

## Introduction

A substantial quantity of radionuclides was released to the atmosphere and discharged into the North Pacific Ocean in the spring of 2011 during the Fukushima nuclear power plant (FNPP) accident. Here, we present analysis of Fukushima-derived cesium observed from water samples collected in the North Pacific from oceanographic transects occupied from 2012 to 2014. The horizontal and vertical distributions of observed Fukushima derived radionuclides, specifically  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$ , were examined to investigate the spreading of the radioactive plume and to shed light on the underlying physical processes.

### Fukushima location and source

The FNPP is located at approximately  $141.0^\circ\text{E}$ ,  $37.4^\circ\text{N}$  in an oceanographically active region between the subtropical and subpolar gyres. This particular location meant that once beyond the continental shelf, FNPP contaminated waters entered the Kuroshio and Oyashio confluence region characterized by strong currents and eddy mixing. Starting a few days after the March 11 tsunami, overheating at the FNPP led to an explosive release of gases and volatiles to the atmosphere, which were deposited as fallout. It was estimated that 70–80% of the discharge to atmosphere was deposited over the ocean. The direct discharge to the ocean of radioactive waters from emergency cooling waters and groundwater peaked on April 6, 2011.

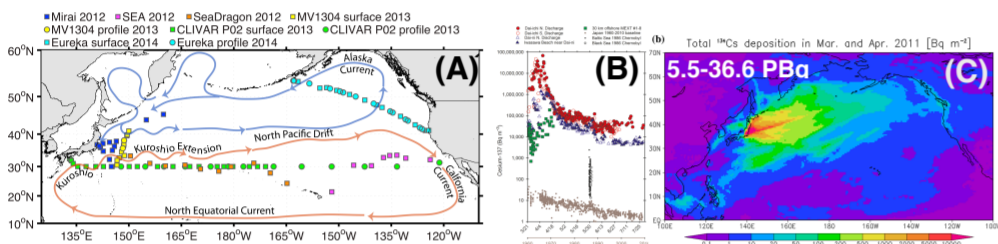
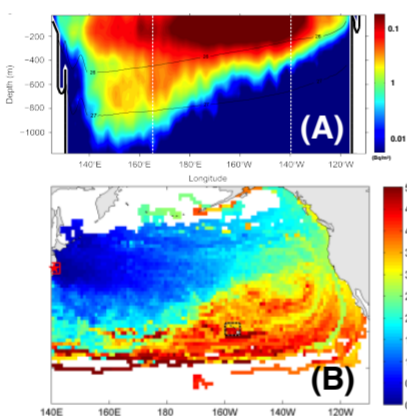


Figure 1: (A) The 2012, 2013 and 2014 sampling locations, color-coded by expedition. Squares and circles denote surface and profile sampling locations, respectively. Blue and orange arrows schematically illustrate subpolar and subtropical gyres. (B) Surface ocean  $^{137}\text{Cs}$  concentrations from March 21 to July 31, 2011 from sites near the FNPP. These are compared on the lower x-axis (1960–2010) to the historical record of  $^{137}\text{Cs}$  (Buesseler et al., 2011). (C) Total  $^{134}\text{Cs}$  deposition until the end of April 2011 by atmospheric transport model calculation over the North Pacific Ocean (Aoyama et al., 2015).

### Numerical prediction

Numerical simulations suggest that the bulk of the tracer moved eastward following the surface currents in the North Pacific, crossing the basin from Japan to the US West Coast in about 3–5 years, and penetrating vertically to depths of 200 to 600 m. Model simulation and speed estimates based on the historical drifters passing near Fukushima suggest tracer arrival to the east of  $170^\circ\text{W}$  at  $30^\circ\text{N}$  by June 2012 and the speed estimates are slightly faster than the eastward progression of the observed  $^{134}\text{Cs}$  from 2012 to 2013 along  $30^\circ\text{N}$ .

Figure 2: (A) Vertical sections of  $^{137}\text{Cs}$  concentrations in April 2014 at  $30^\circ\text{N}$  (Rossi et al., 2013). (B) Drifter-based travel time estimates across the North Pacific (Rypina et al., 2014).



## Observational findings

### Surface concentration

- The leading edge of the eastward progression of the surface signal along the  $30^\circ\text{N}$  is estimated to have been about  $15^\circ$  of longitude/year ( $\sim 5\text{ cm/s}$ ), which is slightly slower than historical drifters and numerical model simulation.
- Higher surface concentrations in the central Pacific along the  $30^\circ\text{N}$  as compared to west of  $160^\circ\text{E}$  by a few  $\text{Bq/m}^3$ , suggesting that the main body of the plume associated with the major discharge event in early April 2011 was located between  $160^\circ\text{E}$  and  $160^\circ\text{W}$  in May 2013.
- No  $^{134}\text{Cs}$  was detected east of  $160.6^\circ\text{W}$  as of spring 2013.
- Concentrations in the Gulf of Alaska were between  $0.6$  and  $5.4\text{ Bq/m}^3$  and this is slightly higher than the 2014 concentration found at Line-P. Numerical models indicate the currents north of  $40^\circ\text{N}$  move with a faster advection speed compared to  $30^\circ\text{N}$ , and predict an earlier arrival of tracer into the Gulf of Alaska and west coast of Canada.

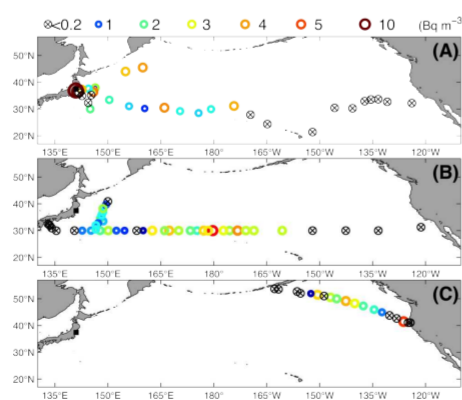


Figure 3: North Pacific surface  $^{134}\text{Cs}$  concentration in (A) 2012, (B) 2013 and (C) 2014. Concentrations indicated by both circle size and color. Circles with crosses indicate concentrations below the detection limit ( $< 0.2\text{ Bq/m}^3$ ).

## Observational findings

### Vertical distribution

- Vertical distribution along  $30^\circ\text{N}$  is characterized by subsurface maxima at all stations west of  $160.6^\circ\text{W}$ .
- The depth of the subsurface maximum, and the depth of the deepest  $^{134}\text{Cs}$  penetration were greater in the west and shoaled to the east.
- No  $^{134}\text{Cs}$  was detected east of  $160.6^\circ\text{W}$ . West of the dateline, Cs profiles suggest subsurface maxima at 300 m with penetration to 500–550 m (equivalent to 26–26.5  $\sigma_\theta$  density surfaces).

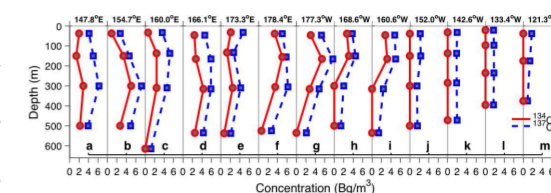


Figure 4: Profiles of observed  $^{134}\text{Cs}$  (red) and  $^{137}\text{Cs}$  (blue) concentrations along  $30^\circ\text{N}$ .

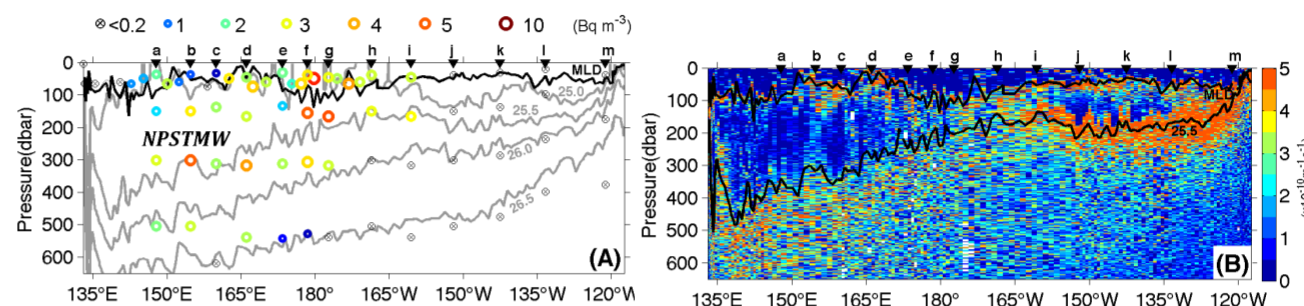


Figure 5: (A) Colored circles represent 2013  $30^\circ\text{N}$   $^{134}\text{Cs}$  concentrations in  $\text{Bq/m}^3$  surface and profile samples. Gray contours illustrate the 25.0, 25.5, 26.0 and 26.5  $\sigma_\theta$  isopycnal surfaces. Black line denotes MLD. (B) Potential vorticity ( $10^{-10}\text{ m}^{-1}\text{s}^{-1}$ ) fields are shown as colored shading. The two black solid lines denote the MLD (upper curve) and the 25.5  $\sigma_\theta$  potential density isopycnal surface (lower curve).

## Discussion

The physical processes responsible for the deep  $^{134}\text{Cs}$  penetration in the western Pacific could be related to distinct water mass subduction pathways, however the timing and rapidity of deep penetration over the broad scales observed has yet to be clarified.

- The wintertime deep convective mixing of 2011 and 2012 winters were about 290 to 360 m. The homogeneous low PV waters ( $< 2.0 \times 10^{-10}\text{ m}^{-1}\text{s}^{-1}$ ) extend below the mixed layer down to the 25.5  $\sigma_\theta$  west of the  $180^\circ$ . The  $^{134}\text{Cs}$  was observed to have penetrated to a deeper level than the typical North Pacific Subtropical Mode Water (NPSTMW) layer depth, suggesting that the particular water mass associated with this Cs penetration was denser than the typical NPSTMW. The deepest penetrations were in the density range of the Central Mode Water (CMW), which would imply a connection to the subduction of Cs contaminated waters during CMW formation, however the timing and rapidity of the deep penetration are unlikely to be explained by CMW processes.
- North Pacific Intermediate Water (NPIW), characterized by salinity minimum water near 26.8  $\sigma_\theta$  isopycnal, is another distinct water mass extensively observed in the North Pacific subtropical gyre. Considering the estimated NPIW formation time scale of 1–1.5 years, the Fukushima Cs discharged near NPIW formation site might have been transported to the mid-depth subtropical gyre circulation following the NPIW pathways.

### Temperature and Salinity from Argo profiles

Mixed layer depth and STMW variations for last 5 winters are examined using Argo float profiles in the region of  $28^\circ\text{--}35^\circ\text{N}$ ,  $140^\circ\text{E}\text{--}150^\circ$  (numbers of profiles used are 2110, 1053, 834, 2972 and 295 in 2011, 2012, 2013, 2014 and 2015, respectively).

- Winter time deep convective mixing last 5 years is observed as deep as 400 m depth which corresponds well with Kuroshio Extension Observatory (KEO) observation.
- Depth of the STMW layer seen in low PV water reaches as deep as 400 m depth which corresponds well with 2013 CLIVAR P02 observation.
- No obvious evidence of deep mixing event in 2011 and 2012 to explain the deep Cs penetration found 2013 observation.
- Depth of 26.0  $\sigma_\theta$  where the isopycnal of Cs found in 2013 is observed deeper than 400 m throughout a year which is 100m to 200 m deeper than  $16^\circ\text{C}$  layer.
- No strong interannual variations were observed in the depth of  $20^\circ\text{C}$ ,  $16^\circ\text{C}$  and 26.0  $\sigma_\theta$ .

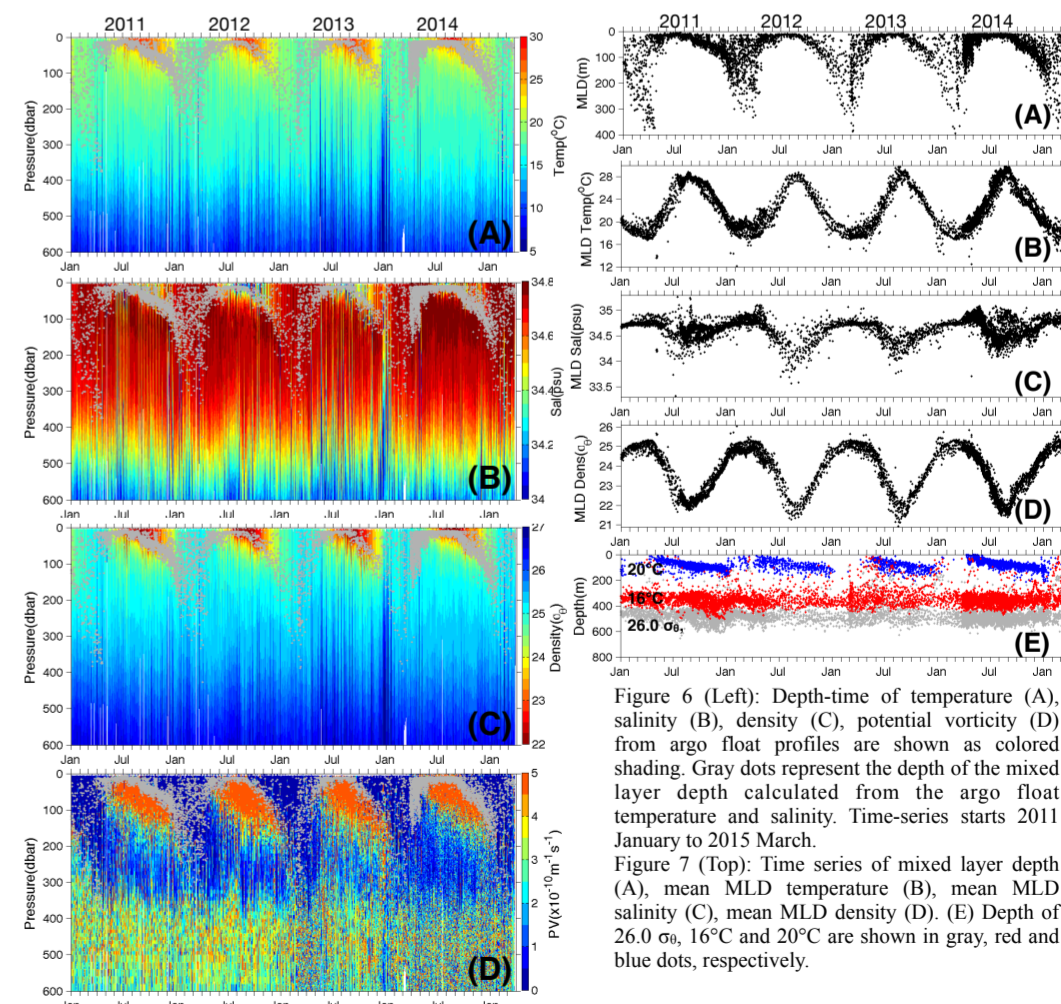


Figure 6 (Left): Depth-time of temperature (A), salinity (B), density (C), potential vorticity (D) from Argo float profiles are shown as colored shading. Gray dots represent the depth of the mixed layer depth calculated from the Argo float temperature and salinity. Time-series starts 2011 January to 2015 March.

Figure 7 (Top): Time series of mixed layer depth (A), mean MLD temperature (B), mean MLD salinity (C), mean MLD density (D). (E) Depth of 26.0  $\sigma_\theta$ ,  $16^\circ\text{C}$  and  $20^\circ\text{C}$  are shown in gray, red and blue dots, respectively.