



OPEN ACCESS

EDITED BY

Wu Men,
Nanjing University of Information Science
and Technology, China

REVIEWED BY

Yukun Fan,
Chinese Academy of Sciences (CAS),
China
Angel Bautista Vii,
Philippine Nuclear Research Institute
(PNRI), Philippines

*CORRESPONDENCE

A. J. Timothy Jull
✉jull@email.arizona.edu

RECEIVED 26 February 2026

REVISED 21 March 2026

ACCEPTED 26 March 2026

PUBLISHED 23 April 2026

CITATION

Jull AJT, Chang C-C, Burr GS, Cheng L,
Russell J, Lin M, Crocker DR,
Thiemens M, Biddulph D, Caffee MW,
Woodruff T, Glynn C and Santos GM
(2026) Levels of ^{129}I in coastal Pacific
Ocean waters from southern California,
2011–2020 and the legacy of
Fukushima.
Front. Mar. Sci. 13:1818503.
doi: 10.3389/fmars.2026.1818503

COPYRIGHT

© 2026 Jull, Chang, Burr, Cheng, Russell,
Lin, Crocker, Thiemens, Biddulph, Caffee,
Woodruff, Glynn and Santos. This is an
open-access article distributed under the
terms of the [Creative Commons
Attribution License \(CC BY\)](https://creativecommons.org/licenses/by/4.0/). The use,
distribution or reproduction in other
forums is permitted, provided the
original author(s) and the copyright
owner(s) are credited and that the
original publication in this journal is
cited, in accordance with accepted
academic practice. No use, distribution
or reproduction is permitted which does
not comply with these terms.

Levels of ^{129}I in coastal Pacific Ocean waters from southern California, 2011–2020 and the legacy of Fukushima

A. J. Timothy Jull^{1,2,3*}, Ching-Chih Chang^{1,3}, George S. Burr⁴,
Li Cheng³, Joellen Russell¹, Mang Lin⁵, Daniel R. Crocker⁶,
Mark Thiemens⁶, Dana Biddulph⁷, Marc W. Caffee^{8,9},
Tom Woodruff⁸, Christopher Glynn¹⁰ and Guaciara M. Santos¹⁰

¹Department of Geosciences, University of Arizona, Tucson, AZ, United States, ²Isotope Climatology and Environmental Research Centre, Institute for Nuclear Research, Debrecen, Hungary, ³University of Arizona Accelerator Mass Spectrometry (AMS) Laboratory, Tucson, AZ, United States, ⁴Department of Geosciences, National Taiwan University, Taipei, Taiwan, ⁵State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China, ⁶Department of Chemistry, University of California, San Diego, San Diego, CA, United States, ⁷Pima Community College, Tucson, AZ, United States, ⁸Department of Physics and Astronomy, Purdue University, West Lafayette, IN, United States, ⁹Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN, United States, ¹⁰Department of Earth System Science, University of California, Irvine, Irvine, CA, United States

The Fukushima Daiichi Nuclear Power Plant accident released radionuclides directly into the ocean as a result of the Great East Japan Earthquake on March 11, 2011. This material has been transported across the Pacific Ocean and detected in the northeastern Pacific. We began a surface ocean ^{129}I monitoring program a few months after this disaster in June 2011, with samples from Scripps Pier, La Jolla, California, USA, with the expectation that surface currents originating off the east coast of Japan could eventually carry radionuclides to the La Jolla site. We could not identify a significant distinct signal that can be traced to Fukushima from the record from 2011–2020. We have however recorded a systematic seasonal ^{129}I time series record that appears to be due to surface circulation variations along the California coast, or perhaps other unexplained effects. We have reported on some of these effects previously, where we summarized results up to 2018. Since then, we have analyzed additional samples obtained during our sampling program for 2018–2020 from Scripps and also report other results collected during 2015–2016 from Newport Beach, CA, which had not been reported. These results support and expand on the previously published dataset.

KEYWORDS

California coast, Fukushima, iodine-129, ocean water, tracers

1 Introduction

The Great East Japan Earthquake and related tsunami that occurred on March 11, 2011 triggered nuclear shutdowns, failures, and partial meltdowns at the Fukushima Daiichi reactor complex. This resulted in a series of radioactive releases, including large quantities of radioactive iodine, xenon and cesium. [Bowyer et al. \(2011\)](#) reported an atmospheric signal of

^{133}Xe (half-life: 5.2 days) in Washington state (USA) by March 16, 2011. At about the same time, Priyadarshi et al. (2011) noted an increase in ^{35}S in sulfate aerosols collected on the coast at La Jolla, California by March 22, 2011, which they attributed to neutron flux leakage from the damaged reactor producing ^{35}S from thermal neutron reactions on ^{35}Cl . Increased levels of ^{131}I (half-life: 8.06 days) were detected in Taiwan and on the Tibetan Plateau by 29 March (Huh et al., 2012; Hsu et al., 2012), with ^{137}Cs (half-life: 30.1 yr) arriving at the same time in Taiwan but delayed a few days in Tibet. Elevated radionuclide levels were also detected in Japan and an anthropogenic pulse in atmospheric radioactivity was rapidly observed around the world (Adachi et al., 2013). As a result of contaminated water from the reactor being directly discharged into the ocean, high values of ^{129}I (half-life 15.7 million years) were observed close to Japan by Hou et al. (2013) and Povinec et al. (2013), with an estimated total 2.4–7 GBq of ^{129}I discharged into the ocean (Povinec et al., 2013; Guilderson et al., 2014). There have been many studies of radioactive plumes in the ocean due to the Fukushima accident (e.g. Buesseler et al., 2011; Aoyama et al., 2013; Cascuberta et al., 2017; Charette et al., 2013; Guilderson et al., 2014; Povinec et al., 2013; Smith et al., 2015; Smith et al., 2017).

The high mobility of ^{129}I in nature makes it a useful tracer for environmental research due in part to its significant anthropogenic production (Edwards, 1962; Muramatsu and Ohmomo, 1986; Santschi et al., 1996; Raisbeck et al., 1995; Schmidt et al., 1998; Hou et al., 2009; Povinec et al., 2010). The two natural production pathways for ^{129}I are: 1) spontaneous fission of ^{238}U , and 2) the interaction of cosmic rays with xenon in the atmosphere. Over the past 70 years, anthropogenic ^{129}I sources have overtaken natural production in the environment, and are dominated by nuclear fuel reprocessing activities, but also include above-ground nuclear testing and accidents. Iodine-129 levels in surface ocean waters are about 1–2 orders of magnitude higher than in estimated pre-nuclear era $^{129}\text{I}/^{127}\text{I}$ values of between 5×10^{-13} and 1.5×10^{-12} (Fabryka-Martin et al., 1984; Moran et al., 1998; Edmonds and Morita, 1998; Biddulph et al., 2006). The two primary sources of the anthropogenic signal are the industrial nuclear fuel reprocessing plants in Sellafield (England) and La Hague (France), which contribute anthropogenic ^{129}I in Atlantic Ocean surface waters (Yiou et al., 1994; Yiou et al., 2002). This ^{129}I signal has been traced globally in the marine environment (Xing et al., 2015; Fehn and Snyder, 2000). Zhang et al. (2024) noted that this signal dominates the ^{129}I record in China and they did not detect a significant effect from either the Fukushima or Chernobyl accidents.

Some examples of accidental anthropogenic ^{129}I releases to the environment prior to the 2011 Fukushima incident included the Chernobyl reactor accident (Paul et al., 1987; Kutschera et al., 1988) and nuclear submarine accidents (Alfimov et al., 2004; Povinec et al., 2010; Hu et al., 2010). The Chernobyl nuclear disaster released between 40–48 GBq of ^{129}I (Aldahan et al., 2007; Kashparov et al., 2003) directly to the atmosphere. The estimated total amount of ^{129}I released because of the Fukushima accident overlap with those for Chernobyl, from 6.6 GBq ^{129}I (Steinhauser et al., 2014) to 55 GBq ^{129}I (Hou et al., 2013). In the case of Fukushima, 80% of the total radioactivity was released directly into the ocean. Nuclear submarine accidents are considered a negligible source, <370 GBq (Hu

et al., 2010) in comparison to the amount of radioactivity released in the Fukushima accident. The estimated total radioactivity released from Fukushima is in the range of 340–800 PBq (Steinhauser et al., 2014).

A relatively large $^{129}\text{I}/^{127}\text{I}$ signal in the ocean was observed immediately following the Fukushima accident along the east coast of Japan. Suzuki et al. (2013) reported that before the accident, seawater ^{129}I near Fukushima was $0.94\text{--}1.83 \times 10^7$ atoms/L, while after the accident, ^{129}I increased from 1.08 to 89.8×10^7 atoms/L, with an average of 9.3×10^7 atoms/L, approximately 8 times higher than before the accident. Further, Hou et al. (2013) measured an $^{129}\text{I}/^{127}\text{I}$ ratio of 2.2×10^{-9} in surface seawater collected 40 km offshore the Fukushima site. Guilderson et al. (2014) estimated that the amount of ^{129}I directly released into the ocean was ~ 1 kg. Herod et al. (2013) also measured $^{129}\text{I}/^{127}\text{I}$ ratios in precipitation in Vancouver and Saturna Island, Canada immediately following the Fukushima accident and showed that ratios of up to 11×10^{-9} were observed about 6–10 days after the accident, demonstrating that transport of ^{129}I occurs through the atmosphere, as well as through the ocean. Herod et al. (2013) further noted variable ^{129}I increases in precipitation during the following 9 months after Fukushima.

We have previously reported a detailed study of ^{129}I at Scripps Pier (La Jolla, California) conducted from 2011–2018 (Chang et al., 2019). In order to expand the time-series record, we update this record with new data up to February 2020, when the sampling program had to be abandoned due to the COVID pandemic. We had previously collected seawater samples from the Scripps Pier, La Jolla, California during the period 2011–2018, except for a period in 2015. We are also able to include previously unreported information from samples collected at Newport Beach, California (101 km NNW of Scripps Pier) during 2015–2016, which can add to our understanding of the ^{129}I record. These samples were obtained during fieldwork for a separate radiocarbon and stable-isotope study conducted by the University of California, Irvine (see Hauksson et al., 2024). The location of the sampling sites is shown in Figure 1.

2 Materials and methods

Seawater samples were collected between June 2011 and February 2020 at weekly to biweekly intervals at Scripps Pier (32° 52'N, 117°15.4'W), University of California San Diego, from an intake pipe 10 m below the surface. Results up to May 2018 have been previously reported by Chang et al. (2019). We report new results in this paper up to February 27, 2020, when sampling was ceased due to the COVID pandemic. Separately, samples had also been collected from the Newport Beach Pier (33°36.3'N, 117°55'W) between January 9, 2015 and August 29, 2016. These samples were stored in plastic water containers at the University of California Irvine until June 2021, when they were retrieved for analysis. Total iodine was measured for the Irvine samples by reduction of all species to I^- and measurement by inductively-coupled plasma mass spectrometry (ICPMS, Agilent 8900) at the Arizona Center for Emerging Contaminants (ALEC) at the University of Arizona. A



FIGURE 1

Location of the sampling sites at Newport Beach Pier and Scripps Pier in southern California. A larger scale map shows the North Pacific and California currents. Adapted from public-domain map from the US Geological Survey.

liquid-liquid extraction method for ^{129}I was used in this study, following the approach of Biddulph et al. (2006) and Chang et al. (2019): The seawater samples (500 mL) were filtered with a 0.22 μm membrane filter. Before starting the iodine extraction process, H_3PO_4 and NaHSO_3 were added to convert all IO_3^- into iodide (I^-). To this solution, 3 to 5 mL of CHCl_3 was added to a separatory funnel, and 5 drops of 1 M NaNO_3 . The sample was then shaken vigorously, and time was allowed for the immiscible settling of denser CHCl_3 . The CHCl_3 was taken into a 20 mL glass scintillation vial and 10–15 mg of Ag powder was added to the solution. This process was repeated 5 times and the resulting solution was allowed to react overnight. The CHCl_3 was then evaporated under a fume hood. The dried Ag+AgI residue was rinsed with distilled water 3 times and dried.

Once dry, the samples were pressed into copper cathodes for measurement by accelerator mass spectrometry (AMS). Measurements were performed at the University of Arizona with a 3 MV NEC Pelletron accelerator. The 4+ charge state was selected at a terminal voltage of 3 MV with a transmission of 10%. Errors include statistical uncertainties and a random machine error of 4.3%. The chemical blank produced about 0.1 counts/second while the seawater signal yielded about 2 counts/second. Samples were normalized and calibrated with 2 standards with $^{129}\text{I}/^{127}\text{I}$ of 63.57×10^{-12} and 8.38×10^{-12} from the Purdue laboratory. All the

samples were measured for 200 seconds, repeated 6 times, for a total counting time of 1200 seconds. The samples from the Newport Beach site were processed in the same way at the University of Arizona but were measured using the Purdue University PRIME Laboratory's FN-based AMS, as the University of Arizona AMS machine was no longer available. Samples measured at PRIME Lab were run at a terminal voltage of 2.6 MV, selecting charge state 5+. From the results shown, it is clear the data from the two machines are in excellent agreement.

3 Results and discussion

Previous $^{129}\text{I}/^{127}\text{I}$ data showed that from June 2011 to May 2018, $^{129}\text{I}/^{127}\text{I}$ in seawater off La Jolla, California coast varied from 40 to 80×10^{-12} with a quasi-seasonal cycle with relatively high values in the autumn and lower values in the summer (Chang et al., 2019). Additional samples were collected after May 2018 until February 2020. Results are shown in Table 1, and Figure 2; Supplementary Table S1 includes the previous measurements from Chang et al. (2019). The figure shows a continuation of the previous trend but the degree of oscillation appears more dampened. The period 2018–2020 shows a fluctuation of generally higher

TABLE 1 New results from the 2015–2016 study of $^{129}\text{I}/^{127}\text{I}$ and ^{129}I concentrations from the Newport Beach (CA) pier compared to the $\delta^{14}\text{C}$ results of Hauksson et al. (2024).

Sample Name	Total Iodine		$^{129}\text{I}/^{127}\text{I}$	^{129}I	$\Delta^{14}\text{C}$	$\delta^{13}\text{C}$	mM
	Conc. [$\mu\text{g/L}$]	RSD	(10^{-12})	10^6 atoms/L			DIC/L
NBP 1-9-2015	19.76	2.6	58.5 ± 4.0	5.38 ± 0.05	9.2 ± 2.6	1.32	2.26
NBP 2-6-15	15.37	0.9	61.7 ± 4.2	4.41 ± 0.02	10.3 ± 2.7	1.14	2.24
NBP 3-23-15	28.22	5.7	63.3 ± 4.3	8.31 ± 0.12	10.1 ± 2.8		
NBP 4-29-15	15.11	3.3	57.9 ± 3.7	4.07 ± 0.06	10.2 ± 2.8	1.38	2.22
NBP 5-27-15	16.91	0.8	53.4 ± 4.0	4.20 ± 0.01	5.2 ± 2.6	1.33	2.33
NBP 6-17-15	15.32	2	49.2 ± 3.7	3.50 ± 0.03	10 ± 2.7	1.44	2.24
NBP 7-24-15	12.56	2.1	56.7 ± 4.5	3.31 ± 0.44	5.2 ± 1.5	1.38	2.26
NBP 8-28-15	23.24	2.2	51.2 ± 3.7	5.54 ± 0.04	5.2 ± 1.5	1.63	2.29
NBP 9-23-15	15.90	2.9	57.3 ± 3.1	4.23 ± 0.04	8.6 ± 1.6	1.41	2.22
NBP 10-30-15	54.18	3	59.8 ± 4.8	15.07 ± 0.07	6.7 ± 1.6	-0.3	2.32
NBP 11-30-15	26.52	3.9	59.9 ± 5.2	7.38 ± 0.09	11.1 ± 1.6	1.45	2.23
NBP 12-18-15	27.67	0.9	52.8 ± 3.9	6.79 ± 0.02	5.6 ± 2.0	1.33	2.30
NBP 1-29-16	43.00	5.2	50.3 ± 4.7	10.06 ± 0.11	7.1 ± 1.5		
NBP 3-28-16	17.26	0.8	58.7 ± 3.3	4.71 ± 0.01	2.3 ± 1.6		
NBP 4-29-16	18.81	1.7	54.9 ± 3.9	4.80 ± 0.03	4.5 ± 1.9	1.21	2.38

Values for $\Delta^{14}\text{C}$, $\delta^{13}\text{C}$ and millimoles (mM)/L of dissolved inorganic carbon (DIC) are reproduced from Hauksson et al. (2024). Iodine concentrations were measured by reduction of iodine species to I^- and measurement by ICP-MS at the Arizona Laboratory for Emerging Contaminants, University of Arizona.

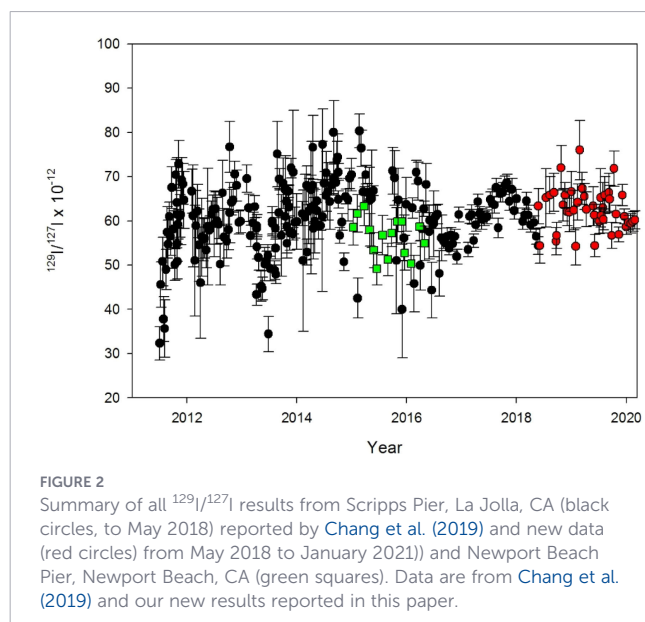
values from 54.4 to 76×10^{-12} , with even more damping (58 to 72×10^{-12}) in the period from summer 2019 to Feb 2020. By contrast, the 2015–2016 data from Newport Beach show a range of 49.2 to 63.3×10^{-12} , like the La Jolla results. In Figure 2, the Newport Beach data are shown as red squares and are consistent with the trends of the Scripps Pier data. Complete data are given in the Supplementary Table S1.

As previously discussed by Chang et al. (2019), all these values are within the range for the California current system reported by Guilderson et al. (2014). Results from Newport Beach were also measured for total iodine concentration, which showed

considerable variability. Using these values, we obtained ^{129}I concentrations from 0.48 to 1.5×10^7 atoms/L. Remarkably, there is no correlation between $^{129}\text{I}/^{127}\text{I}$ ratio and total I concentration, with a Pearson correlation coefficient, $R = 0.018$. We can compare these values to the expected input of ^{129}I from the Fukushima NPP accident. Smith et al. (2015, Smith et al., 2017) measured ^{137}Cs along a sampling line (Line P) from the British Columbia coast (approximately 1300 km). They observed an increase of approx. 6–8 mBq/L ^{137}Cs during the period up to 2014. We can assume that this seawater would eventually travel down the California coast. However, unpublished data available online (<http://www.ourradioactiveocean.org/results.html>) show minimal ^{137}Cs along the southern California coast ($< 2 \text{ Bq/m}^3$) in recent measurements. Using the activity ratio from the radioactive waters measured by Povinec et al. (2013) and others off the Japanese coast for $^{129}\text{I}/^{137}\text{Cs}$ of $0.5\text{--}5 \times 10^{-6}$, we can estimate that the ^{129}I signal equivalent to the measured ^{137}Cs on the west coast would be equivalent to $0.3\text{--}1.2 \times 10^6$ ^{129}I atoms/L. However, from the data shown in Figure 1, we observed higher values from ~ 30 to 70×10^7 atoms/L, so this suggests that an excursion attributable to the Fukushima event may not be observable in the southern California samples. In order to assess this question further, we also need to evaluate other possible sources of ^{129}I .

3.1 Pacific Ocean ^{129}I background value

The main sources of anthropogenic ^{129}I found in Pacific Ocean waters were derived from nuclear weapons testing that took place in the 1950s–1960s, a Japanese nuclear fuel reprocessing plant, the Hanford (Washington, USA) nuclear facility and most recently, the Fukushima accident (Suzuki et al., 2008; Chang et al., 2019).



Overall, the Pacific $^{129}\text{I}/^{127}\text{I}$ background value is $\sim 30 \times 10^{-12}$ while within the California Current System it is $\sim 50 \times 10^{-12}$ (Guilderson et al., 2014). By contrast, in the western Pacific, studies of $^{129}\text{I}/^{127}\text{I}$ in corals by Sakaguchi et al. (2018) from the Sea of Japan varied between 71.3 and 51.6×10^{-12} since 1999. Corals from locations to the south, such as along the Eastern Philippines range from 44 to 67.9×10^{-12} since the year 2000 (Bautista VII et al., 2025) and Chang et al. (2016) measured values of $\sim 40 \times 10^{-12}$ in the South China Sea. Qi et al. (2023) have noted that $^{129}\text{I}/^{127}\text{I}$ in surface waters in a transect across the Pacific Ocean show higher levels in the northeastern Pacific (about 150–140°W, from 34 to 134×10^{-12}), which they attribute to atmospheric deposition from European sources. Chang et al. (2019) proposed an alternative source, that this higher amount of ^{129}I could be coming from the Hanford site in Washington, USA. The Columbia River has an average flow rate of 7252 m³/s (Moran et al., 1998) and is the largest river in North America by volume that discharges into the Pacific Ocean. Suzuki et al. (2008) reported that the Hanford site had released considerable amounts of ^{129}I , about 266 kg, into the atmosphere from 1944 through 1972. Within the Hanford separation area water wells, concentrations of 10^{10} – 10^{17} atoms/L of ^{129}I have been reported (Brauer and Rieck, 1973). The Washington State Department of Health reported that during 1944–1972, 1778 Tbq of ^{131}I was released into the Columbia River. This implies a contribution of around 0.78 Mbq of ^{129}I released to the Columbia River, if we adopt a ratio of the fast fission yields ($^{129}\text{I}/^{131}\text{I}$) = 1.03/3.36 (<https://www-nds.iaea.org/sgnucdat/c3.htm>).

Kilius et al. (1994) collected 13 different species of seaweed samples at 15 sites near the Columbia River mouth in the Pacific Ocean and in the Columbia River Estuary; $^{129}\text{I}/^{127}\text{I}$ levels reached 176.3×10^{-11} . To investigate the possible ^{129}I source from the Hanford site, 15 river water and seawater samples in Oregon and Washington, USA were also collected and analyzed by Chang et al. (2019). High levels of $^{129}\text{I}/^{127}\text{I}$ were found in several river water samples. The highest $^{129}\text{I}/^{127}\text{I}$ water samples that were measured came from the Columbia River, near the Hanford site. The $^{129}\text{I}/^{127}\text{I}$ reached 5.31×10^{-8} , which is more than 1000 times higher than the California Current System background value. At the mouth of the Columbia River, $^{129}\text{I}/^{127}\text{I}$ is 5.03×10^{-8} . As river water mixes with ocean water, ^{129}I is diluted significantly by seawater and was shown by Chang et al. (2019) to decrease with distance from the Columbia River.

Chang et al. (2019) calculated an inflow rate of ^{129}I from the Columbia River into the Pacific Ocean of 9 to 95×10^{21} atoms/yr, or 0.01 to 0.13 GBq ^{129}I /yr. They also concluded that the contribution of ^{129}I to the California Current System from the Hanford site is measurable and could explain the relatively elevated regional Pacific background value of 50×10^{-12} .

3.2 Intra-annual ^{129}I variations

From June 2011 to February 2020, $^{129}\text{I}/^{127}\text{I}$ in seawater off the La Jolla, California coast varied from 40 to 80×10^{-12} , which is similar to the Pacific background value, with a possible overprint from ^{129}I coming down the Columbia River from the Hanford site discussed earlier by (Chang et al., 2019). Similar results are seen at

Newport Beach, with a tighter range of $^{129}\text{I}/^{127}\text{I}$, varying between 49 to 63×10^{-12} . There is no confirmation of one unusual report by Stan-Sion et al. (2015) that extremely high values ($>10^{-9}$) could be detected at La Jolla beach. We showed in our previous work that the $^{129}\text{I}/^{127}\text{I}$ time series does not follow chlorophyll, salinity or temperature time series trends. We therefore proposed that one explanation of these differences is that ^{129}I and ^{127}I represent different reservoirs. This is supported by the Newport Beach data that show no correlation between total ^{127}I and $^{129}\text{I}/^{127}\text{I}$. Recently published ^{14}C data from Hauksson et al. (2024), collected concurrently at the same Newport Beach sampling location, allow us to compare our ^{129}I results with their ^{14}C and $\delta^{13}\text{C}$ findings. Intriguingly, although there is no direct correlation between Γ and $\Delta^{14}\text{C}$, there is a weak correlation of the ratio of $^{129}\text{I}/^{127}\text{I}$ both $\Delta^{14}\text{C}$ ($R = 0.33$) and total DIC ($R = 0.34$). By contrast, there is no correlation of ^{129}I or total I concentration with DIC ($R = 0.03$ and 0.024 , respectively). We expect that these differences involve biological processes, since inorganic iodide-iodate isotopic exchange is very slow (Myers and Kennedy, 1950). Volatile iodine species, especially methyl iodide (CH_3I) rapidly exchange iodine between the ocean and atmosphere (Saiz-Lopez et al., 2012). Once the marine iodine is moved into the atmosphere by sea spray, it can be oxidized to I_2 and travel as aerosols until it is rained out (Miyake and Tsunogai, 1963; Tsunogai and Henmi, 1971). Iodine has ample opportunity to be removed from the surface waters of the California Current as volatile species and is carried by prevailing winds over the continent. There is no doubt that ^{129}I will be very sensitive to upwelling, since there is an order of magnitude more ^{129}I in the surface as compared with deep waters, but the signal will also be affected by removal of volatile species through air-sea interactions. This process is affected primarily by wind speed (Fuge and Johnson, 1986). Qi et al. (2023) proposed a 2-component mixing scheme between upwelled deeper water and surface water to explain the changes in $^{129}\text{I}/^{127}\text{I}$ in their detailed study across the Pacific Ocean.

3.3 Can we dismiss any local sources?

We also evaluated the possibility of a contribution of ^{129}I from the decommissioning of the San Onofre Nuclear Generation Station (SONGS) located on the coast between the two sampling locations of Newport Beach Pier (63 km) and Scripps Institution Pier (40.6 km). SONGS ceased operation in 2013 and is being decommissioned. According to reports from the operator, liquid discharges are below detection limit for ^{131}I . To assess this possibility, we took values from the operator's 2017 report (Bates, 2018). This report showed that 8.51×10^6 L of effluent, diluted to 6.13×10^9 L of water, was discharged in 2017. The detection limit of ^{131}I was reported as $<6.50 \times 10^{-8}$ $\mu\text{Ci/L}$ in the effluent before dilution. According to our calculation of this result, this means that the diluted water released $<2.65 \times 10^4$ ^{131}I atoms/L. Taking the fission yield of $^{129}\text{I}/^{131}\text{I}$ of ~ 0.33 , this suggests the release is $<8.8 \times 10^3$ ^{129}I atoms/L. If the ^{129}I accumulated for one year, this might be an upper limit of $<2.8 \times 10^5$ ^{129}I atoms/L, but this is speculative. Given the concentration of surface water in this area is ~ 3.3 – 15.1×10^6 $^{129}\text{I/L}$, it is most unlikely that this should significantly contribute to the signal observed at our study locations.

3.4 Comparing ^{129}I with model estimates

There have been several model results for the transport of radionuclides from Fukushima. Han et al. (2013) estimated 3.2 to 3.9 years for Fukushima radiogenic material to reach the U. S. west coast. Povinec et al. (2013) suggested that Fukushima signal will arrive at the U. S. west coast in 4–5 years which implies 2015–2016.

Chang et al. (2019) had used an OSCURS model results to suggest that water from Fukushima, Japan could reach the Northeast Pacific coast by May 2014. This model result is supported by some reports of debris arriving along the northwest coast of the United States that year.

Rossi et al. (2013) also predicted that contaminated (^{137}Cs) water should reach the northwestern American coast at 45°N in 2014, based on a regional eddy-resolving simulation. They also suggested that these waters would reach the Californian coast sometime later (2016–2025), due to offshore Ekman drift at the coast, which is associated with coastal upwelling. In addition, it was recognized that mixing with relatively depleted upwelled water could obscure the signal through dilution, which would agree with the study of Qi et al. (2023). It seems reasonable that the seawater with elevated ^{129}I had already become thoroughly diluted through mixing, evaporation or biological uptake as it traveled across the ocean and is therefore not detectable above the background level in southern California. We expect that mixing is the simplest explanation, although further work would be needed to resolve which mechanism is more important.

4 Conclusion

Since the accidental release at the Fukushima Daiichi Nuclear Power Plant, radionuclides have been transported and deposited all over the world. However, after nine years of travel (2011–2020), the levels of ^{129}I in coastal waters off the southern California coast do not show any excess that could be attributed to contaminated seawater from the Fukushima nuclear accident. It appears that the currents carrying the excess ^{129}I either did not travel to the southern California coast, or the excess ^{129}I was diluted in transit, possibly by mixing with upwelled water lower in ^{129}I or by biological uptake, consistent with other studies. The weak connection observed in the Newport Beach results with DIC suggests further work in understanding the complex interactions of iodine species in ocean water is needed.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AJ: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Validation,

Writing – original draft, Writing – review & editing. C-CC: Conceptualization, Investigation, Methodology, Writing – review & editing. GB: Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. LC: Data curation, Formal analysis, Investigation, Writing – review & editing. JR: Writing – review & editing. ML: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. DC: Investigation, Methodology, Validation, Writing – review & editing. MT: Conceptualization, Investigation, Resources, Supervision, Writing – original draft, Writing – review & editing. DB: Formal analysis, Investigation, Methodology, Software, Writing – review & editing. MC: Investigation, Methodology, Resources, Validation, Writing – review & editing. TW: Investigation, Methodology, Resources, Software, Writing – review & editing. CG: Investigation, Methodology, Resources, Writing – review & editing. GS: Conceptualization, Investigation, Methodology, Resources, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was funded in part by NSF grants EAR1313588 (Jull, Arizona) and EAR2300539 (Santos, UC Irvine). This funded the sampling campaign and also measurements at Arizona. Additional support was MOST grant 107-2116-M-002-001-MY3 that supported the work of Dr. George Burr and European Regional Development Fund grant GINOP-2.3.4-15-2020-0007 “INTERACT” that partly supported the work of A Jull.

Acknowledgments

We are grateful to the assistance of staff at the University of Arizona AMS Laboratory, particularly Rich Cruz, Dotty Sherwood-Cooney and colleagues at Purdue University. We are grateful to assistance in sample collection by colleagues at UC Irvine.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial

intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any

product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2026.1818503/full#supplementary-material>

References

- Adachi, K., Kajino, M., Zaizen, Y., and Lgarashi, Y. (2013). Emission of spherical cesium-bearing particles from an early stage of the Fukushima nuclear accident. *Sci. Rep.* 3, 2554. doi: 10.1038/srep02554
- Aldahan, A., Alfimov, V., and Possnert, G. (2007). ^{129}I anthropogenic budget: Major sources and sinks. *Appl. Geochem.* 22, 606–618.
- Alfimov, V., Aldahan, A., Possnert, G., and Winsor, P. (2004). Anthropogenic iodine-129 in seawater along a transect from the Norwegian coastal current to the North Pole. *Mar. pollut. Bull.* 49, 1097–1104. doi: 10.1016/j.marpolbul.2004.08.019
- Aoyama, A., Uematsu, U., Tsumune, T., and Hamajima, Y. (2013). Surface pathway of radioactive plume of TEPCO Fukushima PNPP1 released ^{134}Cs and ^{137}Cs . *Biogeosciences* 10, 265–283. doi: 10.5194/bg-10-3067-2013
- Bates, A. (2018). *Annual radioactive effluent release report – 2017* (San Onofre Nuclear Generating Station (SONGS), Units 1, 2 and 3). Available online at: <https://s3.amazonaws.com/cms.ipressroom.com/339/files/201911/2016+Effluent+Rpt.pdf>. Docket Nos. 50-206, 50-361 and 50-362. Report to the U.S. Nuclear Regulatory Commission, April 24, 2018 Available online at: <https://www.nrc.gov/docs/ML1904/ML1904A506.pdf> (Accessed March 20, 2026).
- Bautista, A. T. VII, Limlingan, S. J. M., Valdez, J. D. G., Bauyon, M. M. T., Magtaas, R. A. H., Jagonoy, A. M., et al. (2025). Investigating iodine-129 in coral cores along the East Philippines as a tracer of the North Equatorial Current bifurcation and marker of the Anthropocene. *Chemosphere* 377, 144342. doi: 10.1016/j.chemosphere.2025.144342
- Biddulph, D. L., Beck, J. W., Burr, G. S., and Donahue, D. J. (2006). Two 60-year records of ^{129}I from coral skeletons in the South Pacific Ocean. *Radioactivity in the environment*. 8, 592–598. doi: 10.1016/S1569-4860(05)0047-2
- Bowyer, T. W., Biegalski, S. R., Cooper, M., Eslinger, P. W., Haas, D., Hayes, J. C., et al. (2011). Elevated radionuclides detected remotely following the Fukushima nuclear accident. *J. Environ. Radioact.* 102, 681–687. doi: 10.1016/j.jenvrad.2011.04.009
- Brauer, F. P., and Rieck, H. G. (1973). ^{129}I , ^{60}Co and ^{106}Ru measurements on water samples from the Hanford Project environs (Richland, Washington: Battelle Pacific Northwest Laboratories). Available online at: <https://www.osti.gov/servlets/purl/4202520/>. USAEC Report BNWL SA-4478 (Accessed March 21, 2026).
- Buesseler, K., Aoyama, M., and Fukasawa, M. (2011). Impacts of the Fukushima Nuclear Power Plants on marine radioactivity. *Environ. Sci. Technol.* 45, 9931–9935. doi: 10.1021/es202816c
- Cascuberta, N., Christl, M., Buesseler, K. O., Lau, Y. S., Vockenhuber, C., Castillejo, M., et al. (2017). Potential releases of ^{129}I , ^{236}U , and Pu isotopes from the Fukushima Dai-ichi Nuclear Power Plants to the Ocean from 2013 to 2015. *Environ. Sci. Technol.* 51, 9826–9835. doi: 10.1021/acs.est.7b03057
- Chang, C. C., Burr, G. S., Jull, A. J. T., Russell, J. L., Biddulph, D., White, L., et al. (2016). Reconstructing surface ocean circulation with ^{129}I time series records from corals. *J. Environ. Radioact.* 165, 144–150. doi: 10.1016/j.jenvrad.2016.09.016
- Chang, C. C., Burr, G. S., Jull, A. J. T., Russell, J., Priyadarshi, A., Lin, M., et al. (2019). Measurements of ^{129}I in the Pacific Ocean at Scripps Pier and Pacific Northwest sites: A search for effects from the 2011 Fukushima Daiichi Nuclear Power Plant accident and Hanford. *Sci. Total. Environ.* 689, 1023–1029. doi: 10.1016/j.scitotenv.2019.06.372
- Charette, M. A., Breier, C. F., Henderson, P. B., Pike, S. M., RYPina, I. I., Jayne, S. R., et al. (2013). Radium-based estimates of cesium isotope transport and total direct ocean discharges from the Fukushima Nuclear Power Plant accident. *Biogeosciences* 10, 2159–2167. doi: 10.5194/bg-10-2159-2013
- Edmonds, J. S., and Morita, M. (1998). The determination of iodine species in environmental and biological samples. *Pure. Appl. Chem.* 70, 1567–1584. doi: 10.1515/iupac.70.0179
- Edwards, R. R. (1962). Iodine-129: Its occurrence in nature and its utility as a tracer. *Science* 137, 851–853. doi: 10.1126/science.137.3533.851
- Fabryka-Martin, J., Bentley, H., Elmore, D., and Airey, P. L. (1984). Natural iodine-129 as an environmental tracer. *Geochim. Cosmochim. Acta* 49, 337–347.
- Fehn, U., and Snyder, G. (2000). ^{129}I in the Southern Hemisphere: Global redistribution of an anthropogenic isotope. *Nucl. Instrum. Methods Phys. Res. B* 172, 366–371.
- Fuge, R., and Johnson, C. C. (1986). The geochemistry of iodine – a review. *Environ. Geochem. Health* 8, 31–54. doi: 10.1007/978-3-642-65933-1_28
- Guilderson, T. P., Tumey, S. J., Brown, T. A., and Buesseler, K. O. (2014). The 129-iodine content of subtropical Pacific waters: impact of Fukushima and other anthropogenic 129-iodine sources. *Biogeosciences* 11, 4839–2852. doi: 10.5194/bg-11-4839-2014
- Han, G. J., Li, W., Fu, H. L., Zhang, X. F., Wang, X. D., Wu, X. R., et al. (2013). An ensemble estimation of impact times and strength of Fukushima nuclear pollution to the east coast of China and the west coast of America. *Sci. China Earth Sci.* 56, 1447–1451. doi: 10.1007/s11430-012-4520-2
- Hauksøn, N. E., Xu, X., Pedron, S., Martinez, H. A., Lewis, C. B., Glynn, D. S., et al. (2024). Time series of surface water dissolved inorganic carbon isotopes from the Southern California Bight. *Radiocarbon* 66, 863–878. doi: 10.1017/rdc.2023.73
- Herod, M. N., Suchy, M., Cornet, R. J., Kieser, W. E., Clark, I. D., and Graham, G. (2013). The atmospheric transport of iodine-129 from Fukushima to British Columbia, Canada and its deposition and transport into groundwater. *Water Resour. Res.* doi: 10.1002/2015WR017325
- Hou, X. L., Hansen, V., Aldahan, A., Possnert, G., Lind, O. C., and Lujanienė, G. (2009). A review on speciation of iodine-129 in the environmental and biological samples. *Anal. Chim. Acta* 632, 181–196. doi: 10.1016/j.aca.2008.11.013
- Hou, X. L., Povinec, P. P., Zhang, L., Shi, K., Biddulph, D., Chang, C. C., et al. (2013). Iodine-129 in seawater offshore Fukushima: Distribution, inorganic speciation, sources and budget. *Environ. Sci. Technol.* 47, 3091–3098. doi: 10.1021/es304460k
- Hsu, S.-C., Huh, C.-A., Chan, C. Y., Lin, S. H., and Lin, F. J. (2012). Hemispheric dispersion of radioactive plume laced with fission nuclides from the Fukushima nuclear event. *Geophys. Res. Lett.* 39, L00G22. doi: 10.1029/2011GL049986
- Hu, Q.-H., Weng, J. Q., and Wang, J. S. (2010). Sources of anthropogenic radionuclides in the environment: a review. *J. Environ. Radioact.* 101, 426–437. doi: 10.1016/j.jenvrad.2008.08.004
- Huh, C. A., Hsu, S. C., and Lin, C. Y. (2012). Fukushima-derived fission nuclides monitored around Taiwan: Free tropospheric versus boundary layer transport. *Earth Planet. Sci. Lett.* 319–320, 9–14. Available online at: <http://doi:10.1016/j.epsl.2011.12.004>.
- Kashparov, V. A., Lundin, S. M., Zvarych, S. I., Yashchenko, V. I., Levchuk, S. E., Khomutinin, Y. V., et al. (2003). Territory contamination with the radionuclides representing the fuel component of Chernobyl fallout. *Sci. Total. Environ.* 317, 105–119. doi: 10.1016/S0048-9697(>03<)>00336-x
- Kilius, L. R., Rucklidge, J. C., and Soto, C. (1994). The dispersal of ^{129}I from the Columbia River estuary. *Nucl. Instrum. Methods Phys. Res. B* 92, 393–397.
- Kutschera, W., Fink, D., Paul, M., Hollos, G., and Kaufman, A. (1988). Measurement of the $^{129}\text{I}/\text{I}$ ratio in Chernobyl fallout. *Phys. Scr.* 37, 310–313. doi: 10.1007/0-306-46927-8_17
- Miyake, Y., and Tsunogai, S. (1963). Evaporation of iodine from the ocean. *J. Geophys. Res.* 68, 3989–3993. doi: 10.1029/jz068i013p03989
- Moran, J. E., Fehn, U., and Teng, R. T. D. (1998). Variations in $^{129}\text{I}/^{127}\text{I}$ ratios in recent marine sediments: evidence for a fossil organic component. *Geology* 152, 193–203. doi: 10.1176/pn.47.3.psychnews.47_3_18-a
- Muramatsu, Y., and Ohmomo, Y. (1986). Iodine-129 and Iodine-127 in environmental samples collected from Tokaimura/Ibaraki, Japan. *Sci. Total. Environ.* 48, 33–43.
- Myers, O. E., and Kennedy, J. W. (1950). The kinetics of the iodine-iodate isotopic exchange reaction. *J. Am. Chem. Soc.* 72, 897–906. doi: 10.1021/ja01158a006
- Paul, M., Fink, D., Hollos, G., Kaufman, A., Kutschera, W., and Magaritz, M. (1987). Measurement of ^{129}I concentrations in the environment after the Chernobyl Reactor

- accident. *Nucl. Instrum. Methods Phys. Res. B* 29, 341–345. doi: 10.4159/harvard.9780674067349
- Povinec, P. P., Gera, M., Holy, K., Hirose, K., Lujanienė, G., Nakano, M., et al. (2013). Dispersion of Fukushima radionuclides in the global atmosphere and the ocean. *Appl. Radiat. Isot.* 81, 383–392. doi: 10.1016/j.apradiso.2013.03.058
- Povinec, P. P., Lee, S.-H., Kwong, L. L. W., Oregioni, B., Jull, A. J. T., Kieser, W. E., et al. (2010). Tritium, radiocarbon, ^{90}Sr and ^{129}I in the Pacific and Indian Oceans. *Nucl. Instruments. Methods Phys. Res. B* 268, 1214–1218. doi: 10.1016/j.nimb.2009.10.136
- Priyadarshi, A., Dominguez, G., and Thiemens, M. H. (2011). Evidence of neutron leakage at the Fukushima nuclear plant from measurements of radioactive ^{35}S in California. *Proceedings. Natl. Acad. Sci. U.S.A.* 108, 14422–14425.
- Qi, Y., Matuszaki, H., Yamagata, T., and Nagai, H. (2023). Iodine cycling in the subarctic Pacific Ocean: Insights from ^{129}I . *Geochim. Cosmochim. Acta* 344, 12–41. doi: 10.1016/j.gca.2023.01.006
- Raisbeck, G. M., Yiou, F., Zhou, A. Q., and Kilius, L. R. (1995). ^{129}I from nuclear fuel reprocessing facilities at Sellafield (U.K.) and La Hague (France): potential as an oceanographic tracer. *J. Mar. Syst.* 6, 561–570.
- Rossi, V., Sebeille, E. V., Gupta, A. S., Garçon, V., and England, M. H. (2013). Multi-decadal projections of surface and interior pathways of the Fukushima Cesium-137 radioactive plume. *Deep-Sea. Res. I* 80, 37–46. doi: 10.1016/j.dsr.2013.05.015
- Saiz-Lopez, A., Plane, J. M. C., Baker, A. R., Carpenter, L. J., von Glasow, R., Gómez Martín, J. C., et al. (2012). Atmospheric chemistry of iodine. *Chemical Reviews* 112, 1773–1804. doi: 10.1021/cr200029u
- Sakaguchi, A., Inaba, R., Sasa, K., Matsunaka, T., Hosoya, S., Takahashi, T., et al. (2018). Reconstruction of anthropogenic ^{129}I temporal variation in the Japan Sea using a coral core sample. *Mar. Environ. Res.* 142, 91–99. doi: 10.1016/j.marenvres.2018.09.003
- Santschi, P. H., Schink, D. R., Corapcioglu, O., Oktay-Marshall, S., Fehn, U., and Sharma, P. (1996). Evidence for elevated levels of iodine-129 in the deep western boundary current in the middle Atlantic bight. *Deep. Sea. Res. I* 43, 259–265.
- Schmidt, A., Schnabel, C., Handl, J., Jakob, D., Michel, R., Synal, H.-A., et al. (1998). On the analysis of iodine-129 and iodine-127 in environmental materials by accelerator mass spectrometry and ion chromatography. *Sci. Total. Environ.* 223, 131–156.
- Smith, J. N., Brown, R. M., Williams, W. J., Robert, M., Nelseon, R., and Moran, S. B. (2015). Arrival of the Fukushima radioactivity plume in North American continental waters. *Proc. Natl. Acad. Sci. U.S.A.* 112, 1310–1315. doi: 10.1073/pnas.1412814112
- Smith, J. N., Rossi, V., Buessler, K. O., Cullen, J. T., Cornett, J., Nelson, R., et al. (2017). Recent transport history of Fukushima radioactivity in the Northeast Pacific Ocean. *Environ. Sci. Technol.* 51, 10494–10502. doi: 10.1021/acs.est.7b02712
- Stan-Sion, C., Enachescu, M., and Petre, A. R. (2015). AMS analyses of I-129 from the Fukushima Daiichi nuclear accident in the Pacific Ocean waters of the Coast La Jolla – San Diego, USA. *Environ. Sciences: Processes. Impacts* 17, 932–938. doi: 10.1039/c5em00124b
- Steinhauser, G., Brandl, A., and Johnson, T. E. (2014). Comparison of the Chernobyl and Fukushima nuclear accidents: a review of the environmental impacts. *Sci. Total. Environ.* 470–471, 800–817. doi: 10.1016/j.scitotenv.2013.10.029
- Suzuki, T., Otosaka, S., Kuwabara, J., Kawamura, H., and Kobayashi, T. (2013). Iodine-129 concentration in seawater near Fukushima before and after the accident at the Fukushima Daiichi Nuclear Power Plant. *Biogeosciences* 10, 3839–3847. doi: 10.5194/bg-10-3839-2013
- Tsunogai, S., and Henmi, T. (1971). Iodine in the surface water of the ocean. *J. Oceanography. Soc. Japan* 27, 67–72. doi: 10.1007/bf02109332
- Xing, S., Hou, A., Aldahan, A., Possnert, G., Shi, K., Yi, P., et al. (2015). Iodine-129 in snow and seawater in the Antarctic: Level and source. *Environ. Sci. Technol.* 49, 6691–6700. doi: 10.1021/acs.est.5b01234
- Yiou, F., Raisbeck, G. M., Christensen, G. C., and Holm, E. (2002). $^{129}\text{I}/^{127}\text{I}$, $^{129}\text{I}/^{137}\text{Cs}$ and $^{129}\text{I}/^{99}\text{Tc}$ in the Norwegian coastal current from 1980 to 1998. *J. Environ. Radioact.* 60, 61–71.
- Yiou, F., Raisbeck, G. M., Zhou, Z. Q., and Kilius, L. R. (1994). ^{129}I from nuclear fuel reprocessing; potential as an oceanographic tracer. *Nucl. Instruments. Methods Phys. Res. B* 92, 436–439.
- Zhang, L., Chen, N., Hou, X., Han, Y., Zhang, T., Lei, D., et al. (2024). Reconstructing atmospheric ^{129}I deposition over 170 years with the varved sediment in the Sihailongwan Maar Lake, northeast China. *Sci. Total. Environ.* 926, 172301. doi: 10.1016/j.scitotenv.2024.172031