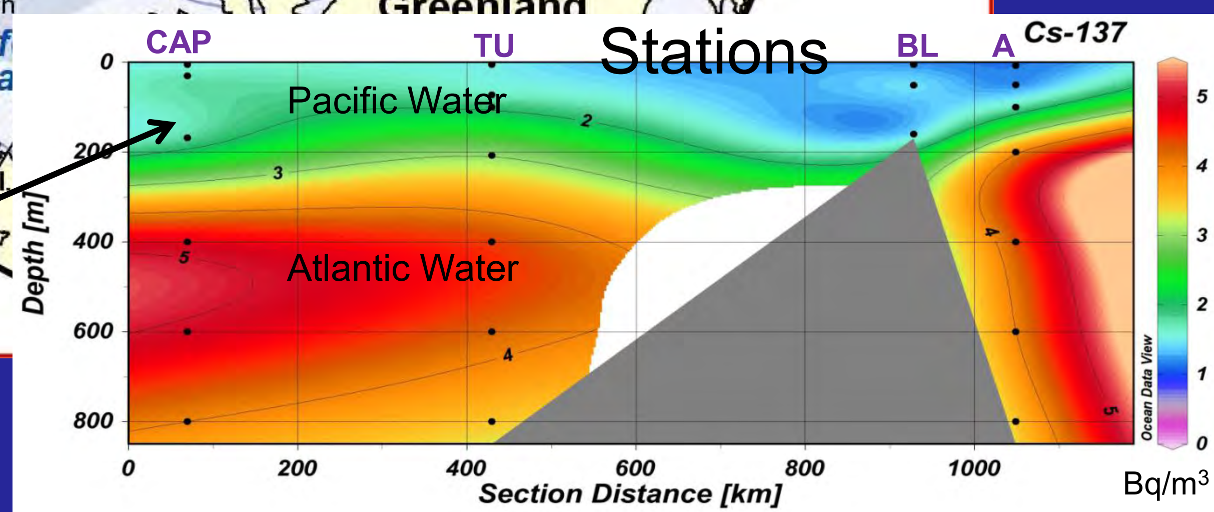
Samples collected on CCGS Louis S. St. Laurent – Sept., 2012, 2014, 2015, 2016



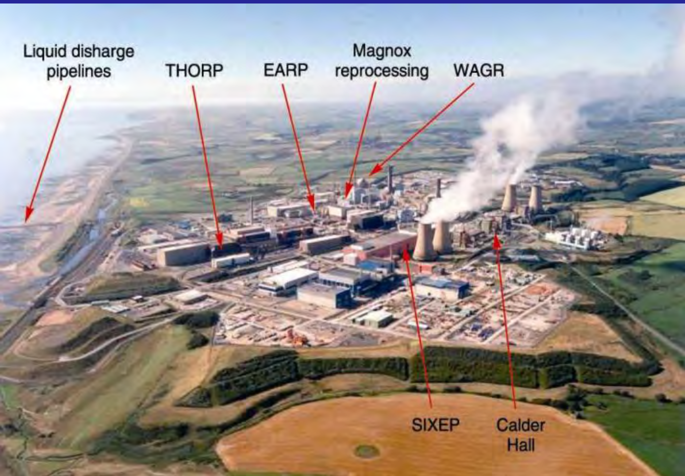
90°E
Russia
Laptev Sea
Kara Sea
Barents Sea
Siberia
East Siberian Sea
Eurasian Basin
Nansen Basin
Amundsen Basin
Lomonosov Ridge
Makarov Basin
Mendeleev Ridge
180°
0°
Fram Strait
Chukchi Sea
CAP
Pacific Inflow
TU
Canadian Basin
BL
Alaska
Canada Basin
A
Beaufort Sea
Greenland
Baffin Bay
Banks I.
Canada
90°W

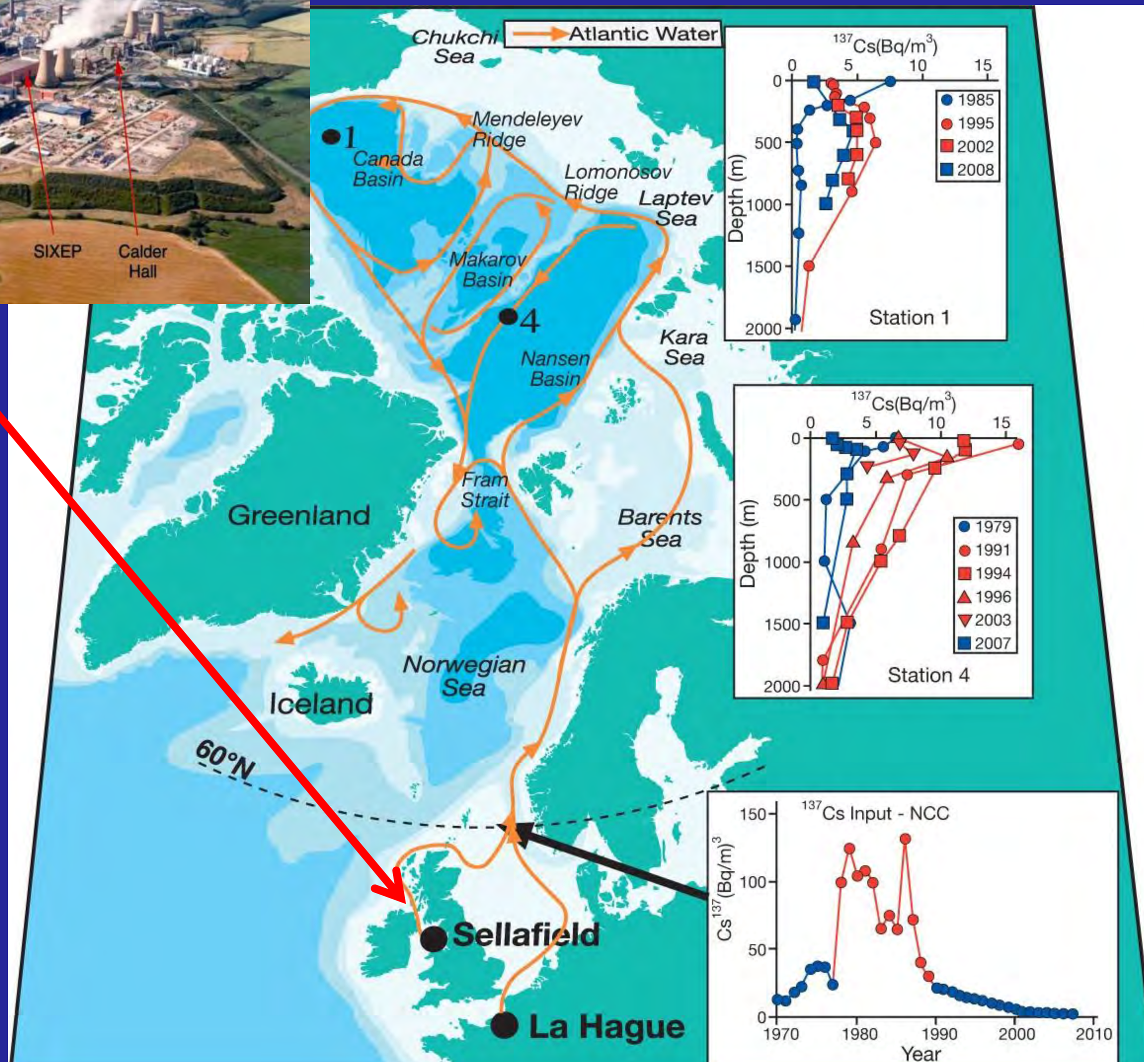


Only fallout ^{137}Cs measured in Pacific Water in 2012, 2014, 2015



^{137}Cs comes from Sellafield: a nuclear fuel reprocessing plant and the only global point source for radioactivity discharges to ocean comparable to Fukushima.



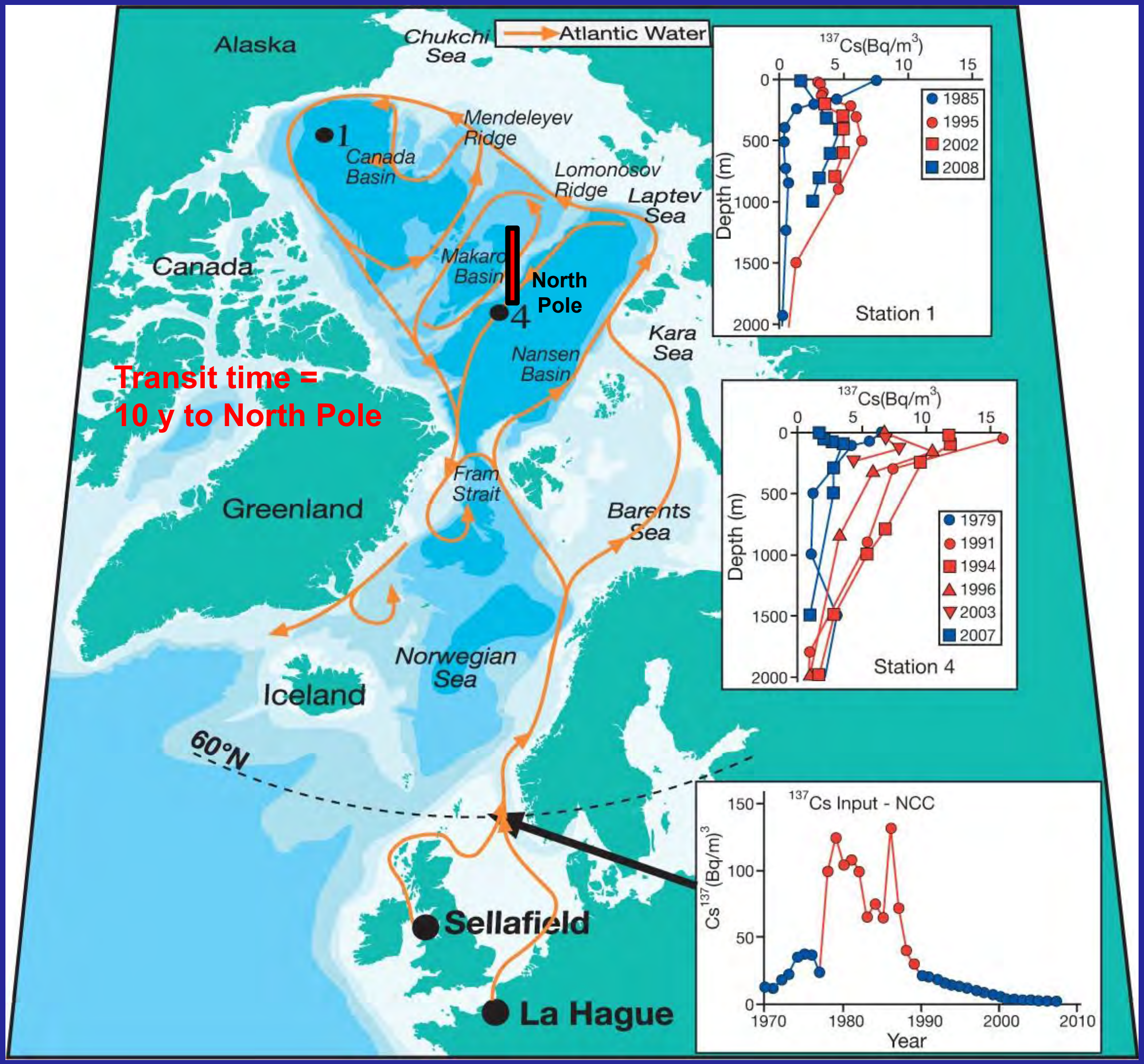


Fukushima = 15-30 PBq (2011)

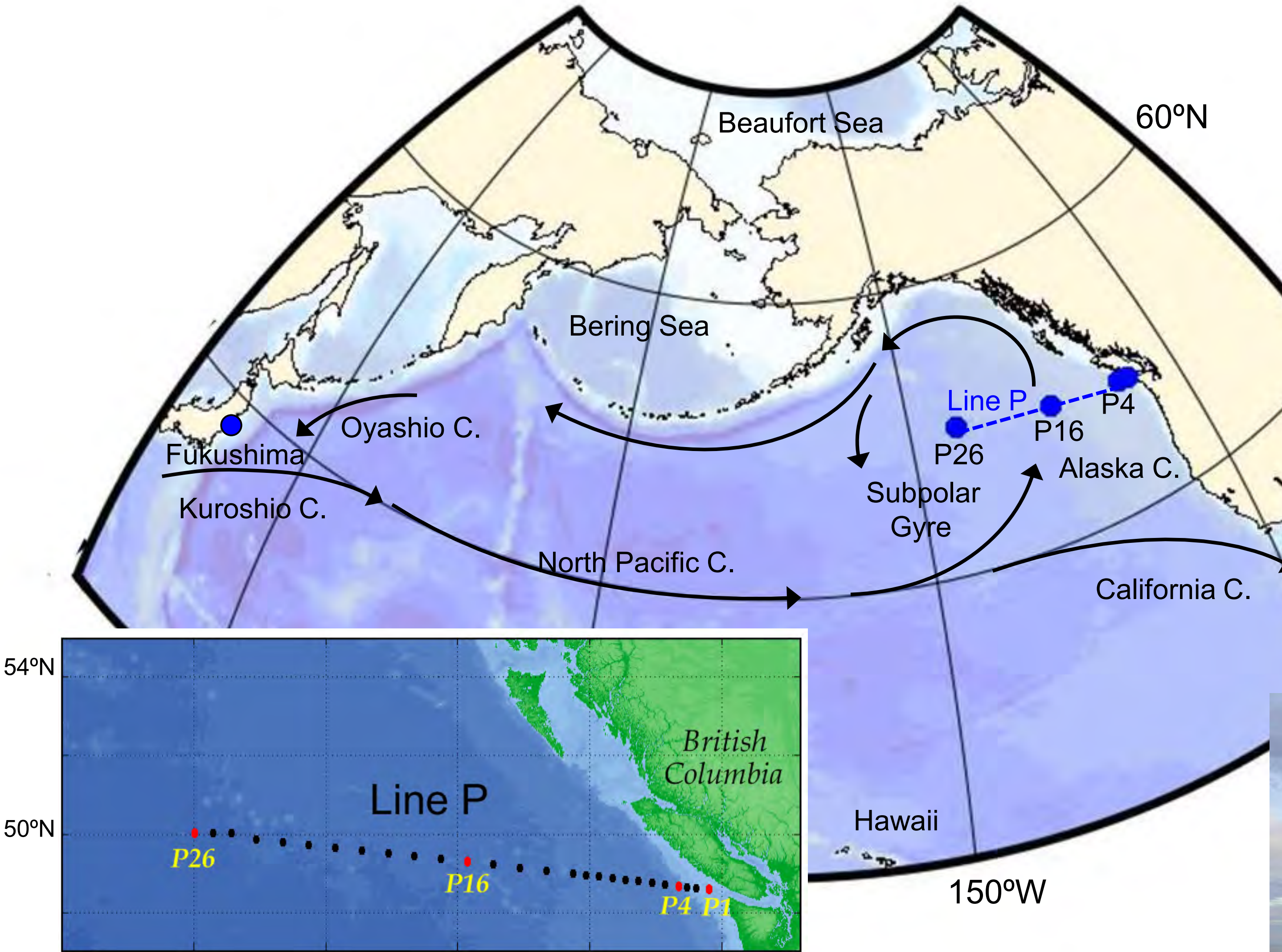
Sellafield = 40 PBq (1955-2012)

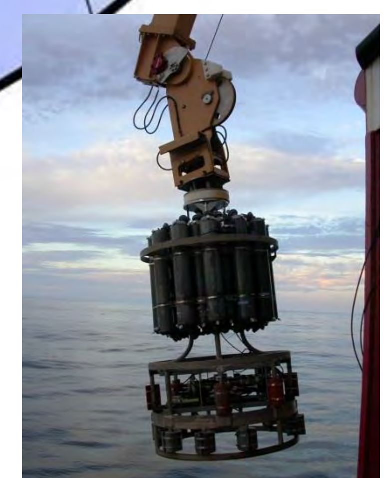
^{137}Cs is transported northward into the Arctic Ocean to the North Pole (Sta. 4) and Canada Basin (Sta. 1). Red water depth profiles show arrival of peak (inset) inputs. Comparison with input function used to estimate circulation time scales, eg. 10 y to North Pole.

Circulation of ^{137}Cs in Arctic Ocean



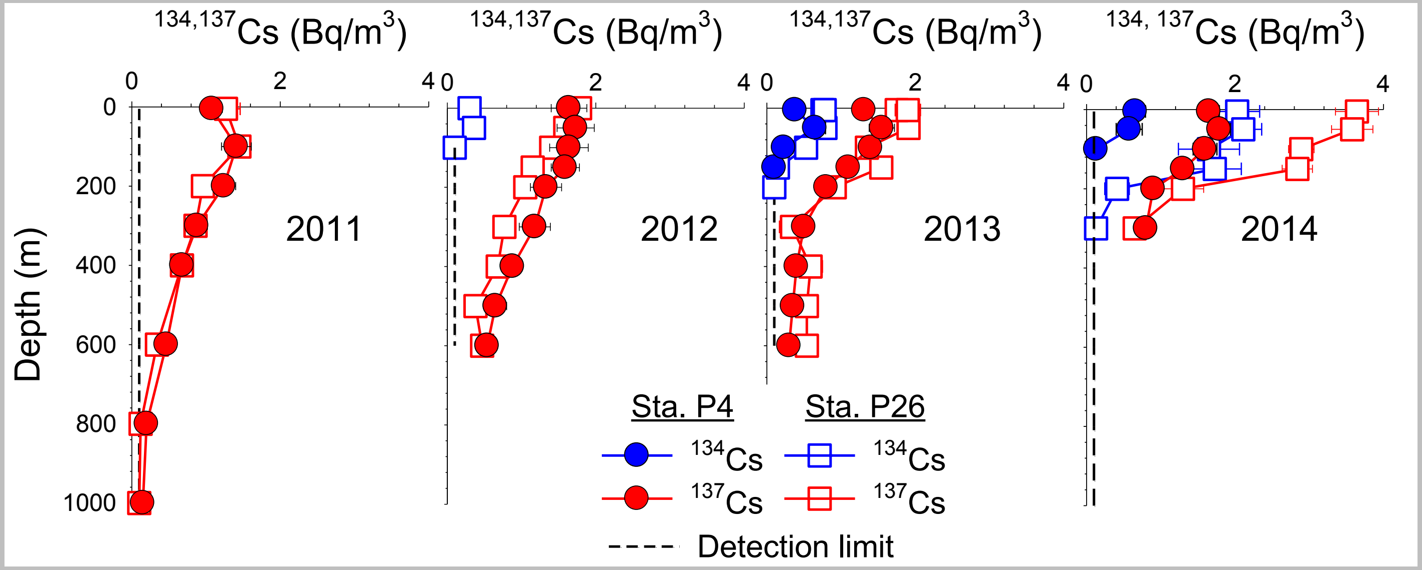
^{137}Cs is transported northward into the Arctic Ocean to the North Pole (Sta. 4) and Canada Basin (Sta. 1). Red water depth profiles (inset) show arrival of peak inputs.

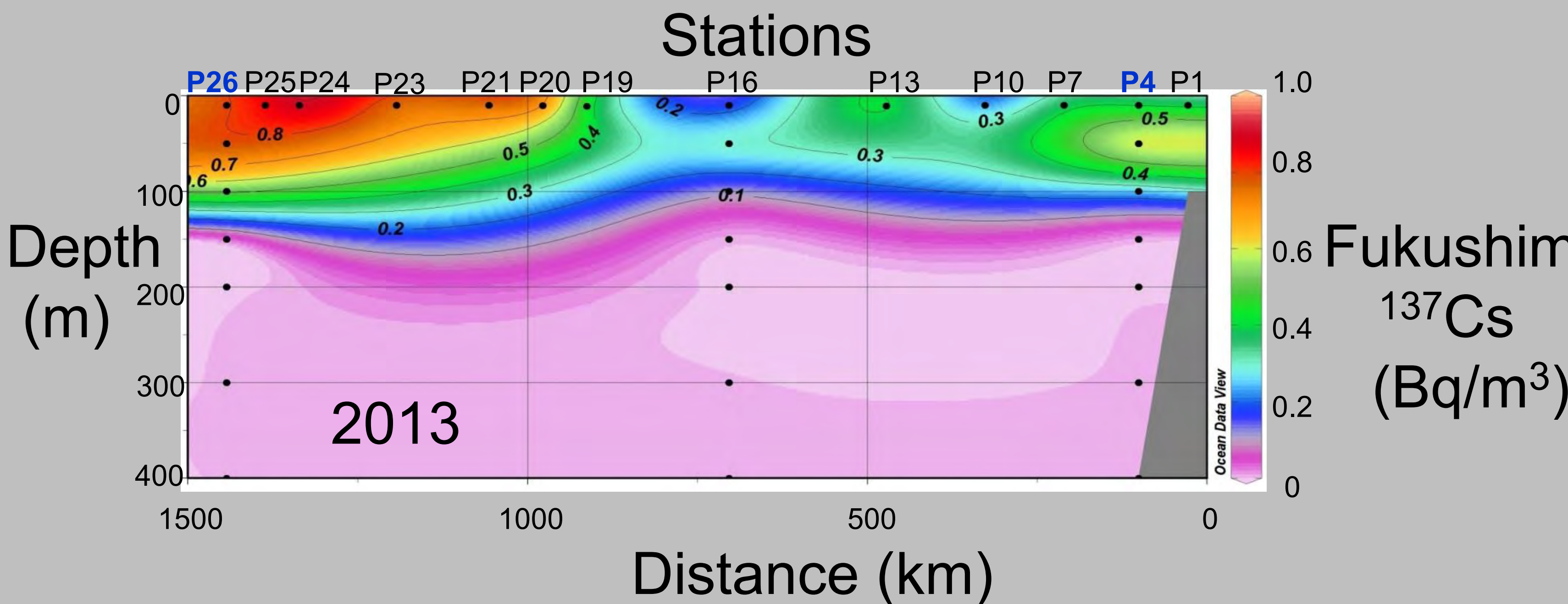




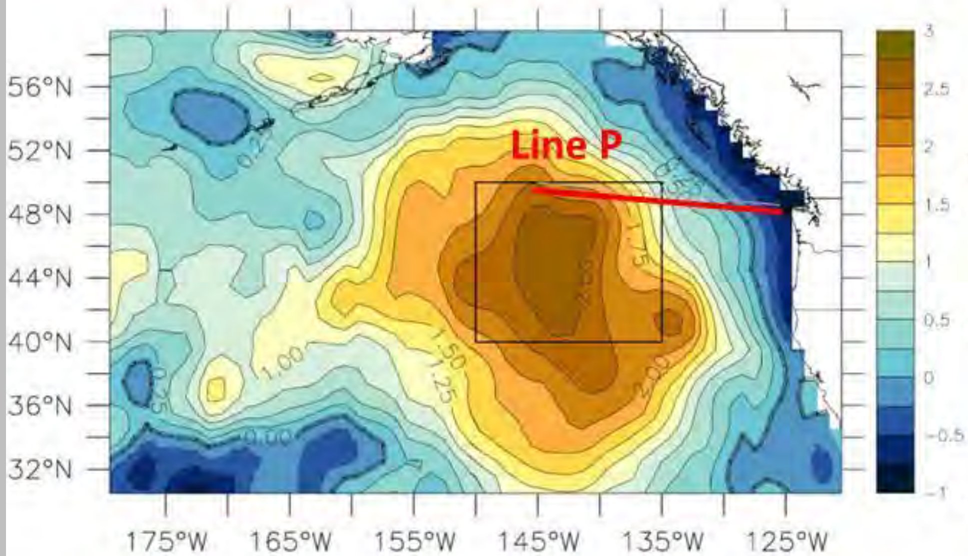
Seawater samples of about 60 l collected using standard niskin bottles to depths of 500 - 1000 m on CCGS Tully.

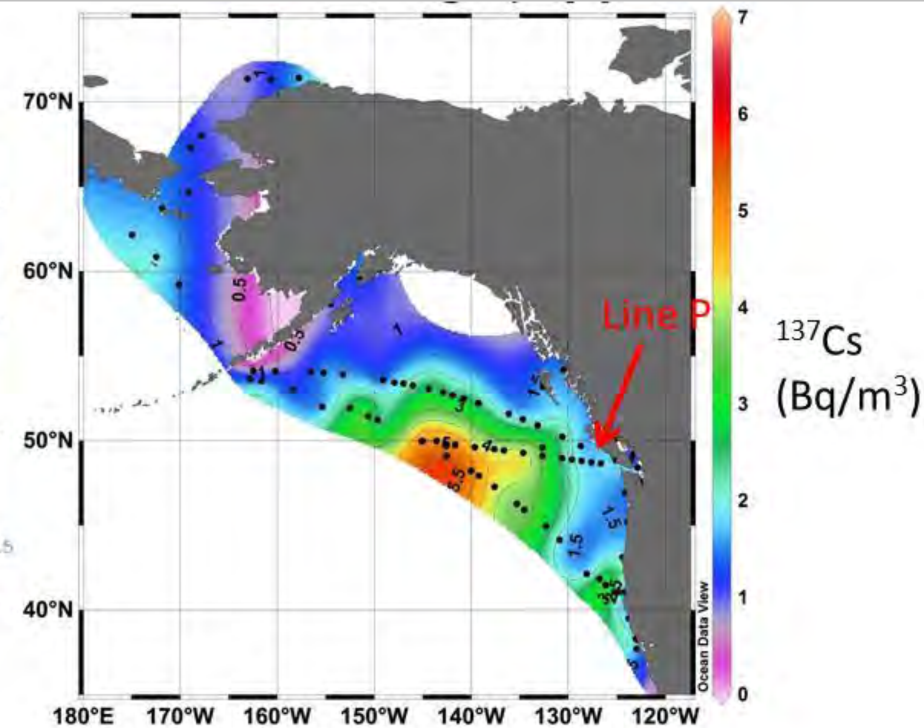
Seawater passed through KCFC resin cartridges at sea, shipped to BIO and analysed for ^{134}Cs and ^{137}Cs using Ge hyperpure Gamma ray detectors.





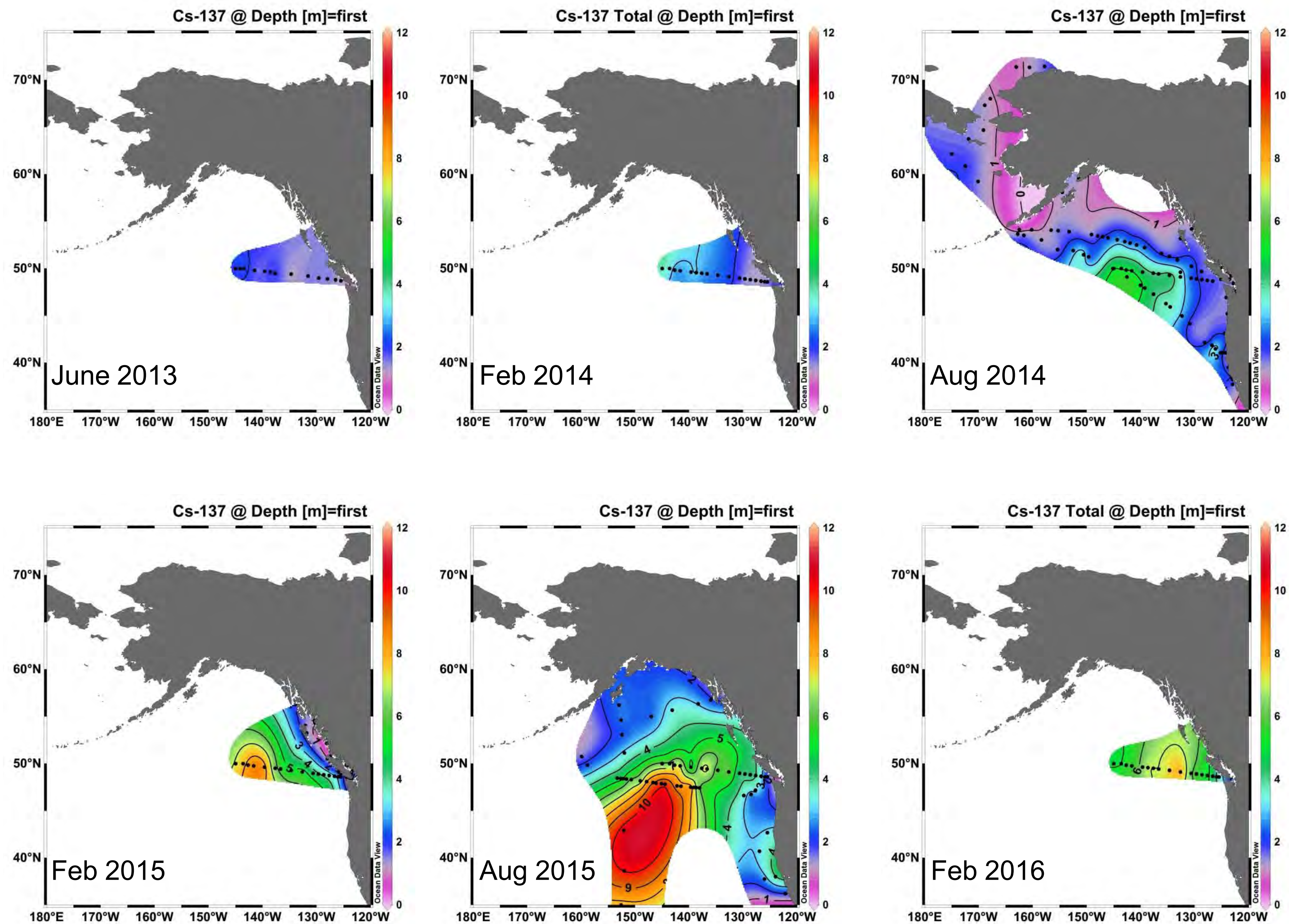
^{134,137}Cs time series at sta. P4 and P26 shows arrival of Fukushima ^{134}Cs and ^{137}Cs on Line P. Water-depth section indicates an eastward, decreasing ^{137}Cs concentration gradient from P26 to P1 in the upper 100 m that reflects ^{137}Cs transport from Fukushima onto the continental shelf.



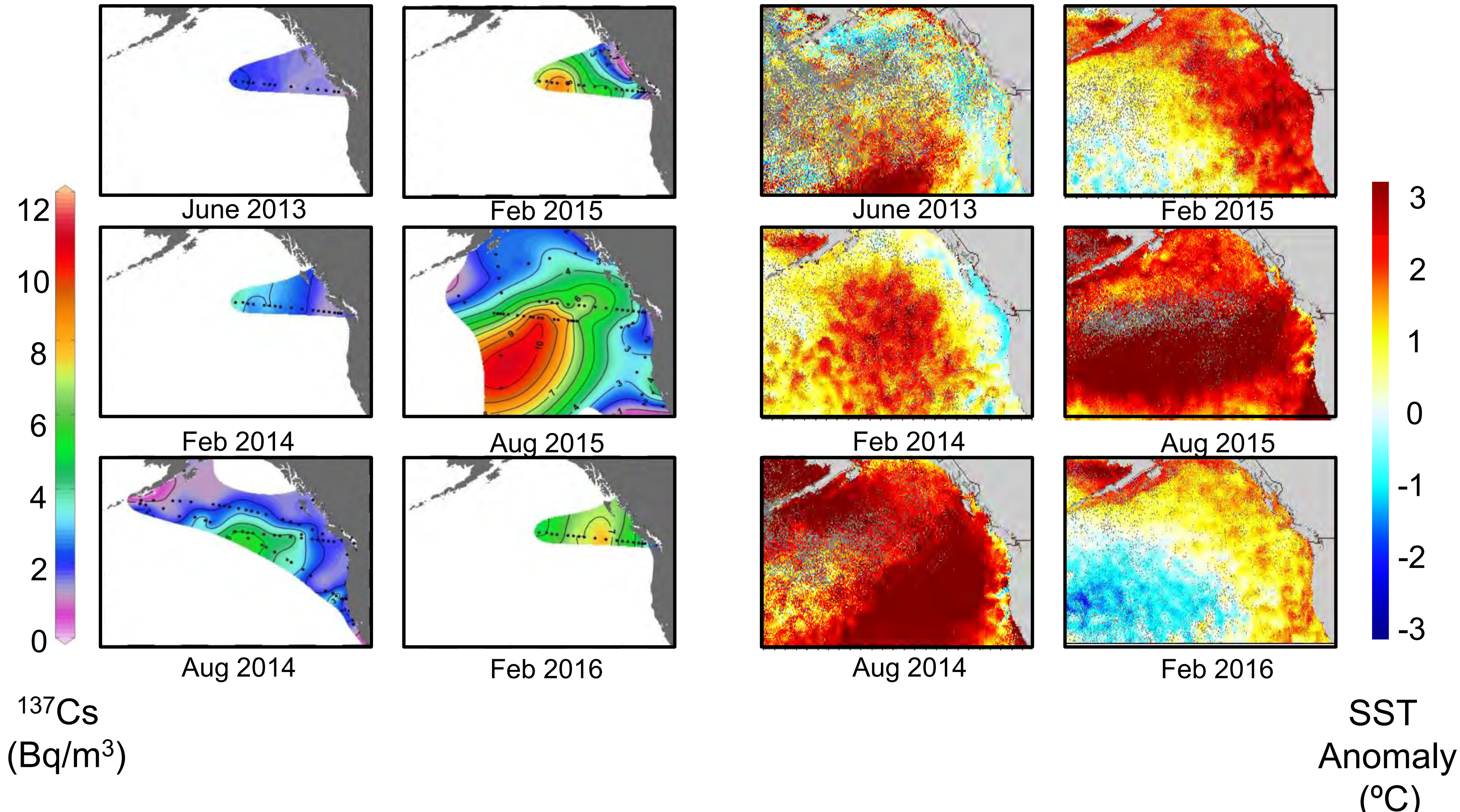


Sea surface temperature anomalies (°C) in NE Pacific Ocean for February 2014. Anomalies are calculated relative to the mean from 1981 – 2010 (Bond et al., GRL, 2015).

^{137}Cs surface water distribution (fallout background = 1.5 Bq/m^3) in NE Pacific from 3 cruises in July-Sept., 2014. Maximum ^{137}Cs is associated with the “warm blob” of high temperature surface mixed layer water that has formed offshore as a result of anomalously low and steady westerly winds and reduced convective mixing.

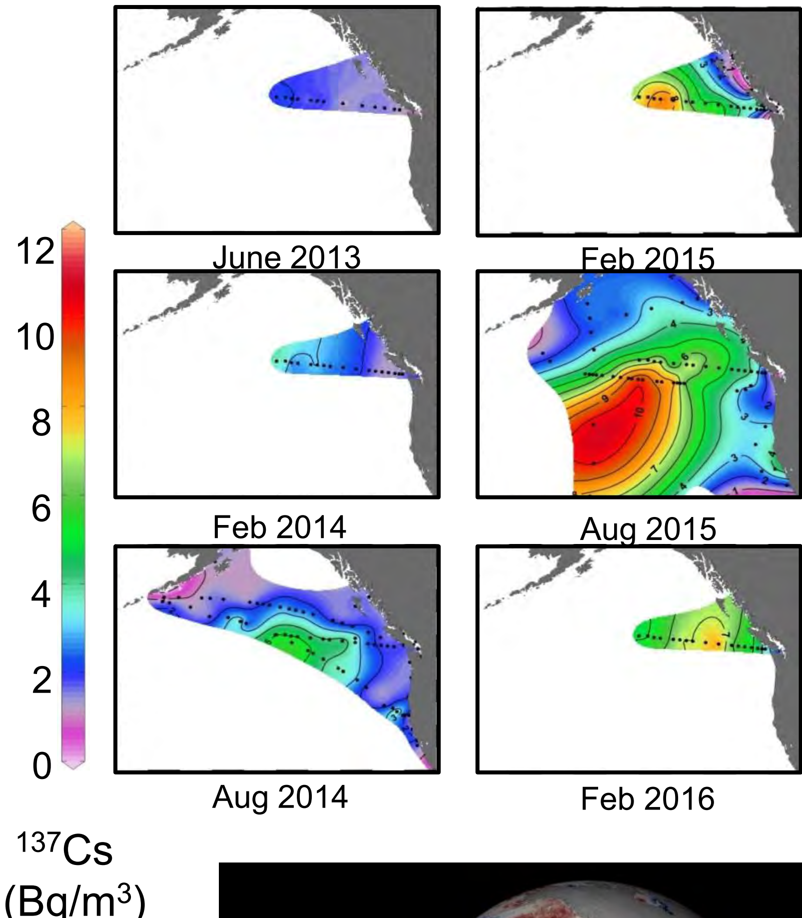


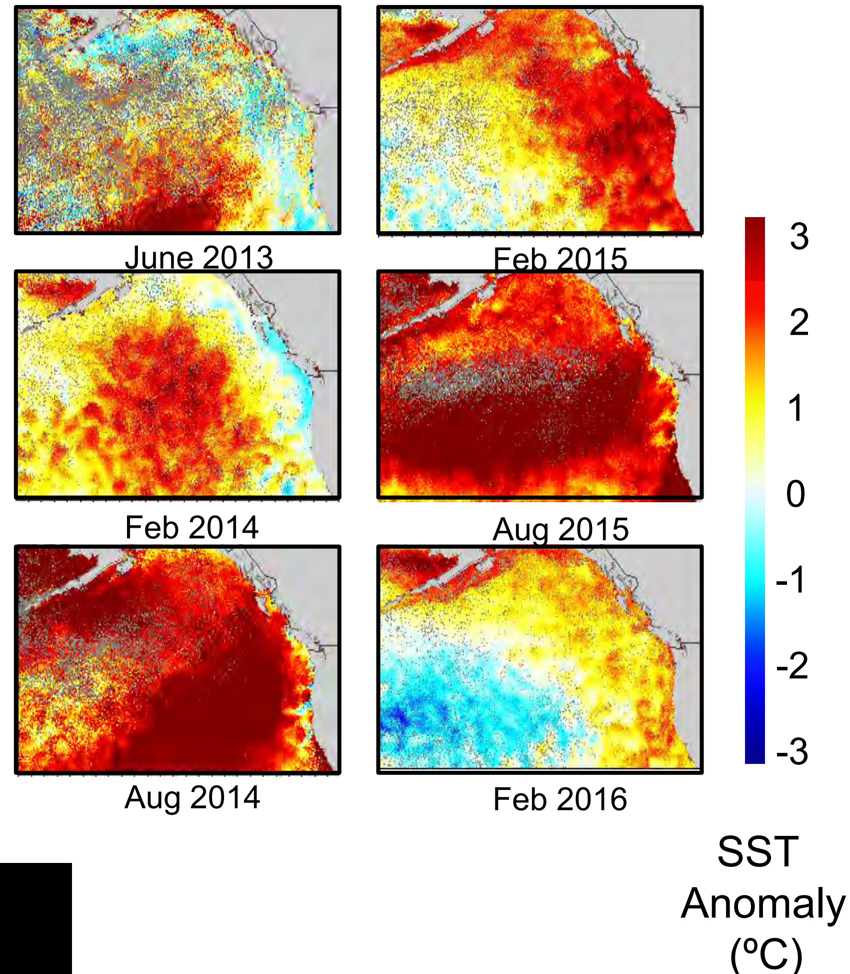
Time series of ^{137}Cs areal distributions based on Canadian and US results.

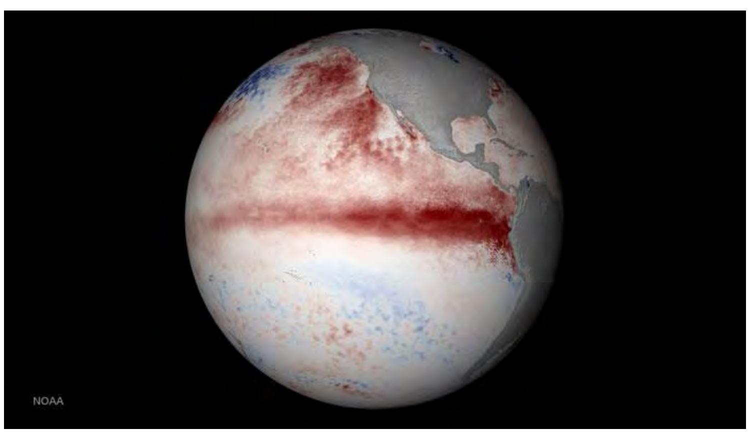


Left two columns: ^{137}Cs surface water distributions for June 2013 to Feb 2016 show spatial evolution of the Fukushima plume as it nears the Canadian coastline.

Right two columns: SST anomaly distributions for same time period outline the development of the "Warm Blob" which occupies the same water masses as Fukushima tracer patch and whose configuration is shaped by an anomalously high atmospheric pressure system over the northeast Pacific in 2013-14.

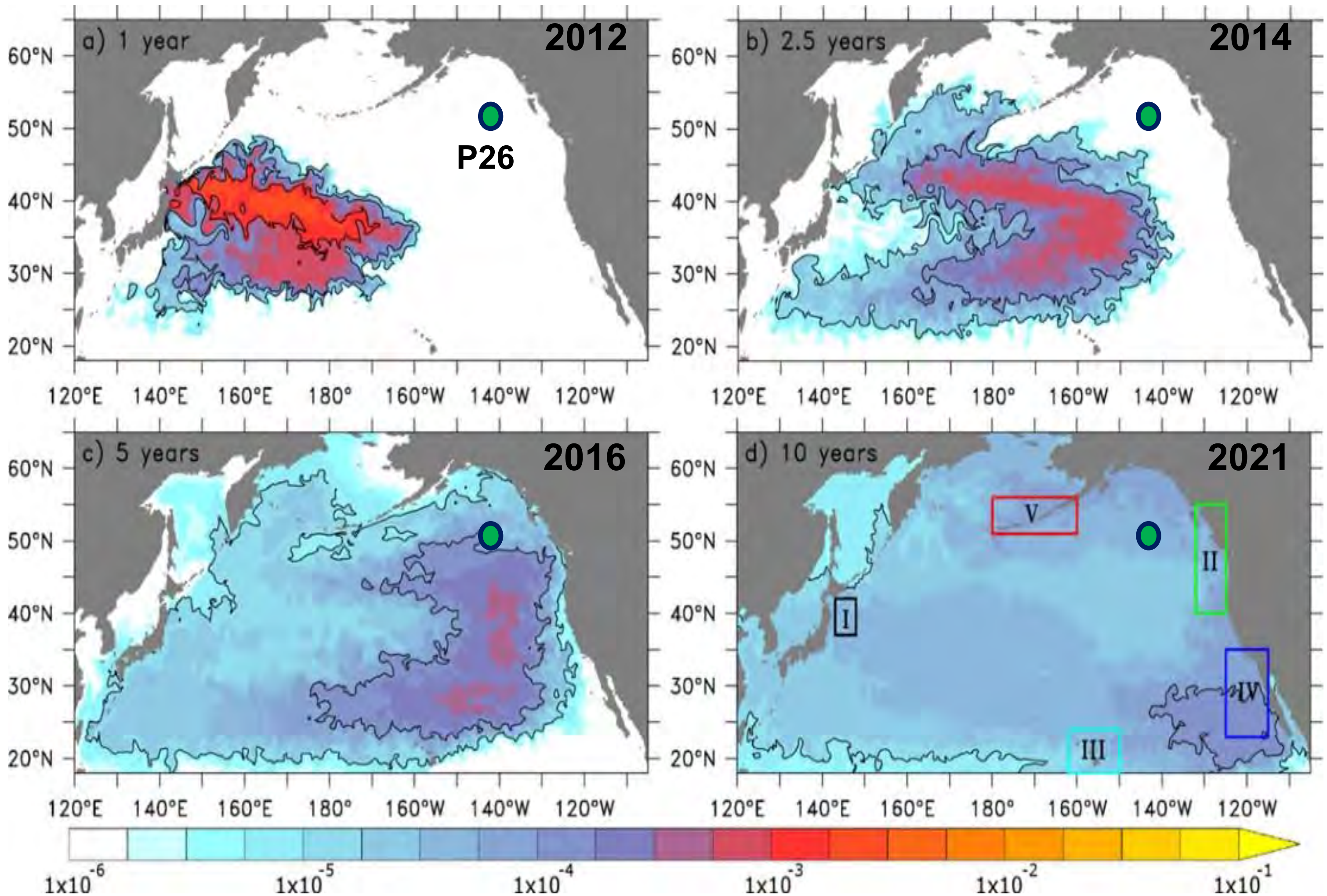






By August 2015; Blob had elongated southeastward and second El Nino related warm anomaly had developed near equator.

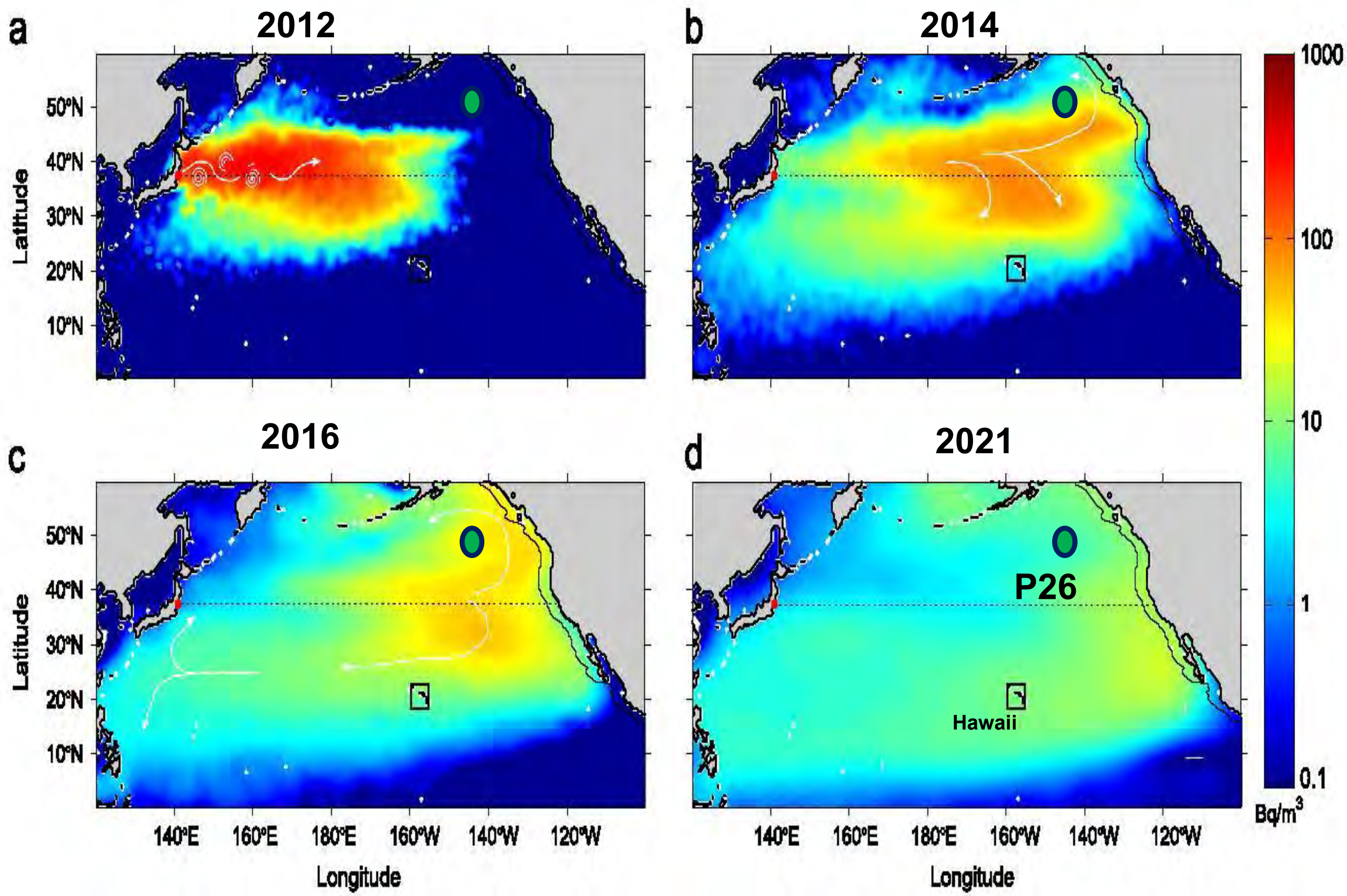
How do Fukushima model predictions conform to our actual results?



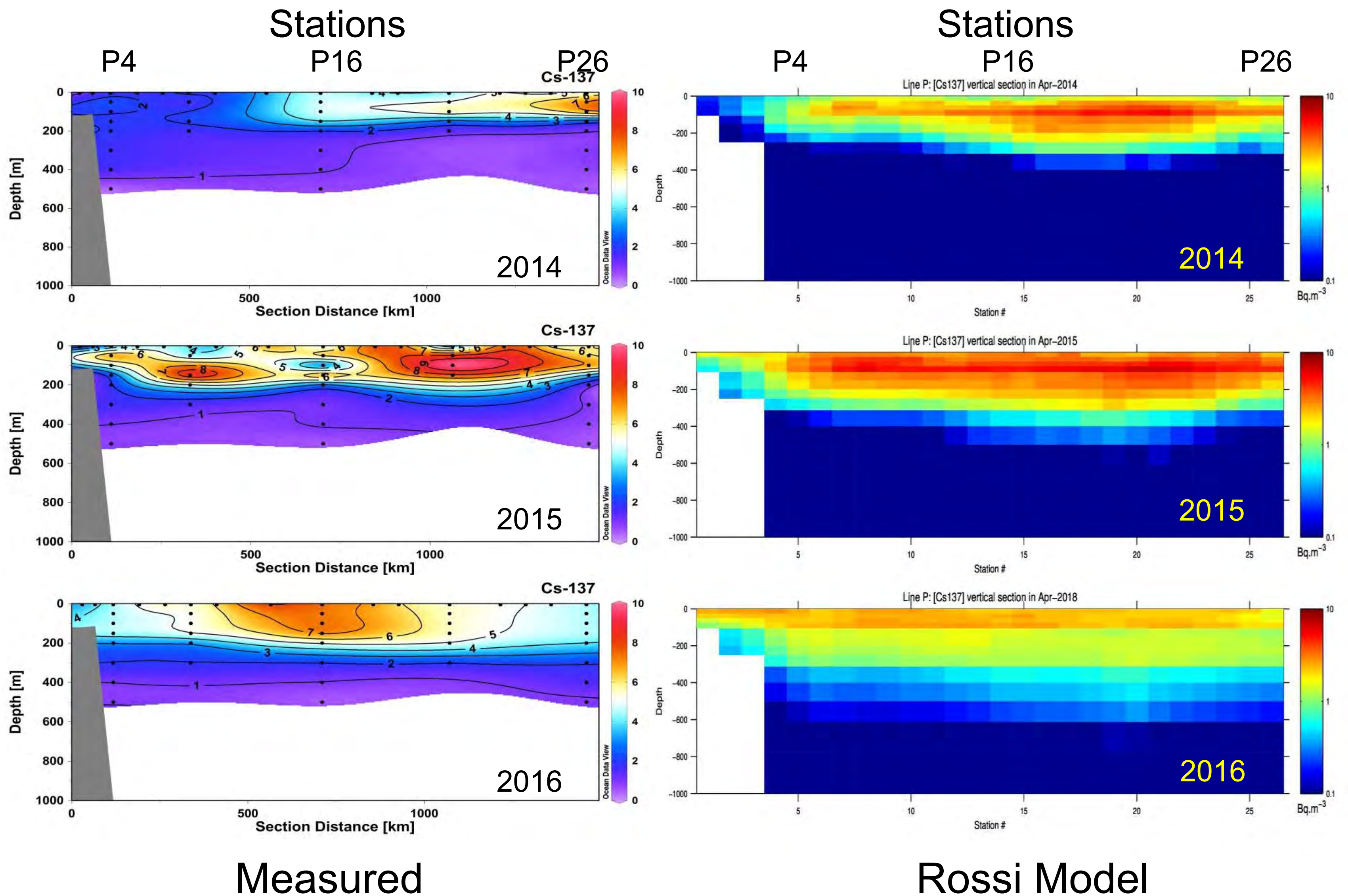
Behrens et al. (2012) Global Ocean Circulation Model (^{137}Cs)

Based on Nemo (0.1º horizontal mesh size) and estimates an arrival time of the ^{137}Cs plume at Sta. P26 of 3-5 y by current transport.

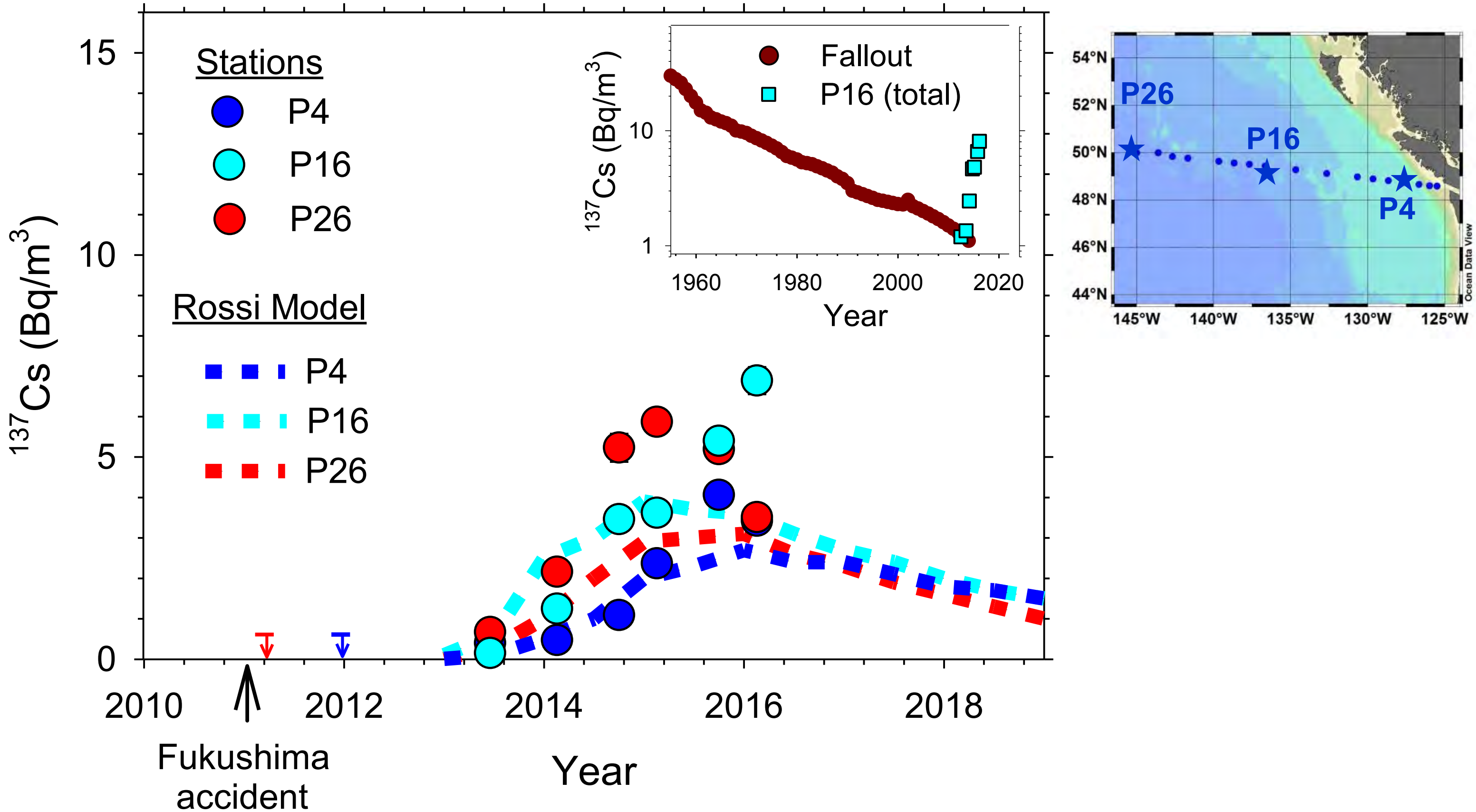
Rossi et al. (2013) Ocean Circulation Model



Both models show progression of ^{137}Cs surface water plume across Pacific for 2012, 2014, 2016 and 2021. Green symbol is for Sta. P26. By 2016, major component of ^{137}Cs inventory has been transported from western to eastern North Pacific.

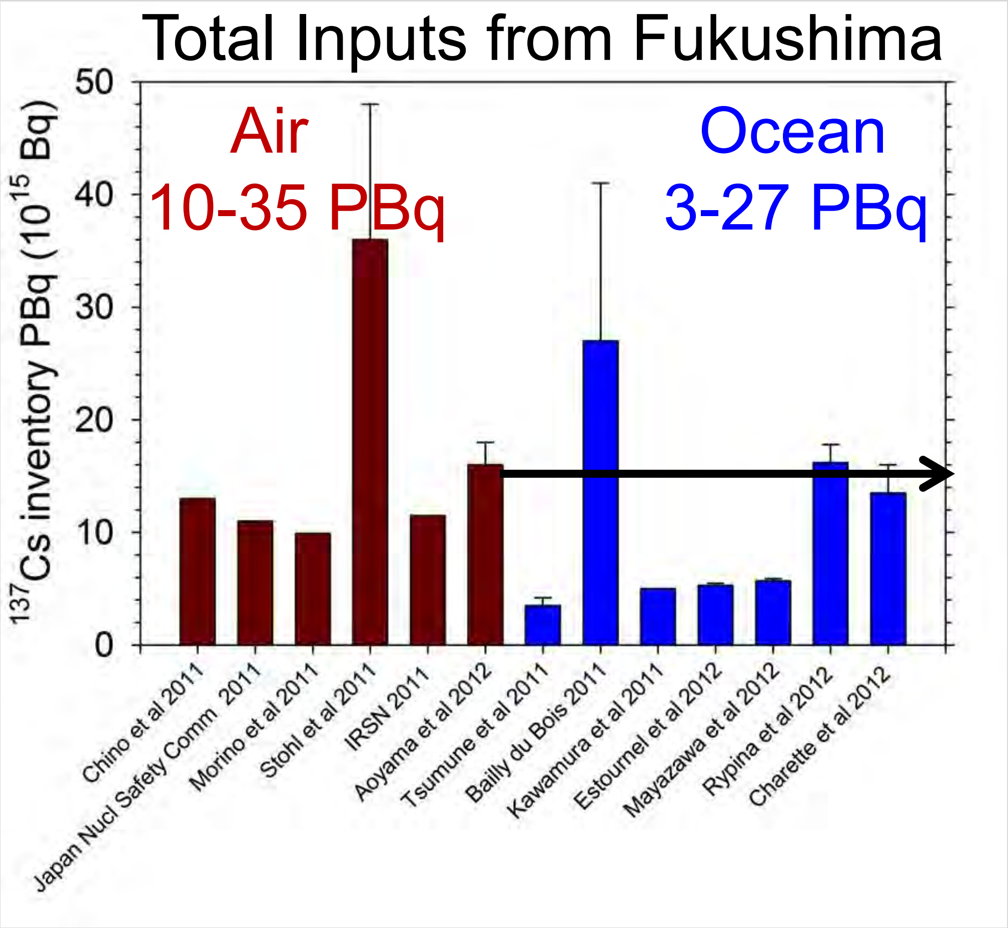


<u>Left hand side</u>: Time series of measured Line P ^{137}Cs sections illustrate the continuing onshore transport and descent of the tracer signal:
<u>Right hand side</u>: Rossi et al. (2013; 2014) model simulations for Line P ^{137}Cs sections are in good agreement with the measured time series.



Fukushima ^{137}Cs in surface water at Stas. P4, P16 and P26. Fukushima ^{137}Cs was below detection limit in 2011, but measurable at Sta. P26 in 2012 and measurable at all stations in 2013. In Feb. 2016 levels of ^{137}Cs were still increasing over the shelf, but had begun to decline at Sta. 26 in the interior of the subpolar gyre. Model results are for Rossi et al. Inset: model ^{137}Cs results are compared to historical record for ^{137}Cs fallout levels in North Pacific Ocean.

Why do we care about data agreement with models?



Total discharge (~ 15 PBq) estimated from Comparisons of DFO monitoring and model results.

Total inputs from Fukushima still poorly constrained. DFO results indicate that Rossi model may be correct if input function is ~ 15 PBq rather than 22 PBq; Use monitoring and model to constrain overall discharges.

Table 1. Source estimates for ^{137}Cs from FDNPP (all in PBq)

Reference	Total atmospheric fallout	Atmospheric fallout on ocean	Direct discharge to ocean	Total in N. Pacific
Chino et al., 2011	13			
Stohl et al., 2012	36 (23-50)			
Terada et al., 2012	8.8			
Katata et al., 2012	11			
Mathieu et al., 2012	20.6			
Kobayashi et al., 2013	13	7.6	3.5	
Winiarek et al., 2014	19.3			
Saunier et al., 2013	15.5			
Katata et al., 2015	14.5			
Kawamura et al., 2011		5	4	
Estounel et al., 2012		5.8 ± 0.1	4.3 ± 0.2	
Tsumune et al., 2012, 2013			3.5 ± 0.7	
Miyazawa et al., 2013			5.6 ± 0.2	
Bailly du Bois et al., 2012		11.5	27 ± 15	
Charette et al., 2013			13.5 ± 2.5	
Rypina et al., 2012			16.2 ± 1.6	
Aoyama et al., 2015	15.2-20.4	11.7-14.8		15.2-18.3
Inomata et al., 2015				15.3 ± 2.6
Tsubono et al., 2016		10.5 ± 0.9		16.1 ± 1.4

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Fukushima Monitoring Summary (2015-16)

1. Fukushima radioactivity levels continued to increase on Line P through 2015 with ^{137}Cs levels increasing to 10 Bq/m^3 compared to fallout background of 1.5 Bq/m^3.

2. In Feb. 2016 levels of ^{137}Cs were still increasing over the shelf, but had begun to decline in the interior of the subpolar gyre.

3. Circulation pattern of the Fukushima signal was similar to that of the “Warm Blob” which was governed by a ridge of high atmospheric pressure that persisted over NE Pacific through 2014.

4. High pressure system limited convective mixing through 2014 which reduced the deepening of the Fukushima plume; it finally descended to depths below 200 m on Line P in 2015 as oceanographic conditions normalized.