Title: Reconstructing Surface Ocean circulation with 129I time series records from corals

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Reconstructing Surface Ocean circulation with $^{129}$I time series records from corals

Ching-Chih Chang$^{1,2,*}$, George S Burr$^{1,3}$, A. J. Timothy Jull$^{1,2}$, Joellen L. Russell$^2$, Dana Biddulph$^1$, Lara White$^1$, Nancy G Prouty$^4$, Yue-Gau Chen$^5$, Chuan-Chou Shen$^5$, Weijian Zhou$^6$, Doan Dinh Lam$^7$

$^1$ NSF-Arizona AMS Laboratory, University of Arizona, Tucson, AZ, 85721 USA
$^2$ Department of Geosciences, University of Arizona, Tucson, AZ, 85721 USA
$^3$ Department of Oceanography, National Sun Yat-Sen University, Kaohsiung, Taiwan
$^4$ US Geological Survey Pacific Coastal & Marine Science Center, Santa Cruz, CA, 95060 USA
$^5$ Department of Geosciences, National Taiwan University, Taipei, Taiwan
$^6$ Shaanxi Province Key Laboratory of Accelerator Mass Spectrometry Technology and Application, Institute of Earth Environment, CAS, Xi’an 710043, China
$^7$ Institute of Geology, Vietnamese Academy of Science and Technology, Hanoi, Vietnam
Highlights:
1. New $^{129}$I time series records from Con Dao and Xisha Islands, the South China Sea, Rabaul, and Papua New Guinea and Guam are presented.
2. Nuclear weapons testing was the primary $^{129}$I source in the Western Pacific in the latter part of the 20th Century, notably from testing in the Marshall Islands.
3. Radiogenic iodine was carried primarily through surface ocean currents.
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$^2$ Department of Geosciences, University of Arizona, Tucson, AZ, 85721 USA
$^3$ Department of Oceanography, National Sun Yat-Sen University, Kaohsiung, Taiwan
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$^5$ Department of Geosciences, National Taiwan University, Taipei, Taiwan
$^6$ Shaanxi Province Key Laboratory of Accelerator Mass Spectrometry Technology and Application, Institute of Earth Environment, CAS, Xi’an 710043, China
$^7$ Institute of Geology, Vietnamese Academy of Science and Technology, Hanoi, Vietnam

*Ching-Chih Chang: cchchang@email.arizona.edu

Postal Address: 1118 E 4th St. Rm267 Tucson, AZ 85712

Abstract

The long-lived radionuclide $^{129}$I (half-life: $15.7 \times 10^6$ yr) is well-known as a useful environmental tracer. At present, the global $^{129}$I in surface water is about 1-2 orders of magnitude higher than pre-1960 levels. Since the 1990s, anthropogenic $^{129}$I produced
from industrial nuclear fuels reprocessing plants has been the primary source of \(^{129}\text{I}\) in marine surface waters of the Atlantic and around the globe. Here we present four coral \(^{129}\text{I}\) time series records from: 1) Con Dao and 2) Xisha Islands, the South China Sea, 3) Rabaul, Papua New Guinea and 4) Guam. The Con Dao coral \(^{129}\text{I}\) record features a sudden increase in \(^{129}\text{I}\) in 1959. The Xisha coral shows similar peak values for \(^{129}\text{I}\) as the Con Dao coral, punctuated by distinct low values, likely due to the upwelling in the central South China Sea. The Rabaul coral features much more gradual \(^{129}\text{I}\) increases in the 1970s, similar to a published record from the Solomon Islands. The Guam coral \(^{129}\text{I}\) record contains the largest measured values for any site, with two large peaks, in 1955 and 1959. Nuclear weapons testing was the primary \(^{129}\text{I}\) source in the Western Pacific in the latter part of the 20th Century, notably from testing in the Marshall Islands. The Guam 1955 peak and Con Dao 1959 increases are likely from the 1954 Castle Bravo test, and the Operation Hardtack I test is the most likely source of the 1959 peak observed at Guam. Radiogenic iodine found in coral was carried primarily through surface ocean currents. The coral \(^{129}\text{I}\) time series data provide a broad picture of the surface distribution and depth penetration of \(^{129}\text{I}\) in the Pacific Ocean over the past 60 years.

Keywords: \(^{129}\text{I}\), coral, radioactive tracers, ocean mixing, surface ocean circulation

1. Introduction

The potential value of \(^{129}\text{I}\) as an environmental tracer has been known since the early 1960s, at a time when above-ground nuclear testing was actively releasing radioactive iodine into the environment (Edwards, 1962; Studier et al., 1962). Features that make \(^{129}\text{I}\)
attractive as an environmental tracer include: 1) a very high level of anthropogenic production, 2) pronounced biological uptake as an essential trace element, 3) high solubility and ready mobility as a dissolved species in marine and fresh waters, 4) intimate connection to organic carbon and the carbon cycle, 5) a long half-life ($15.7 \times 10^6$ yr), 6) benign radiological characteristics as compared with other isotopic tracers associated with nuclear weapons and nuclear engineering, 7) utility in calculating doses and natural pathways of potentially hazardous $^{131}$I, and 8) the very high sensitivity of the Accelerator Mass Spectrometry (AMS) technique which facilitates rapid detection of minute quantities of $^{129}$I. Tracer applications using $^{129}$I have focused primarily on the movement of seawater on the surface and at depth, especially in the North Atlantic, Arctic and adjacent seas (Raisbeck and Yiou, 1999; Yiou et al., 2002; Hou et al., 2009; Keogh et al., 2010). This is due in large part to the fact that more than 90% of the world's $^{129}$I is being released into the North Atlantic from nuclear fuels reprocessing plants at Sellafield, England, and LaHague, France (Aldahan et al., 2007; Hou et al., 2009; Hu et al., 2010). To understand the progressive spread of $^{129}$I in the ocean it is necessary to have data that shows variations in time and space. That is, time series from multiple localities. In the Atlantic these have come from seawater and seaweed samples collected over a period of many years from a variety of locations (Cooper et al., 1998; Hou et al., 2000). In the Pacific, a growing number of coral records document the progressive rise in $^{129}$I in surface waters since the advent of nuclear engineering technologies (Biddulph et al. 2006; Bautista et al., 2016).
Although $^{129}\text{I}$ levels are much lower in the Pacific as compared to the North Atlantic, they are still orders of magnitude above pre-nuclear values. Limited $^{129}\text{I}$ data from seawater samples are available for the Pacific Ocean. Cooper et al. (2001) published seawater results from the North Pacific that showed an anthropogenic component which gives 0.12-0.7×10^8 atoms/kg $^{129}\text{I}$ in seawater. Moran et al. (1998) observed anthropogenic $^{129}\text{I}$ in marine sediments collected off the coasts of Oregon, Baja California, Ecuador and Peru. Suzuki et al. (2008) reported surface water $^{129}\text{I}/^{127}\text{I}$ levels off the coast of Japan that were well above the value expected from nuclear weapons testing fallout which is 46-71×10^{-12}, and concluded that the source of the excess must be atmospheric fallout, from distant European nuclear fuels reprocessing plants. Biddulph (2004) and Biddulph et al. (2006) established two South Pacific $^{129}\text{I}$ coral time series records, one from Easter Island and one from the Solomon Islands. In these records, distinct increases in $^{129}\text{I}$ were observed between the 1930s and 1990s. These time series records are similar to the Atlantic Ocean time series records of Smith et al. (1998) and Yiou et al. (2002), showing the arrival of anthropogenic $^{129}\text{I}$, and quasi-periodic finestructure. The pre-nuclear levels of $^{129}\text{I}$ in the South Pacific coral records were consistent with the pre-nuclear marine value quoted by Fabryka-Martin et al. (1984) of 6×10^{-13}.

There are many advantages to using corals to construct $^{129}\text{I}$ time series. Corals are widespread and common, and many reef-building corals produce annual growth bands which can be identified using X-ray or UV imagery (Figure 1). Corals of this type have found wide use for paleoclimatic reconstructions of sea surface temperature, surface
salinity and ocean circulation, as well as paleoenvironmental studies quantifying anthropogenic impacts on coastal environments.

Iodine is an essential element in plants and animals. A natural advantage of studying $^{129}$I in corals stems from the fact that most of the iodine in the earth's surface environment is found in seawater (Fuge and Johnson, 1986), and corals readily incorporate iodine into their skeletons (Mendel, 1900). Iodine has been shown to occur as thyroxine, or a thyroxine-like substance, in the gorgonian coral *Leptogorgia virgulata* (Kingsley et al., 2001). This substance was found in the coral axis, polyp epithelium, spicule-forming cells, and in the periphery of the spicules, evidently to facilitate healthy spicule growth. For this study, $^{129}$I/$^{127}$I time series were constructed by continuously sampling successive growth years from a banded coral and measuring $^{129}$I/$^{127}$I ratios for each year by Accelerator Mass Spectrometry (Biddulph 2004). Systematic analyses of corals from different localities allows for the development of two-dimensional time-series grids so that the spatiotemporal movement of $^{129}$I in the surface ocean can be understood. Towards this goal, we present $^{129}$I results from a wide range of coral sites in the Pacific Ocean, including coral cores from: 1) Con Dao, Vietnam, 2) Xisha Islands, China, 3) Guam, and 4) Rabaul, Papua New Guinea (Figure 2).

2. Material and Methods

2.1 Sampling Locations

The sampling locations are shown in Figure 2. Coral cores were collected from Xisha Islands (N16°33.6’, E111°39.8’), China, Con Dao, CD-4, Vietnam (N8°33’25.7’’),
Guam, Agat-1 (N13°21.49688, E144°38.55825), and Rabaul, Papua New Guinea (S4°11’ 53”, E152°5’ 57”).

Xisha Islands, Con Dao, and Guam are all Northern Hemisphere sites while Rabaul, Papua New Guinea is in the South Pacific, near the equator. Both Xisha Islands and Con Dao are located in the South China Sea (SCS), which is a semi-enclosed ocean basin that connects the Pacific Ocean and the Indian Ocean. The climate and surface currents in the SCS are influenced profoundly by the East Asian Monsoon. In winter, the northeastern seasonal wind drives surface currents from northeast to southwest and in the summer they travel in the opposite direction. Guam is a tropical island located in the Western Pacific. The seasonal northeast trade winds dominate its climate and surface currents. The Guam site was selected because of its position, immediately downstream from the most probable 1950s source of $^{129}$I in the North Pacific (discussed below). In Rabaul, Papua New Guinea, the surface currents are also strongly monsoonal. Half the year (May to October) the currents flow towards the northwest and in the other half of the year (December to March) they flow towards the southeast.

Samples were cored from live Porites corals using hydraulic drilling equipment. The cores were oriented perpendicular to the primary growth axes of the corals to facilitate annual subsampling of growth rings. All of the coral cores have clear annual banding to identify age. Annual bands in the Xisha Islands coral were produced during the years 1960-2001, the Con Dao coral lived from 1920-2006, the Guam coral studied here lived from 1950-1970, and the Rabaul coral lived from 1973-1996.
2.2 Methods

The sample pretreatment followed the method described by Biddulph et al. (2006). The coral slab was subsampled at annual resolution (the average coral sample mass is ~15 g). Subsamples were cleaned with H₃PO₄ and dissolved in 17% H₃PO₄. The resulting sample solution was filtered with a 0.22 μm membrane filter, leaving only dissolved iodine in solution. Between 3 to 5 ml of CHCl₃ were then added to the solution in a separatory funnel, and 5 drops of 1 M NaNO₂ were added to oxidize iodine to I₂. The sample was then shaken vigorously and time was allowed for CHCl₃ to separate immiscibly to the bottom of the funnel. The CHCl₃ was decanted into a 20 ml glass scintillation vial containing 10-15 mg Ag powder. This process was repeated 5 times and the I₂ was left in the solution with the Ag powder overnight to allow time for it to react with the dissolved iodine. After that, the CHCl₃ was evaporated under a fume hood. When the sample was dry, it was rinsed with distilled water 3 times and dried. The sample was then pressed into a cathode for the AMS measurement. 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 2.5 MV with a transmission of 11%. Errors include statistical uncertainties and a random machine error of 4.3% (Biddulph et al., 2006). We used a chemical process blank for the blank correction. The blank produced about 0.1 count/second while the modern coral signal yielded about 2 counts/second.

3. Results

3.1 Southern Hemisphere: Rabaul, Papua New Guinea (Figure 3)
The Rabaul coral shows very similar trends to the Solomon Island coral (Biddulph et al., 2006), with a gradual increase in the 1970s. This is to be expected as the two sites both lie in the path of the South Equatorial Current and feature very similar coral $^{14}$C values (Burr et al., 2009). The maximum $^{129}$I/$^{127}$I values observed in these corals were $\sim 15 \times 10^{-12}$ in 1996, steadily increasing since about 1970.

3.2 Northern Hemisphere: Con Dao, Xisha Islands, Guam (Figure 4)

The only North Pacific record that we obtained that reaches the pre-nuclear era is the Con Dao, Vietnam coral. From 1920-1958, $^{129}$I/$^{127}$I levels are $\sim 1 \times 10^{-12}$ while in 1959, there is a sudden rise. $^{129}$I increases up to 25 times above the pre-nuclear values in less than 5 years. Since the early 1960s, $^{129}$I/$^{127}$I values have steadily increased at the site to about 40 times pre-nuclear values. The data show interesting quasi-periodic fluctuations from the late 1990s to 2004. The Xisha Islands coral covers the period 1960-2001, starting just after the sudden rise in $^{129}$I/$^{127}$I observed at Con Dao. The Xisha Islands coral shows similar $^{129}$I/$^{127}$I values to the Con Dao coral as expected, since both of them are from the South China Sea. However, the Xisha record contains a number of low $^{129}$I/$^{127}$I values not observed at Con Dao. A straightforward explanation for the difference between the two sites is evident from the bathymetry of the surrounding waters. The Con Dao site is coastal, situated on a shelf with water depths of less than 100 m. The Xisha site is surrounded by deep water, with an average depth of about 1000 m, which gives way to depths in excess of 4000 m towards the east. This portion of the South China Sea is well known as a site of vigorous seasonal upwelling (Chen et al., 2001). Upwelling will bring
low $^{129}\text{I}/^{127}\text{I}$ deep water up to the surface and dilute the surface water. This is consistent with the observation that where the Xisha and Con Dao records disagree, the Xisha $^{129}\text{I}/^{127}\text{I}$ values are always lower.

The Guam coral is unique among all of the corals studied. There are two large $^{129}\text{I}/^{127}\text{I}$ peaks that reach $157\times10^{-12}$ in 1955 and $96.4\times10^{-12}$ in 1959, more than 100 times pre-nuclear values. These must be due to above-ground nuclear weapons testing carried out in the 1950s in the Pacific Ocean.

4. Discussion

4.1 Survey of 1950s above-ground nuclear weapons testing sites

Even from a cursory inspection of the results shown above, it is clear that nuclear weapons testing was the primary source of elevated $^{129}\text{I}$ observed in corals starting in the 1950s. Thus an important preliminary consideration is to survey possible sources in the Pacific region.

There were a total of 269 atmospheric nuclear weapons tests conducted in the 1950s by the United States, Russia, and the United Kingdom (UNSCEAR, 2000). Four test sites are located in the North Pacific. These include: 1) Johnston Island, 2) Enewetak Atoll, 3) Bikini Atoll and 4) Christmas Island. The nuclear weapons testing at Johnston Island started in 1958 and ended in 1962. In those five years, 12 atmospheric tests were conducted and most of these were high-altitude nuclear explosions. In 1958, two of the largest high-altitude nuclear tests were conducted, each involving 3.8-megaton devices
deployed by rockets. The explosions occurred at altitudes of 43 and 77 kilometers above Johnston Island. Enewetak Atoll and Bikini Atoll are both in the Marshall Islands. In total, 66 tests were conducted at these two sites. The Marshall Islands testing program accounts for 14% of all U.S. tests, and these account for nearly 80% of the total yield of the weapons detonated by the U.S., out of an estimated total of 210 megatons. The largest among these was the 15 megaton Castle Bravo test in 1954. This test spread large quantities of nuclear fallout on many of the surrounding islands and in the sea. In 1958, an additional series of 31 nuclear tests were conducted at the two sites as part of Operation Hardtack I. These produced a total yield of approximately 26 megatons. At Christmas Island, in Kiribati, 33 atmospheric nuclear weapon tests were conducted in the late 1950s and early 1960s. In 1957 and 1958, a series of 9 hydrogen bombs tests were conducted with a total yield of 7.8 megatons (Yang et al., 2000).

4.2 Southern Hemisphere $^{129}$I results

As noted above, the $^{129}$I time series records for the Solomon Islands and Papua New Guinea are quite similar, owing to the fact that they are located in a common surface ocean circulation regime (Stewart, 2008). Both records show steady increases in $^{129}$I/$^{127}$I values from the late 1950s, with maximum values of about 20 times pre-nuclear values by the latter half of the 1990s (Figure 4). In this area, surface seawater currents transport water from the Northern Hemisphere to the Southern Hemisphere (Aoyama et al., 2011) and the increases in $^{129}$I in the 1970s and 1980s may reflect a relatively slow, steady supply of Northern Hemisphere water to the region. During the same period $^{129}$I in Easter Island corals experienced only a modest increase to about 5 times pre-nuclear values in
the late 1950s and a very subdued gradual increase through the 1990s (Figure 4). Easter Island is located near the core of the South Pacific Gyre, far from the influence of anthropogenic $^{129}$I carried in surface ocean currents from the Northern Hemisphere (Bidulph et al., 2006). Compared to other Southern Hemisphere $^{129}$I data, Rabaul and Solomon Island corals are higher than Antarctic surface seawater which is 6.1-13×$10^{-12}$ (Xing et al., 2015), and are similar to river water samples collected in Argentina (Negri et al., 2013).

4.3 Northern Hemisphere coral $^{129}$I results
The primary atmospheric source of anthropogenic $^{129}$I in the 1950s is from nuclear weapons testing (Hu et al., 2010). The coral $^{129}$I results presented here provide a quantitative measure of anthropogenic $^{129}$I input into the Pacific Ocean. There are two special features in our coral records. The first is the presence of the two large $^{129}$I/$^{127}$I peaks seen in the Guam coral in 1955 and 1959, and the second is the sudden rise of $^{129}$I in the Con Dao coral, in 1959. These provide an opportunity to trace the source of the iodine and follow the surface ocean current pathways that the $^{129}$I was carried in. The 1955 $^{129}$I/$^{127}$I peak in Guam reaches 157×$10^{-12}$ which is more than 100 times the pre-anthropogenic background (probably from a single nuclear weapons test). Recently, Andrews et al. (2016) measured $^{14}$C in Guam corals and found similar large peaks related to nuclear weapons testing. Further afield, time series records from corals collected from the Philippines also show large $^{129}$I/$^{127}$I peaks, albeit with different timing (Bautista et al., 2016). From a coral collected on the Pacific Ocean side (east coast) of the Philippines, at Baler, they observe a distinct and rapid increase in $^{129}$I/$^{127}$I in 1960, with a
peak in 1963. This coral shows no distinct peaks in the 1950s however. A second Philippine coral, from the South China Sea side (west coast) of the Philippines, at Spratly Islands, shows what appears to be a peak in the late 1950s, not seen in the Baler record, but does not reach back in time far enough to record the entire peak. Coral records from the Pacific also show clear evidence of nuclear testing from other bomb-related anthropogenic radioisotopes. For example, Sakaguchi et al. (2016) observed several $^{236}$U peaks in time series from the South China Sea from the 1950s that can only have come from nuclear weapons testing and correspond very well to our $^{129}$I records. Another example was observed by Fallon et al. (2008) and shows that coral $\Delta^{14}$C increased by 40‰ from -50‰ to -10‰ from February 1955 to November 1955 at Langkai Island, Indonesia. This significant increase must also be related to nuclear weapons testing upstream, most likely from the 1954 Castle Bravo test at Bikini Atoll, discussed next.

Fan el al. (2016) measured $^{129}$I in marine sediments from Jiaozhou Bay, in the East China Sea. Their record shows peaks since 1957, which are related to nuclear weapons testing. In addition to the nuclear weapons testing signal, they also observe $^{129}$I peaks related to Chinese nuclear weapon testing, the Chernobyl accident, Chinese nuclear power plants, and Japanese and European nuclear fuels reprocessing. Overall, the trends they observe in the East China Sea are consistent with our findings in the South China Sea, at Con Dao.

4.3.1 Bikini Atoll, Marshall Islands nuclear weapon testing site, 1954 Castle Bravo Test
There were a total of 23 nuclear weapons tests between 1946 and 1956 at Bikini Atoll, Marshall Islands, and the site was closed in 1958. In 1954, the largest and most powerful
American nuclear weapon ever produced was detonated at this site and nicknamed "Castle Bravo." This test created the worst radiological disaster in U.S. testing history. The Castle Bravo test, with a yield of 15 megatons, was about 1000 times more powerful than the two atom bombs that were dropped on Japan during World War II. The test produced a huge amount of fallout. The gritty, white ash traveled more than 200 miles within a day (Hanson, 1995). Some people exposed to the fallout apparently experienced skin burns and significant loss of hair. As a result, the U.S. initiated “Project 4.1” to study the biomedical consequences of this test. The examination of fish caught after the explosion revealed that radioactive contamination had spread to the west, across the Pacific Ocean, to the south coast of Japan and east coast of Taiwan (Sevitt, 1955). Radioactive fish were also reported from the north of the island of New Guinea. The Japanese government sent an observation ship to examine the water and zooplankton and found that the contamination was contained mostly in the upper 50-100 meters of the sea (Sevitt, 1955). In addition, bomb-produced $^{137}\text{Cs}$ in the Marshall Islands also showed an increase from the late 1940s, with peak values in 1954. (Nakano and Povinec, 2003). It was concluded that the Castle Bravo test produced more significant exposures in the Pacific region than any other test (UNSCEAR, 2000).

4.3.2 Operation Hardtack I

In addition to the 1954 Castle Bravo test, there was a series of 35 nuclear weapon tests named Operation Hardtack I conducted in 1958. These included two high altitude nuclear weapons tests launched from Johnston Island. Near surface testing was mostly conducted at two sites of the Marshall Islands: Enewetak Atoll and Bikini Atoll (total of 31 tests),
and only two were conducted at the Pacific Proving Grounds, with a yield of 1.7 kilotons. The yield of the tests from the Marshall Islands ranged from 1.4 kilotons to 9.3 megatons, contributing to a total yield of approximately 26 megatons (Yang, 2000). Hence, this is the most likely source of the 1959 peak seen in Guam. Although $^{129}\text{I}/^{127}\text{I}$ values observed for 1959 were not as high as those from the tests in 1955, they did reach levels of $96.4 \times 10^{-12}$, up to 70 times the background value.

4.3.3 OSCURS model

To better understand the sudden rise seen in the Con Dao coral, we need to know approximately how long it takes for ocean currents to travel from the Marshall Islands to the western Pacific. For this we chose to use the OSCURS model (Bonjean and Lagerloef, 2002; http://www.pfeg.noaa.gov/products/las/OSCURS.html). The OSCURS model estimates surface current movements through time. Surface currents are driven by wind, and the OSCURS model uses sea level pressure to calculate east-west wind velocity ($u,v$-wind) components and then uses empirical functions to determine east-west current grids. By adding the long-term geostrophic currents, the total velocity field can be calculated. Given the starting date and the end date at a specific location, the OSCURS model can calculate trajectories. The OSCURS model does not extend back to 1954, so randomly selected dates were chosen to capture a range of surface ocean conditions. The model results indicate that water from the Marshall Islands does not always successfully enter the South China Sea. It may be deflected along the east coast of the Philippines, or join the Kuroshio Current flowing northward, past Japan and eventually into the North Pacific Current and California Current. Water that is carried into the South China Sea can
take as many as 4 years to get to Hainan Dao. It takes only a year to arrive just east of the Philippines but it typically takes 2-3 years more for the water to make its way into the South China Sea, if at all. Due to the model resolution, OSCURS is unable to simulate current motion in the South China Sea. The modeling results imply that a 4-year-delay for surface waters to travel from the Marshall Islands to the South China Sea is possible. Hence, the Castle Bravo test is a possible source of the sudden rise in $^{129}$I observed in 1959. Although this analysis shows that the rapid increase in the South China Sea coral is a marine-derived signal instead of an atmospheric one, we still cannot rule out the possibility that part of the $^{129}$I is transported by the atmosphere from the 1958 tests in the Marshall Islands. In the case of the Castle Bravo test we know that the bulk of atmospheric fallout travelled east, with prevailing winds (Hanson, 1995).

5. Conclusions

$^{129}$I time series in corals offer valuable tracer records that can be used to reconstruct pathways and sources of $^{129}$I in the surface ocean. The four coral records presented here reflect the global increase in $^{129}$I in the surface ocean, derived from nuclear weapons testing during the late 1950s and early 1960s. The $^{129}$I content of a particular coral is directly related to the amount of $^{129}$I in surface waters. The Solomon Island and Papua New Guinea $^{129}$I records both lie in the path of the South Equatorial Current and their $^{129}$I records display marked similarity. Xisha Islands and Con Dao islands are both located in the South China Sea and they also show similar trends, with apparently different local influences. Both of these sites record sharp increases in $^{129}$I from testing conducted during the 1950s. Easter Island and Guam are from very different surface oceanic
regimes and display two extremes in their $^{129}$I time series. Easter Island is far removed from Pacific sources of bomb-produced radionuclides and records a minor increase in $^{129}$I during the latter half of the 20th Century. Guam is located directly downstream from the largest source of bomb-produced radioactivity in the Pacific Ocean, namely the Marshall Islands. The $^{129}$I time series from our Guam record contains two exceptionally large peaks, in 1955 and 1959. Both of these are clearly related to nuclear weapons testing. Our results show the importance of corals as recorders of these effects.

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References


http://oceanworld.tamu.edu/.


Black-and-white figures in print, and color figures online.

**Figure 1.** Reflected UV image of a coral core, CD-4, from Con Dao, Vietnam. To produce this image the core is cut along its long axis and photographed under a UV light source. Annual growth bands correspond to light and dark pairs.

**Figure 2.** Sample sites for this study (black circles) and previous $^{129}$I studies (blue circles from Biddulph 2004 and Biddulph et al. 2006). Known major sources of $^{129}$I are shown for reference (red circles). Arrows indicate averaged surface ocean current velocities. (www.oscar.noaa.gov; Boniean and Lagerloef, 2002) The color bar on the right indicates the speed of the surface currents.
Figure 3 Solomon Islands, Easter Island, and Papua New Guinea $^{129}$I coral records

Figure 4 Con Dao, Xisha Islands and Guam $^{129}$I coral records
**Figure 5** Nuclear weapon testing map and timeline. (modified from UNSCEAR, CTBTO. http://www.ctbto.org/map/#testing)

**Figure 6** OSCURS model simulation starting from different dates.