Observed Eastward Progression of the Fukushima ^{134}Cs Signal Across the North Pacific

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*Sachiko Yoshida, Alison M. Macdonald, Steven R. Jayne, Irina I. Rypina and Ken O. Buesseler
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA
Contact: syoshida@whoi.edu

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}Cs and ^{137}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°E, 37.4°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.

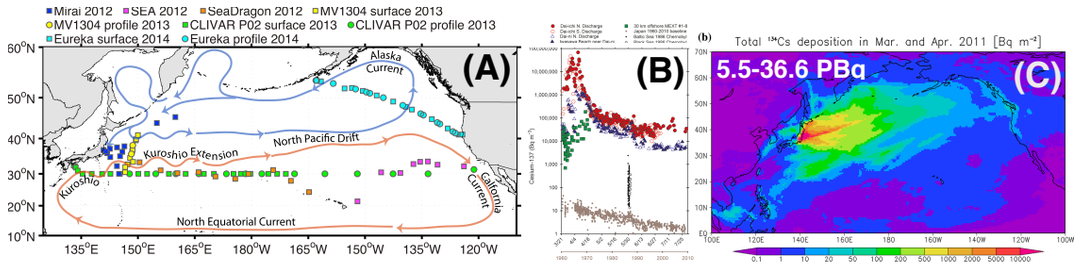

Figure 1: (A) The 2012, 2013 and 2014 sampling locations, color-coded by expedition. Squares and circles denote surface and profile sampling locations, respectively. Blue and orange arrows schematically illustrate subpolar and subtropical gyres. (B) Surface ocean ^{137}Cs concentrations from March 21 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}Cs (Buesseler et al., 2011). (C) Total ^{134}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°W at 30°N by June 2012 and the speed estimates are slightly faster than the eastward progression of the observed ^{134}Cs from 2012 to 2013 along 30°N.

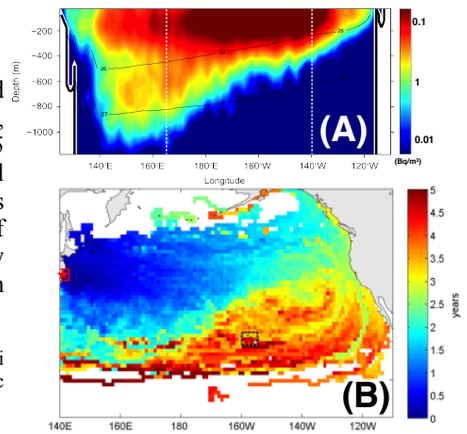

Figure 2:(A) Vertical sections of ^{137}Cs concentrations in April 2014 at 30°N (Rossi et al., 2013). (B) Drifter-based travel time estimates across the North Pacific (Rypina et al., 2014).

References

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Observational findings

Surface concentration

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

Vertical distribution

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

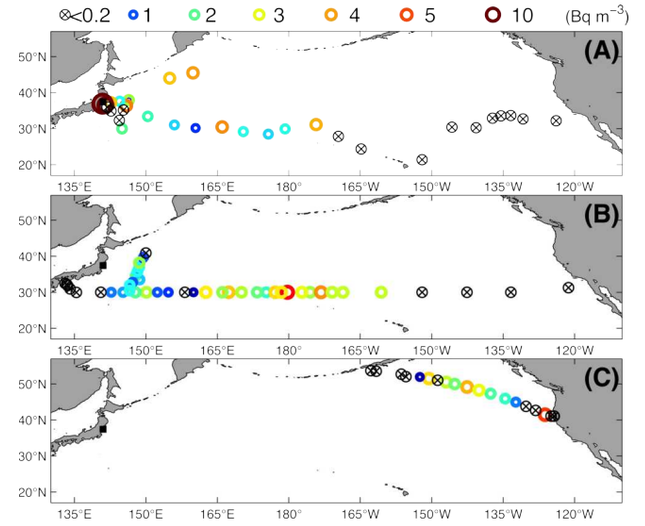

Figure 3: North Pacific surface ^{134}Cs concentration in (A) 2012, (B) 2013 and (C) 2014. Concentrations indicated by both circle size and color. Circles with crosses indicate concentrations below the detection limit (< 0.2 Bq/m^3).

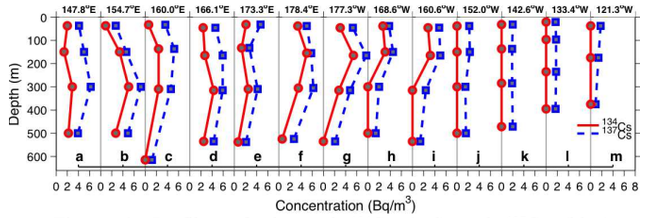

Figure 4: Profiles of observed ^{134}Cs (red) and ^{137}Cs (blue) concentrations along 30°N.

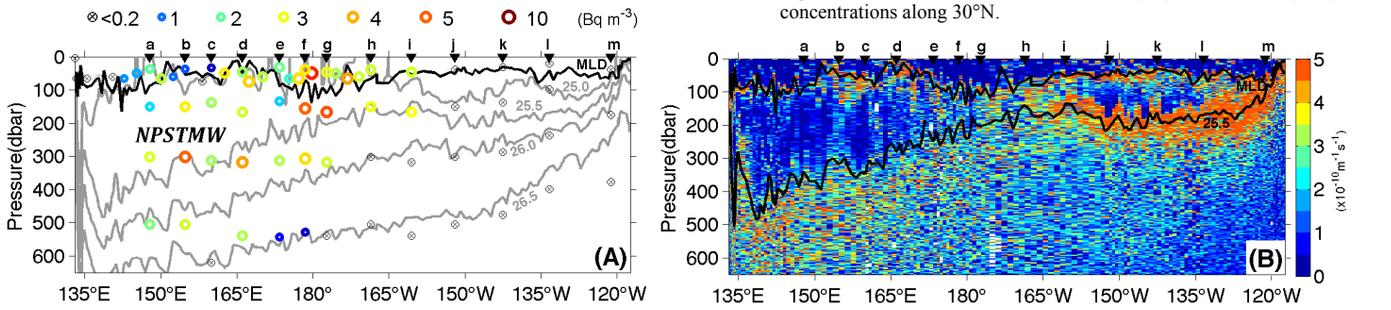

Figure:Figure 5: (A) Colored circles represent 2013 30°N ^{134}Cs concentrations in Bq/m^{3}s surface and profile samples. Gray contours illustrate the 25.0, 25.5, 26.0 and 26.5σ_θ isopycnal surfaces. Black line denotes MLD. (B) Potential vorticity (10^{-10} m^{-1}s^{-1}) fields are shown as colored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

Discussion

The physical processes responsible for the deep ^{134}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 × 10-10 m-1s-1) extend below the mixed layer down to the 25.5 σθ west of the 180°. The ^{134}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 σθ 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.