Spreading of the Fukushima-derived radiocesium in the North Pacific Ocean and its adjacent seas in the past decade

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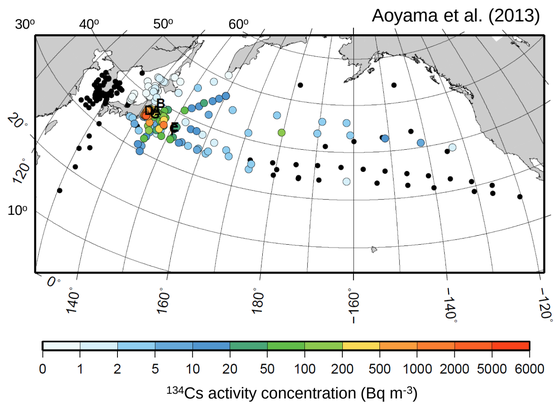
Spreading at the Sea Surface

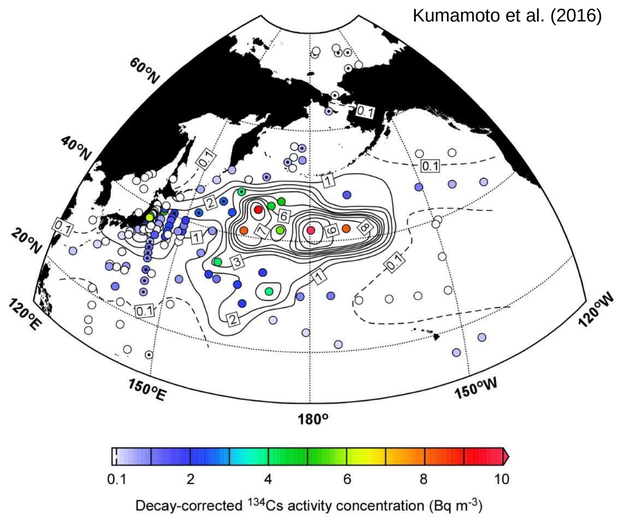
The FNPP1-derived ^{134}Cs has been transported along with the surface currents in the North Pacific Ocean, the clockwise subtropical and anti-clockwise subarctic gyre currents. A strong eastward current between the two gyres in the mid-latitude (35–45ºN) conveyed the FNPP1-derived ^{134}Cs from Japan to the west coast of the North American Continent between 2011 and 2016. Then, it has returned westward along with the Alaska Current and reached the Bering Sea and then the Arctic Ocean (Chukchi Sea) by 2017.

Apr-Jun. 2011

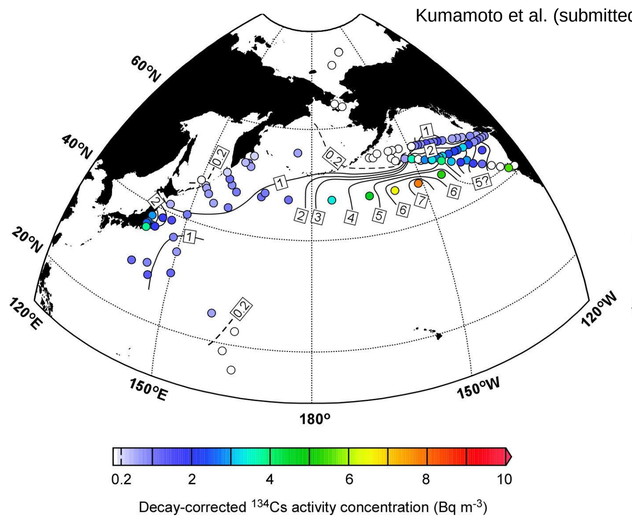


Radiocesium (^{134}Cs) released from the damaged Fukushima Dai-ichi Nuclear Power Plants (FNPP1) was transported into the North Pacific Ocean mainly by the atmospheric deposition (15±5 PBq) and the direct discharge of contaminated water (4±2 PBq).

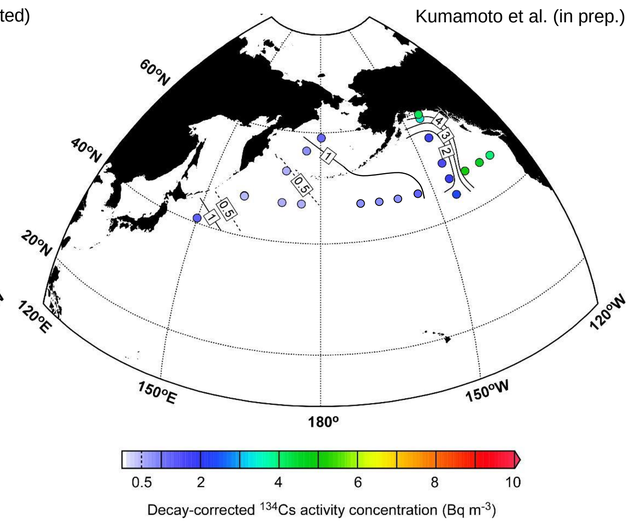
Aug-Dec. 2012



May-Sep. 2014

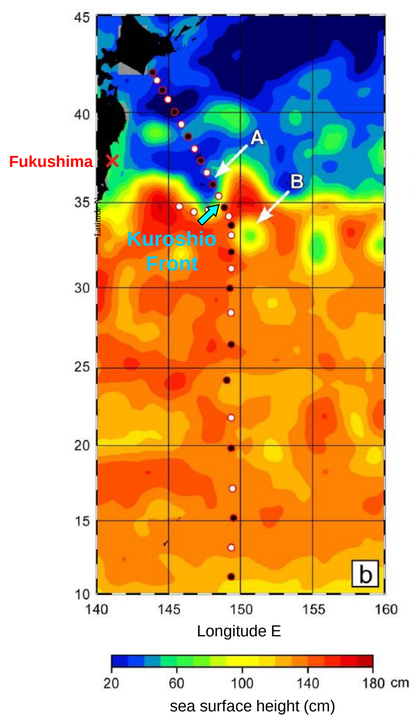


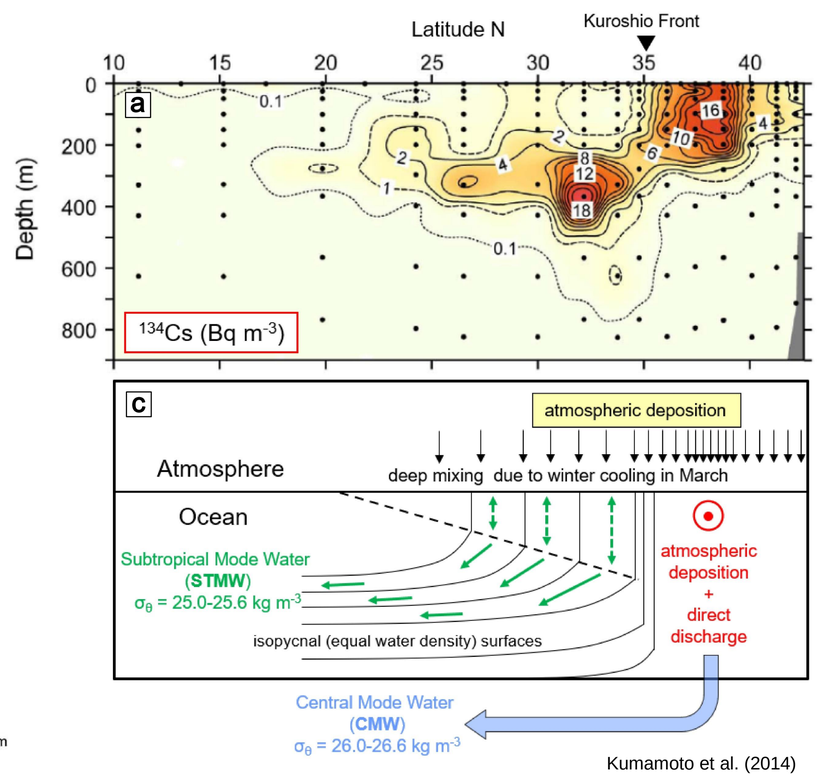
Jun-Aug. 2017



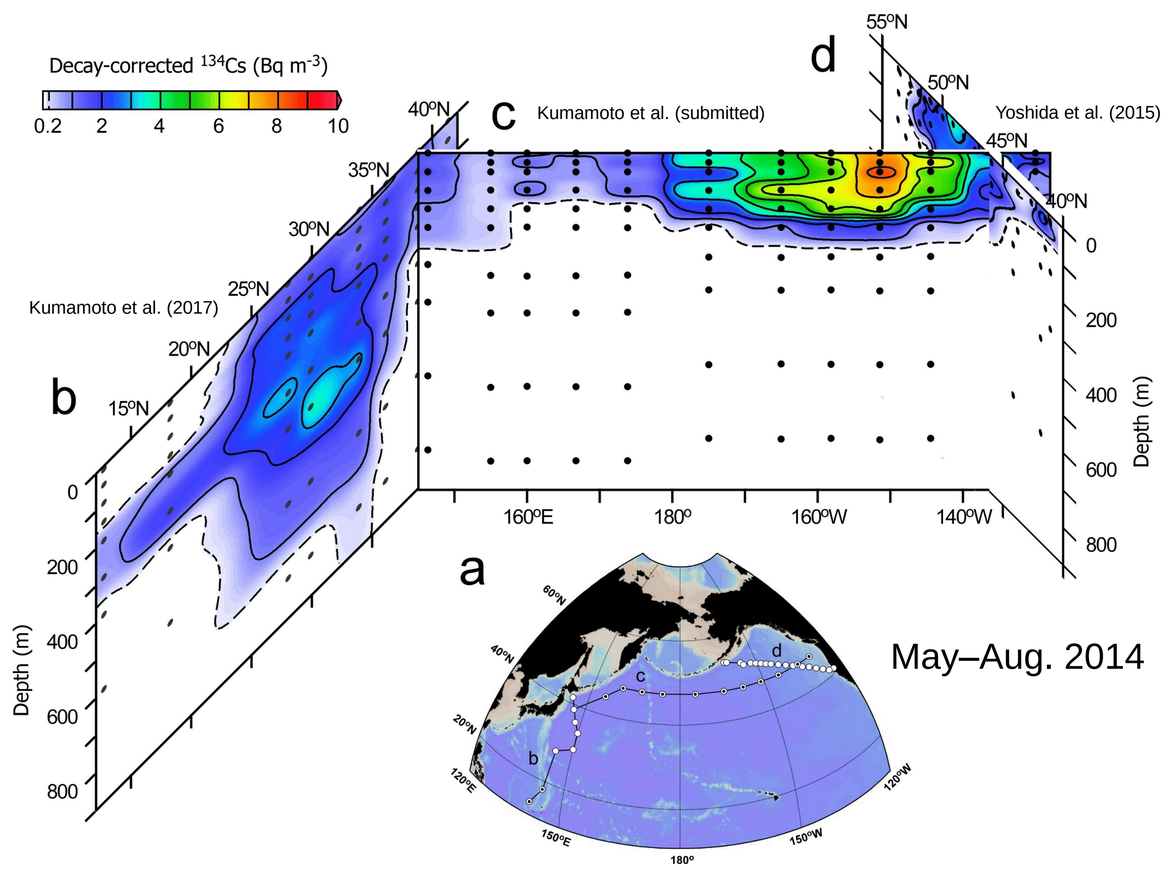
Spreading in the Ocean Interior

Jan–Feb. 2012



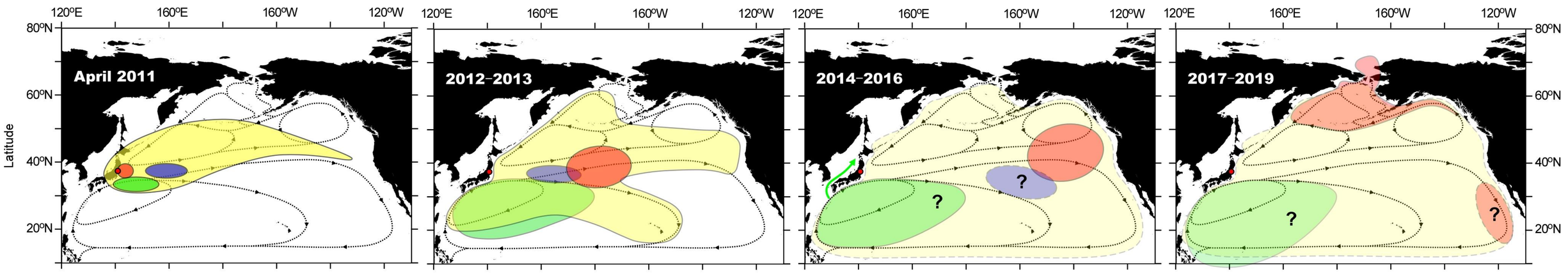


(a) A transect view of ^{134}Cs (Bq m^{-3}) along a meridional line of 143–149ºE (b) in January and February 2012. (c) Schematic explanation of ^{134}Cs transport into subsurface layers due to formation of the subtropical mode water (STMW) and central mode water (CMW) in the North Pacific Ocean in March 2011. It should be noted that the FNPP1-derived ^{134}Cs was transported southward about 2000 km from FNPP1 within 10 months after the accident, which suggests that the transport of the dissolved ^{134}Cs was governed by mesoscale and sub-mesoscale eddies.



(a) Three hydrographic observation lines (b, c, and d) in 2014. (b) A transect view of decay-corrected ^{134}Cs (Bq m^{-3}) along with 143–149ºE between May 2014 and January 2015. (c) Same as (b) but for 47ºN between June and August 2014. (d) Same as (b) but for the northwest-southeast line in the Gulf of Alaska in July 2014. A main body of ^{134}Cs directly-discharged and atmospheric-deposited on the coastal area of FNPP1 was transported eastward in the surface mixed layer of the subarctic area. On the other hand, the ^{134}Cs deposited on the south of the Kuroshio Extension Current was transported southward in the subsurface layer of the subtropical area along with the advection of STMW.

Schematic Views of Spreading in the Past Decade



The atmospheric-released ^{134}Cs in March and April 2011 was deposited mainly on the land of Japan, the subarctic area of North Pacific Ocean, Japan Sea, and Okhotsk Sea (yellow). The ^{134}Cs directly-discharged and atmospheric-deposited on the coastal area of FNPP1 was observed the offshore area of FNPP1 (red). The ^{134}Cs deposited on the south of the Kuroshio Extension Current started traveling southward through the subsurface layers (25.0–25.6 sigma-theta) due to the subduction of STMW (green). The ^{134}Cs in the north of the Kuroshio Extension Current also started traveling southward through the denser subsurface layers (26.0–26.6 sigma-theta) due to the subduction of CMW (blue). The subduction of the mode waters occurred just after the atmospheric deposition in March 2011.

The ^{134}Cs atmospheric-deposited on the North Pacific Ocean spread along with the surface currents. Those on the Japan Sea and Okhotsk Sea became less than the detection limit (yellow). The high-^{134}Cs water plume at the sea surface was transported eastward to around 180º along with the Kuroshio Extension Current and the North Pacific Current. The inventory in the water plume is estimated to be 9−16 PBq (red). Due to the advection of STMW, the FNPP1-derived ^{134}Cs spread in the subsurface layers (200–400 m depth approx.) in the western subtropical area. The inventory in STMW is estimated to be 4−6 PBq (green). In the north of the Kuroshio Extension Current, ^{134}Cs maxima were observed in subsurface layers (100–400 m depth approx.) that corresponds CMW (blue).

The atmospheric-deposited ^{134}Cs probably has spread over the North Pacific Ocean although that was not observed due to the radioactive decay (yellow). The high-^{134}Cs water plume at the sea surface reached the North American Continent (red). The ^{134}Cs in STMW was transported to the Japan Sea through the East China Sea (green). Transport along with CMW is not clear due to the lack of the observational data (blue).

The high-^{134}Cs water plume was returned to the west along with the Alaska Current and reached the Bering Sea and Arctic Ocean. The southward branching along with the California Current has not been observed (red). The ^{134}Cs in STMW reached 5ºN (green). Transport along with CMW is unknown due to the lack of the observational data.

Acknowledgments

This work partially supported by Grant-in-Aid for Scientific Research on Innovative Areas, the Ministry of Education, Culture, Sports, Science and Technology Japan (KAKENHI), 24110005 and JP20H05173.

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Poster presented at Fukushima Dai-ichi and the Ocean: 10 years of study and insight, March 4, 2021, Online Presentation