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April 30, 2014

TO: Coastal Commissioners and Interested Parties

FROM: Charles Lester, Executive Director
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SUBJECT: **Report on the Fukushima Dai-ichi Nuclear Disaster and Radioactivity along the California Coast.**

Coastal Commission staff has received numerous inquiries on the March 2011 accident at the Fukushima Dai-ichi Nuclear Power Plant in Japan. Attached for your information is a report investigating the release of radioactivity materials during the disaster and the implications for residents of California. Staff's conclusions are presented in the summary below, and in greater detail in the attached briefing report.

Report Summary

The Great Tohoku Earthquake and Tsunami of March 11, 2011, led to the partial meltdown of several nuclear reactors at the Fukushima Dai-ichi Nuclear Power Plant, on the northeast coast of Japan, and to the discharge of large amounts of radioactive material to the atmosphere and the North Pacific Ocean. Estimates of the total release range widely, but the accident is generally recognized as the second largest accidental release of radioactivity in history, after only the Chernobyl disaster in 1986. Because the Pacific Coast of North America is downwind and "down-current" of Japan, the accident has led to widespread public concern about the prospect of radioactive contamination along the coast, and, in some cases, the spread of inaccurate or misleading information. The purpose of this report is to provide the Coastal Commission and the general public with a reliable source of information on the Fukushima disaster, the dispersal of radioactive materials in the atmosphere and ocean, and the levels of radioactivity detected in California, based on a review of the best available science.

Several large pulses of radionuclides were released into the atmosphere in the first week after the tsunami, coinciding with explosions and fires in multiple Fukushima reactor buildings. The atmospheric plume, mostly consisting of radioactive gases and volatile elements, was entrained

by the mid-latitude westerly winds and transported around the Northern Hemisphere. Most of the atmospheric radioactivity was deposited in the North Pacific or on land areas of Japan through rainfall or dry deposition. A small fraction reached the West Coast within 4-7 days of the accident, resulting in detectable levels of airborne radioactivity in California. Airborne radionuclides, in particular iodine-131, cesium-134 and cesium-137, were partially transferred to the land surface through fallout, and were detectable at low levels in soils, surface waters, drinking water and food products for several months after the accident.

Radioactive fallout to the North Pacific was augmented by the direct discharge of large volumes of radioactive water from the nuclear power plant in the weeks following the accident. Though the largest releases to the ocean (emergency cooling water used in the damaged reactors) ended in April 2011, on-going leaks from the plant, contaminated river runoff, groundwater leakage and leaching from nearshore sediments continue to introduce new radioactivity to the ocean near Japan. Over the last three years, the radioactive ocean plume has been carried eastward by ocean currents, becoming increasingly diluted as it spreads over an ever-larger area and mixes to greater depths. The leading edge of the plume appears to have reached North America off of Vancouver Island, and could possibly reach California within the next year. However, the concentration of Fukushima-derived radionuclides (chiefly cesium-137, which has a ~30-yr half-life) is expected to be only slightly above the pre-accident background, and far below that of naturally-occurring radioactive elements in the ocean. Radioactive cesium derived from Fukushima has been detected at low levels in the tissues of highly-migratory fish species such as Pacific Bluefin tuna, which appear to have accumulated the cesium in their juvenile rearing grounds in the western Pacific. Cesium has not yet been detected in marine biota local to the eastern Pacific, but some degree of bioaccumulation is likely once the radioactive plume has arrived along the West Coast.

The levels of Fukushima-derived radionuclides detected in air, drinking water, food, seawater and marine life in California are extremely low relative to the pre-existing background from naturally-occurring radionuclides and the persistent residues of 20th century nuclear weapons testing. The additional dose of radiation attributable to the Fukushima disaster is commensurately small, and the available evidence supports the idea that it will pose little additional risk to humans or marine life. However, it should be noted that the long-term effects of low-level radiation in the environment remain incompletely understood, and that this understanding would benefit from increased governmental support for the monitoring of radioactivity in seawater and marine biota and the study of health outcomes linked to radiation exposure.

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The Fukushima Dai-ichi Nuclear Power Plant Disaster & Radioactivity in California

Prepared by the staff of the California Coastal Commission

April 30, 2014

This report was prepared by California Coastal Commission staff to provide information about the Fukushima disaster and to investigate possible effects in California from the radionuclides released during the accident. This report has not been approved by the Commission.

Report Summary

The Great Tohoku Earthquake and Tsunami of March 11, 2011, led to the partial meltdown of several nuclear reactors at the Fukushima Dai-ichi Nuclear Power Plant, on the northeast coast of Japan, and to the discharge of large amounts of radioactive material to the atmosphere and into the North Pacific Ocean. Estimates of the total radiation release range widely, but the accident is generally recognized as the second largest accidental release of radioactivity in history, after only the Chernobyl disaster in 1986. Because the Pacific Coast of North America is downwind and "down-current" of Japan, the disaster has led to widespread public concern about the prospect of radioactive contamination along the coast, and, in some cases, the spread of inaccurate or misleading information. The purpose of this report is to provide the Coastal Commission and the general public with a reliable source of information on the Fukushima disaster, the dispersal of radioactive materials in the atmosphere and ocean, and the levels of radioactivity detected in California, based on a review of the best available science.

Several large pulses of radionuclides were released into the atmosphere in the first week after the tsunami, coinciding with explosions and fires in multiple Fukushima reactor buildings. The atmospheric plume, mostly consisting of radioactive gases and volatile elements, was entrained by the mid-latitude westerly winds and transported around the Northern Hemisphere. Most of the atmospheric radioactivity was deposited in the North Pacific or on land areas of Japan through rainfall or dry deposition. A small fraction reached the West Coast within 4-7 days of the accident, resulting in detectable levels of airborne radioactivity in California. Airborne radionuclides, in particular iodine-131, cesium-134 and cesium-137, were partially transferred to the land surface through fallout, and were detectable at low levels in soils, surface waters, drinking water and food products for several months after the accident.

Radioactive fallout to the North Pacific was augmented by the direct discharge of large volumes of radioactive water from the nuclear power plant in the weeks following the accident. Though the largest releases to the ocean (emergency cooling water used in the damaged reactors) ended in April, 2011, on-going leaks from the plant, contaminated river runoff, groundwater leakage and leaching from nearshore sediments continue to introduce new radioactivity to the ocean near Japan. Over the last three years, the radioactive ocean plume has been carried eastward by ocean currents, becoming increasingly diluted as it spreads over an ever-larger area and mixes to greater depths. The leading edge of the plume appears to have reached North America off of Vancouver Island, and could possibly reach California within the next year. However, the concentration of Fukushima-derived radionuclides (chiefly cesium-137, which has a ~30-yr half-life) is expected to be only slightly above the pre-accident background, and far below that of naturally-occurring radioactive elements in the ocean. Radioactive cesium derived from Fukushima has been detected at low levels in the tissues of highly-migratory fish species such as Pacific Bluefin tuna, which appear to have accumulated the cesium in their juvenile rearing grounds in the western Pacific. Cesium has not yet been detected in marine biota local to the eastern Pacific, but some degree of bioaccumulation is likely once the radioactive plume has arrived along the West Coast.

The levels of Fukushima-derived radionuclides detected in air, drinking water, food, seawater and marine life in California are extremely low relative to the pre-existing background from naturally-occurring radionuclides and the persistent residues of 20th century nuclear weapons testing. The additional dose of radiation attributable to the Fukushima disaster is commensurately small, and the available evidence supports the idea that it will pose little additional risk to humans or marine life. However, it should be noted that the long-term effects of low-level radiation in the environment remain incompletely understood, and that this understanding would benefit from increased governmental support for the monitoring of radioactivity in seawater and marine biota and the study of health outcomes linked to radiation exposure.

Background

Tohoku Earthquake and Tsunami

On March 11, 2011, a magnitude 9.0 earthquake occurred approximately 70 km off the Pacific coast of the Tohoku region of northern Honshu, the main island of the Japan. The earthquake, occurring along a 160-km section of the seafloor, triggered a series of massive tsunamis that struck the coast less than an hour later. Tsunami run-up heights exceeded 30 m in certain locations, traveled as far inland as 10 km (6 mi) in the city of Sendai, and inundated approximately 561 km^2 (217 mi^2) of low-lying coastal areas (*1, 2*). Land subsidence (0.3 - 1.2 m) associated with the earthquake exacerbated the flooding. Together, the earthquake and tsunami led to over 20,000 casualties and $200 – 300 billion in infrastructure damage in Japan, while the tsunami damaged ports as far away as California, Hawai'i and Chile (*2*) and generated a large amount of marine debris (*see* sidebar).

Coastal Commission's Japan Tsunami Marine Debris Cleanup Project

Since January 2013, the Coastal Commission has been partnering with local organizations in each coastal county to conduct volunteer beach cleanups with a specific focus on assessing potential tsunami debris generated by the earthquake and tsunami that struck Japan in March 2011. Funded by a grant from NOAA and the California Office of Emergency Services, these cleanups took place once per quarter in each coastal county. Volunteers were given a new data card, developed by Coastal Commission staff with assistance from NOAA, which highlighted items that had been most commonly reported as potential tsunami debris. Over the course of 60 cleanups during 2013, more than 4,700 volunteers collected debris and data from California's beaches. While no single item was specifically confirmed as tsunami debris, numerous suspect items were found and reported to NOAA. The Coastal Commission now has a baseline of data that it will use in the coming years to compare future cleanup data against in order to better assess where and when tsunami debris is coming ashore in California. This information will help inform the activities of the Commission and the local emergency responders who may be called upon to manage large or potentially hazardous items.

Disaster at Fukushima Dai-ichi Nuclear Power Plant

The third part of this triple disaster occurred when tsunami waves arrived at the Fukushima Dai-ichi nuclear power plant, located on the coast approximately 150 km southwest of the earthquake epicenter, about 45 minutes after the earthquake. Waves of up to 14 m in height overwhelmed the seawall protecting the facility[1], inundating much of the plant and causing the failure of all but one of the plant's emergency generators (which had come online when the electric grid failed during the earthquake), as well as the pumps that provided cooling water to the nuclear reactors (*1*). With the loss of both primary and secondary electrical power, the safety systems designed to protect and cool the fuel in the reactor cores at Units 1, 2 and 3 failed. The reactors overheated, leading eventually to the melting of nuclear fuels. Hydrogen generated during the accident collected within the reactor buildings and exploded, exposing the spent fuel pools in Units 1, 3, and 4, leading to a fire in Unit 4, and venting radioactive gases and volatile elements to the environment. This chain of events resulted in a massive release of radioactive elements ("radionuclides") to the atmosphere in the days between March 12 and March 18, 2011 (e.g., *3*). In the weeks and months that followed, emergency cooling water used to flood the damaged reactors was discharged directly to the Pacific Ocean via the NPP's intake channels, creating a second pathway for the release of radioactive materials (e.g., *4*)

[1] The seawall was built to withstand a tsunami wave of up to 5.7 m in height (*1*).

Radioactivity Released into the Environment

The Fukushima NPP disaster represents the second largest accidental release of anthropogenic radiation to the environment in history, after only the 1986 Chernobyl nuclear power plant disaster in the Ukraine. In contrast to the Chernobyl disaster, which occurred at an inland location, most of the radionuclides released at Fukushima were deposited in the North Pacific Ocean (*3, 5, 6*), either through atmospheric fallout or direct discharge. The total amount of radioactivity released from Fukushima is not well-constrained, but was far smaller than the amounts released during the atmospheric testing of nuclear weapons in the 1940s – 1960s. Without minimizing the magnitude of the Fukushima disaster, it is important to place the accident in the context of the much larger existing sources of environmental radioactivity, including the legacy of weapons testing and the background radiation resulting from the decay of naturally-occurring radioactive elements (e.g., ^{40}K, ^{238}U, etc.) (**Figure 1**). It is also important to understand that the Fukushima release consisted of multiple radionuclides with distinct modes of release, chemical properties, radioactive half-lives, and behavior in the environment, all of which influence the potential for environmental harm.

The primary release of radioactivity to the atmosphere occurred within a week of the accident, from March 12 – 18, 2011, with subsequent releases occurring in much smaller amounts. Estimates of the total atmospheric release range from 11,500 to >20,000 peta Becquerels (PBq, 10^{15} Bq; *see* sidebar), with most of this occurring as xenon-133 (^{133}Xe, $t_{1/2}$ = 5.25 d) and other inert, short-lived noble gases (*3, 7-9*). Other radionuclides such as iodine-131 (^{131}I, $t_{1/2}$ = 8.0 d), cesium-134 (^{134}Cs, $t_{1/2}$ = 2.1 yr) and cesium-137 (^{137}Cs, $t_{1/2}$ = 30.1 yr) were also released in significant quantities and pose greater potential risks to human and ecosystem health due to their reactivity, mobility in the environment, and biological availability. Direct releases of radioactive water to the ocean trailed the reactor meltdown by several weeks, peaking in early April, and continuing at lower levels at least through the fall of 2012 (*4, 10, 11*). Seepage of groundwater contaminated with high levels of radioactive cesium and strontium-90 (^{90}Sr, $t_{1/2}$ = 28.9 yr) from beneath the plant represents a small but on-going source of radioactivity to the ocean, while a growing stockpile of contaminated water is being stored on-site at the plant,

Measuring Radioactivity & Radiation Doses

Scientists use a variety of techniques to measure the abundance of radioactive elements in the environment, and often express these measurements in units that are unfamiliar to the general public. While it is possible to consider radionuclide abundances in units of concentration (e.g., moles per liter, kilograms per liter), more typically the measurement techniques used take advantage of the fact that these elements are undergoing radioactive decay – i.e., the process by which the nucleus of an unstable atom loses energy by emitting elementary particles – which can be detected by a variety specialized instruments. A commonly used unit of radioactivity is the **Becquerel (Bq)**, which represents an amount of a radioactive material producing one atomic decay per second. Units of radioactivity can be converted to more traditional units of concentration using the known radioactive half-life ($t_{1/2}$) or decay rate of the radionuclide in question. For the sake of consistency, and in order to match scientific convention, this briefing paper reports radionuclide abundances in Becquerel – per cubic meter (Bq/m^3) for air samples; per liter ($Bq\ L^{-1}$) for water samples, and per kilogram ($Bq\ kg^{-1}$) for solid samples (soil, sediment, tissues, etc.).

The **radiation dose** received by an organism is related to the total radioactivity, but must also take into account the individual radionuclides involved, which emit different types and amounts of radiation, and also the mode of exposure – i.e., external sources (e.g., cosmic radiation, CT scan) vs. internal sources (inhalation or ingestion of radionuclides). Radiation dose can be measured as the energy released to biological tissue through any mode of exposure, or as the potential for biological damage from some amount of radiation. This latter approach is measured in units of **Sieverts (Sv)**, or more often for low doses, **milli-Sieverts (mSv,** one thousandth of a Sv) or **micro-Sieverts (µSv)**, one millionth of a Sv). To put this in perspective, one chest x-ray delivers a radiation dose of approximately 0.1 mSv; the average annual dose in the U.S., from all sources, is 6.2 mSv (*19*). **Figure 2** provides more examples of doses from various sources.

presenting a risk of future leakage (*12*). Direct discharges to the ocean have been dominated by ^{134}Cs and ^{137}Cs, with estimates of the total radioactive cesium input ranging from about 8 to 80 PBq (*6*).[2]

Table 1 provides a list of the primary radionuclides released as a result of the Fukushima disaster, along with information on their half-lives, estimated abundances, and modes of release. The range and quantities of radionuclides released were strongly influenced by the specifics of the disaster. The Fukushima nuclear accident was characterized by the overheating of reactor cores, leading to the venting of radioactive gas and to hydrogen explosions, and, separately, fires in the spent fuel repository of Unit 4. As a result, Fukushima releases were dominated by gases and volatile fission products (e.g., noble gases, iodine, cesium), with little of the refractory fission products (e.g., isotopes of neptunium, barium, cerium, ruthenium, etc.) and primary nuclear fuels (plutonium, uranium) that contributed to the radioactivity released by the Chernobyl disaster, which consisted of explosions that breached the reactor cores and extensive, long-lasting fires (*6, 14, 15*). In the aftermath of Fukushima, the radionuclides of greatest concern are those which were released in large quantities, are most bioavailable (i.e., easily taken up by organisms) and/or have long half-lives, allowing them to persist in the environment. Accordingly, studies of atmospheric deposition have focused on isotopes of iodine (^{131}I, ^{132}I, ^{133}I), tellurium (^{132}Te) and cesium (^{134}Cs, ^{137}Cs), which were most abundant in the initial fallout, and had the potential to affect human populations within days of the accident. The most abundant radionuclide released at Fukushima, ^{133}Xe, was monitored but presents less of an environmental and health concern because it is an inert gas that was not deposited into the environment. Studies of ocean radiation, taking into account the relatively long transport times associated with ocean currents, have focused on ^{134}Cs, ^{137}Cs, and ^{90}Sr, which will persist in the ocean for decades to come.

The radioactive isotopes listed in Table 1 are known products of nuclear fission, and are thus, by definition, anthropogenic. Prior to the accident, only longer-lived ^{137}Cs was present in the atmosphere and ocean in trace quantities, a relic of atmospheric H-bomb testing in the 1950s and 1960s, and to much lesser degrees, the 1986 Chernobyl disaster and intentional releases from several nuclear reprocessing plants. Detection of the shorter-lived isotopes (e.g., ^{131}I, ^{132}I, ^{132}Te, ^{134}Cs) in atmospheric fallout and ocean water, in addition to elevated activities of ^{137}Cs, provides incontrovertible evidence of a recent source at Fukushima.

Radioactive materials leaked from the Fukushima NPP have been transported in the environment along two main pathways: (1) rapidly, via atmospheric circulation; and (2) slowly, via ocean currents. A third "biological" pathway, encompassing both human activities and radionuclide transport in the tissues of migratory organisms such as birds or fish, is small relative to atmospheric and ocean transport, but is of concern to human and ecosystem health. The following discussion examines each of these pathways and summarizes the best available science on the distribution of radionuclides from Fukushima in the environment (with a particular focus on the California coast), and on the level of risk to humans and marine ecosystems.

[2] Buessler (2014) (ref. 6) reports a range of estimates of the total ^{137}Cs discharge to the ocean; here it is assumed that the ^{134}Cs discharge was roughly the same, based on the widely reported 1:1 activity ratio between these isotopes in Fukushima releases (e.g., *13*).

Atmospheric Transport & Deposition of Fukushima Radiation

Several massive pulses of radionuclides were released to the atmosphere from Fukushima between March 12 and 18, 2011, representing the majority of the radioactivity released by this pathway (*3, 16*). The radioactive plume was rapidly entrained by the strong westerly winds that dominate at this latitude during the winter, and within days was dispersed and transported eastward throughout the Northern Hemisphere. Fukushima-derived radionuclides were first detected in air samples in western North America on March 15, in Western Europe between March 19 – 23, and had circled the globe within 18 days of the accident (*7, 16-18*). The evolution of the radioactive plume over time was controlled in part by atmospheric circulation and in part by the chemical characteristics of the individual radionuclides. For example, the radioactive noble gas ^{133}Xe ($t_{1/2}$ = 5.25 d) is inert and does not deposit, and declined relatively quickly through radioactive decay. Other radionuclides which were abundant in the initial plume, including radioactive iodine ($^{131, 132, 133}$I), ^{132}Te ($t_{1/2}$ = 3.2 d), and three cesium isotopes ($^{134,136, 137}$Cs) can be dissolved in rainwater or deposited as aerosols, which hastens their removal and transfer from the atmospheric plume to terrestrial and marine environments. Based on air and precipitation monitoring at Japanese sites (e.g., *16*) in comparison to North American sites (e.g., *16, 17, 19-23*), and on atmospheric modeling (e.g., *3, 5, 9*), most of the Fukushima-derived radionuclides were removed through rainfall and dry deposition prior to reaching North America (**Figure 3**). One widely-cited study estimates that as of April, 2011, 18% of the total fallout of ^{137}Cs had been deposited in Japan and 80% in the North Pacific Ocean, with just 2% reaching other land areas (*3*).

Atmospheric Radioactivity in Western North America

Air & Particulates

Fukushima-derived radionuclides began to be detected at air monitoring stations along the west coast of North America between March 15 - 18, 2011, three to six days after the explosions at Fukushima Units 1 – 4 (*16, 17, 19, 20, 23-25*). Though many real-time monitoring stations (e.g., EPA's RadNet network, Health Canada's Fixed Point Network) were equipped to detect only gross levels of airborne radiation, other stations were equipped to test for specific radionuclides at very low concentrations[3], including ^{131}I, ^{132}I, ^{132}Te, ^{134}Cs, ^{137}Cs, and in a few locations, ^{133}Xe and other radioactive noble gases (*17, 20, 26*). Measured peak concentration of these radionuclides ranged widely, but in general were hundreds or thousands of times lower than those measured at Japanese stations near Fukushima.

The largest single component of the airborne radioactive plume to reach North America was ^{133}Xe, but as noted above, this noble gas is inert and poses little risk because it is not absorbed by the body or the environment (*8, 20*). Levels of ^{133}Xe in air samples from Canada and the United States declined steadily after a peak in late March, 2011, and had dropped below detection limits by the end of May (*17, 20, 26*). Peak airborne concentrations along the West Coast of the other, more hazardous radionuclides[4] in the weeks following the accident fell within

[3] Including a subset of the U.S. EPA's RadNet stations, Comprehensive Nuclear Test Ban Treaty monitoring stations in the United States, Canada, and Pacific Islands, Oregon Health Authority station in Portland, and a handful of stations operated by academic institutions.

[4] Most air monitoring stations with individual radionuclide capability reported elevated levels of ^{131}I, ^{132}I, ^{132}Te, ^{134}Cs, and ^{137}Cs in the first few weeks following the accident; other radionuclides reported less frequently, and at far lower levels, at the more sensitive stations included ^{136}Cs, ^{129}Te, ^{140}La, ^{99m}Tc, ^{140}Ba, and ^{133}I.

the range of 7 – 104 mBq/m^3 (0.016 – 0.104 Bq/m^3), with much (40-100%) of the total attributable to ^{131}I (*19*).

In California, peak values in air samples were detected on March 17-18 in San Francisco and Berkeley (31 - 35 mBq m^{-3}), March 21 in Anaheim (70.3 mBq m^{-3}) and March 22 in San Bernardino (40.7 mBq m^{-3}) (*19, 23*). Airborne concentrations of radionuclides dropped quickly after March 2011, and, with the exception of longer-lived ^{134}Cs and ^{137}Cs, were generally undetectable within six weeks of the accident (e.g., *17, 19, 24, 25*). ^{134}Cs and ^{137}Cs persisted at trace levels (~1000 times below peak values) in on-going air monitoring at Berkeley through the end of 2012 (*23*).

Precipitation

Wet deposition in precipitation is the primary means by which Fukushima-derived radionuclides have been removed from the atmosphere, as documented by detection of fission products in rainfall occurring in Japan, North America, and Eurasia in the weeks following the disaster (e.g., *17, 21, 27, 28*). ^{131}I, ^{134}Cs or ^{137}Cs from Fukushima were detected at ~20% of 167 sampled National Atmospheric Deposition Program (NADP) monitoring sites in the United States between March 12 – April 5, 2011, including at four of twelve sites in California (*21*). March 2011 was an unusually wet month in California (~200% of normal monthly precipitation in the Bay Area) due to several large storms which resulted in discrete wet deposition events on March 18-20 and 22-26. Radionuclide activities measured in precipitation from these storms at various California locations ranged from about 2 – 20 Bq/L for ^{131}I, the most abundant isotope detected, and 1-2 orders of magnitude lower (~0.03 – 1.4 Bq/L) for ^{132}I, ^{132}Te, ^{134}Cs, and ^{137}Cs (*19, 21-23*).[5] More extended sampling at Oroville and Richmond demonstrated that radionuclide concentrations in rainfall declined rapidly beginning in early April, and that only ^{134}Cs and ^{137}Cs were present, at low levels, after 70 days (*19, 23*). However, it is worth noting that low levels of radioactive cesium (<0.01 Bq/L) were still detectable in rainwater during subsequent wet seasons in 2012 and 2013 (*23*), reflecting the continued presence of Fukushima-derived cesium in the atmosphere.

Governmental Limits on Radionuclides in Food & Drinking Water

U.S. EPA Drinking Water Maximum Contaminant Levels

- **0.04 mSv/yr** *Gross beta & photon radiation* *
- **0.56 Bq/L** *Gross alpha radiation* #

*dose-based limit, equivalent to **~3 Bq/L** of ^{131}I, ^{134}Cs or ^{137}Cs

No alpha emitters were detected in the U.S. following the Fukushima disaster

U.S. FDA Derived Intervention Limits for Food

- **170 Bq/kg** Iodine-131 (*173.9 Bq/L, milk*)
- **1200 Bq/kg** Cesium-134 + 137 (*1221 Bq/L, milk*)
- **160 Bq/kg** Strontium-90 (*162.8 Bq/L, milk*)

Revised Japanese Limit on Radiocesium in Seafood

- **100 Bq/kg** Cesium-134 + 137

Sources: U.S. EPA (*64*); U.S. FDA (*38*); Japanese Ministry of Agriculture, Forestry and Fisheries (*56*)

Surface Waters, Soil & Food

Fukushima-derived radionuclides transferred from the atmosphere to the land through rainout or dry deposition have the potential to contaminate soil and water supplies, and to enter the food chain. Evidence of this is seen in reports from Japan documenting contaminated soils (*28, 29*), surface waters (*28, 30*) and food products (e.g., *31*) in the areas surrounding Fukushima. Other studies have explored impacts to wildlife and

[5] Radionuclides were detected in precipitation at: NADP monitoring stations located in Yosemite and Pinnacles National Parks, and San Bernardino and Los Angeles Counties; the EPA monitoring station in Richmond; and UC Berkeley/LBNL monitoring stations located in Berkeley, Oakland, Albany and Oroville.

ecosystems; findings include elevated levels of radioactive cesium in plant and animal tissues (*32-34*), reduced bird populations (*35*) and physiological and genetic damage in butterflies living near the nuclear plant (*36*). As discussed above, concentrations of radionuclides in air and water samples in California were orders of magnitude lower than in Japan, limiting, in theory, the potential for dangerous levels of contamination on the land surface. This prediction is largely borne out in the available data, though surprisingly little research effort has been devoted to this issue in California.

Researchers at UC Berkeley (BRAWM, RadWatch) have undertaken one of the few "vertically integrated" studies of Fukushima radionuclides in the environment, including measurements in air, rainfall, surface and drinking water, soil, plants, and food items in Northern California (*22, 23, 37*). This sampling effort detected minute quantities of ^{131}I and ^{137}Cs ($\leq$ 0.1 Bq/L) in Berkeley tap-water and runoff in a local creek between March 25 – 30, 2011, but nothing thereafter. Perhaps more importantly from a statewide perspective, no Fukushima radionuclides were detected in snowmelt runoff to Hetch Hetchy reservoir, in the central Sierra Nevada, in June 2011. Sampling of soil and sediments from several California locations[6] detected a clear pulse of ^{131}I, ^{134}Cs and ^{137}Cs between April – June 2011, with only ^{137}Cs remaining above the pre-accident background thereafter (through Nov 2012). Plant and food samples[7] collected in the Bay Area in April and May 2011 contained detectable concentrations of Fukushima-derived ^{131}I, ^{134}Cs, and ^{137}Cs, indicating that low-level contamination of the water and soil had worked its way into local ecosystems (*19, 23, 37*). However, in all cases, the radionuclides were detected at levels many times below those of naturally-occurring radioactive isotopes (e.g., ^{40}K, ^{210}Pb, ^{7}Be) and applicable health limits. For example, measured levels of Fukushima-derived radioactivity in Bay Area milk samples (1.4 – 2 Bq/L, mostly ^{131}I, ^{134}Cs, ^{137}Cs) was still 25 times lower than that attributable to naturally-occurring potassium-40, and hundreds of times lower than the U.S. FDA's "intervention levels" for iodine-131 (174 Bq/L) and radiocesium (1221 Bq/L, $^{134+137}$Cs) (*38*).[8] Moreover, the detectable contamination appears to have been short-lived: Fukushima-derived radionuclides were not found in Bay Area food products after May, 2011 (*19, 23, 37*).

Fukushima Radiation in the Ocean

Over the long term the radioactive signature of the Fukushima accident can be most clearly read in the waters of the North Pacific Ocean. A large fraction of the initial atmospheric release of radionuclides was transferred to the North Pacific through wet and dry deposition in the days following the accident (*3, 5*), so much so that airborne concentrations of radioactive cesium-134 and -137 in North America were orders of magnitude lower than those measured in Japan just a few days earlier (**Figure 3**). Radionuclides also reached the sea via the direct discharge of cooling water from the plant, along with surface run-off and groundwater seepage from contaminated areas of the power plant site. Direct discharges to the ocean began at the end of March 2011, peaked in early April, and continued in smaller amounts at least through the fall of 2012 (*4, 10, 11, 13*). In addition, river runoff and groundwater discharge from contaminated

[6] Topsoil from Oakland, Alameda, Sacramento, San Diego, and Sonoma County; sand from Palo Alto; roadway sediment from Berkeley.

[7] Products tested included milk, yogurt, strawberries, spinach, kale, wild mushrooms, cilantro, arugula, carrots, and tomatoes.

[8] FDA **derived intervention levels** reflect allowable concentrations in food products based on the radiation dose received from consuming the product over one year, and a tolerance threshold of two additional cases of cancer per 10,000 people.

areas, along with seafloor sediments off of Fukushima, are expected to supply relatively small but continuing doses of radioactivity to the North Pacific for years to come (*6, 39, 40*).

In comparison to atmospheric circulation, which within days dispersed radioactive materials over large areas of the globe, ocean currents move slowly; in the three years since the accident, Fukushima-derived radionuclides have spread throughout the North Pacific, but are just beginning to arrive along the North American coast (*41*). The great size and relatively slow circulation of the Pacific have at least two important implications for the spread of radioactivity in the wake of the disaster: First, radioactivity released from Fukushima to the ocean has been massively diluted. Second, in the years since the disaster, radionuclides with short half-lives (e.g., ^{131}I) have been removed through radioactive decay, leaving behind only a fraction of the total radioactivity initially deposited in the ocean in the form of longer-lived radionuclides, chiefly ^{134}Cs ($t_{1/2}$ = 2.1 yr) and ^{137}Cs ($t_{1/2}$ = 30.1 yr).[9] Radioactive cesium persists in the ocean for long enough to be transported significant distances by ocean currents. The total input of ^{137}Cs to the North Pacific from Fukushima are poorly constrained, with estimates ranging from 14 – 90 PBq; estimates of the direct ocean discharge range from 4 to 41 PBq, with most in the range of 10-15 PBq (*6*). For comparison, total ^{137}Cs releases from the Chernobyl disaster were on the order of 100 PBq (of which ~20% reached the ocean), while global fallout from nuclear weapons testing was approximately 950 PBq (with ~76 PBq still present in the North Pacific in 2011) (**Figure 1**) (*6*).

Based on this calculus, in the worst case the Fukushima disaster approximately doubled the amount of ^{137}Cs in the North Pacific, and given that ^{134}Cs and ^{137}Cs were released from Fukushima in an approximate 1:1 ratio (*13*), may initially have tripled the total amount of radioactive cesium in the North Pacific (^{134}Cs, with a two-year half-life, decays much more quickly than ^{137}Cs). However, in order to place the radiocesium release from Fukushima to the Pacific Ocean in the proper context, it is important to understand that the oceans are naturally radioactive, with an average background activity of ~14 Bq/L.[10] Approximately 93% of this background radioactivity is produced by naturally-occurring radionuclides (mostly potassium-40, ^{40}K) derived from the rock weathering and the erosion of continental crust. The remainder, about 7% (~1 Bq/L), is anthropogenic, deriving mostly from fallout from atmospheric nuclear weapons testing, but also from the Chernobyl accident and discharges from nuclear fuel reprocessing plants. The background activity of ^{137}Cs in the North Pacific prior to Fukushima was 0.001 – 0.002 Bq/L; after 10 years, when model simulations indicate the cesium will have spread more or less evenly throughout the entire ocean basin, basin-wide ^{137}Cs concentration may double (to 0.002 – 0.003 Bq/L) due to the accident (*45, 46*), but would still only amount to a tiny fraction of the total radioactivity of the ocean.

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[9] Other long-lived nuclear fission products of potential concern include isotopes of strontium (^{90}Sr, $t_{1/2}$=28.9 yr) and plutonium ($^{238, 239, 240, 241}$Pu). The Fukushima disaster resulted in the release of radioactive strontium, which was detected in the ocean but at levels <3% of the measured ^{137}Cs in the same samples (*42*). ^{90}Sr is much more difficult to measure than cesium, but because its chemical behavior is similar to that of calcium, it is highly biologically-available. Though a very small amount of plutonium may have been released to the atmosphere and deposited near the accident site (*43*), no Pu isotopes have been detected in seawater or sediments off of Japan (*44*).

[10] In the scientific literature, ocean concentrations of radioactive materials are typically reported in units of Bq/m^3, reflecting both the relatively low concentrations of radionuclides in the ocean and the large volume samples often needed to make the measurements. This report uses Bq/L because the liter is a familiar quantity for most readers, and to ease the comparison with levels of radioactivity in precipitation, drinking water, etc. Concentrations in Bq/L can be converted to Bq/m^3 by multiplying by 1000.

In summary, though the Fukushima disaster transferred a massive amount of radioactive material to the ocean, on par with the worst nuclear accidents in history, in aggregate the additional radioactivity added is small compared to both the natural inventory and the legacy of 20th century nuclear weapons testing.

Spread of Fukushima Radioactivity into the North Pacific

Approximately 99% of the direct discharge of radioactivity to the ocean from Fukushima took place in the initial aftermath of the accident, when cooling waters that were used to flood the damaged reactors were discharged to the artificial harbor area immediately seaward of the nuclear power plant (*11*). In early April, ^{137}Cs concentrations in the discharge channels of the plant peaked at more than 50 million times greater than the pre-existing ocean background (*13*). These high volume, high concentration discharges slowed greatly after April 6 when TEPCO succeeded in stopping leaks from the damaged reactor units, but low-level discharge of radioactive water, enough to maintain elevated (1 – 10 Bq/L) cesium concentrations off of the plant, continued at least through the fall of 2012 (*11, 47*). On-going seepage of contaminated groundwater to the ocean has also been detected (*12*). The open nature of the Fukushima coastline results in the rapid flushing of discharged water and radionuclides away from the coast (*15*).

Together with atmospheric fallout, most of which occurred over the ocean to the east of Japan (*3*), the directly-discharged radionuclides formed a plume of radioactive surface water that was advected into the open North Pacific by the strong, eastward flowing Kuroshio Extension current (**Figure 4**). In June 2011, four months after the accident, the plume had spread eastward up to 600 km throughout the "mixed layer" (upper ~150 m) of the ocean, but had not yet penetrated into deeper waters (*10*). ^{134}Cs concentrations between 30 and 600 km offshore ranged from 0.1 – 3.9 Bq/L, with the highest values measured in semi-permanent eddies of the Kuroshio Extension southeast of Fukushima. Interestingly, the Kuroshio Current system appears to have served both as a conduit for the eastward transport of the radioactive plume and as a barrier to southward transport – in the western North Pacific, the surface plume was essentially trapped within and north of the current (*10*, *48*), directing the spread of the plume toward North America rather than Asia or Oceania.

In the months and years following the disaster, the radioactive plume continued to spread eastward into the central North Pacific (e.g., *41, 47, 48, 49, 50*). Beyond coastal Japan, measurements are sparse, and generally not sufficient to delineate the boundaries of the plume in three dimensions, but its general eastward progress can be tracked, and the measured concentrations of ^{134}Cs and ^{137}Cs compared with the predictions of several model simulations of plume evolution (*46, 51, 52*) (*see* **Figure 4**). By the winter of 2012, the leading edge of the plume at ~40º N latitude had crossed the International Dateline (180º E longitude), with an estimated rate of spread of about 8 cm/s (~4 mi/d) and a peak combined $^{134+137}$Cs concentration of 0.02 Bq/L. (*47, 49*). Though still elevated above the pre-accident background, this value is more than 3 million times lower than peak concentrations measured immediately offshore of Fukushima in April, 2011 (*13*), providing some idea of the degree of dilution, radioactive decay, and cesium removal (e.g., through adsorption to sinking particles) that had occurred to that point.

Arrival on the West Coast

The most recently reported measurements of radioactive cesium in North Pacific seawater indicate that the Fukushima plume is beginning its arrival off the west coast of North America. Measurements by the Canadian Ocean Monitoring Program first detected very low concentrations (<0.0005 Bq/L) of Fukushima-derived ^{134}Cs at a station in the Gulf of Alaska (~145º W) in June of 2012, and off of Vancouver Island, British Columbia, in June 2013 (*41*). This early arrival, scarcely three years after the accident, matches well with the predictions of one ocean circulation model (*52*), but the low concentrations detected are more in line with another simulation that predicted a slower transit of the North Pacific (*46*). Further to the south, along a transect approximating 30º N latitude, shipboard sampling found that in late 2013 the leading edge of the cesium plume was north of Hawai'i, between 160 – 150 ºW, but that concentrations were relatively low (≤ 0.008 Bq/L), well below those predicted for this area (>0.05 Bq/L) by the more spatially-accurate model (*50, 52*). The lower-than-expected concentrations observed *in situ* may reflect the fact that a large fraction of the radioactive plume that occupied the central North Pacific in 2012 was mixed into the deep ocean and effectively removed from the eastward-trending surface plume (*48*).

To date, no Fukushima-derived cesium has been detected in seawater along the coast of California, Oregon or Washington (*24*, *37*, *50*).[11] It remains uncertain exactly when, and at what concentration, the radioactive plume will reach the California coast, though the recent detection of cesium off of British Columbia provides some indication that this could occur within the next year. However, the model simulation of Rossi et al. (2013) (*52*), which came the closest to correctly predicting the timing of the plume arrival in the Pacific Northwest, also predicts that offshore currents associated with coastal upwelling in the California Current system could delay the arrival of the plume on the California shoreline for several years. Under this scenario, the radioactive plume would be "held at bay" by the net offshore transport of surface water, only reaching the coastline proper once the cesium has penetrated to the depths of the waters that are upwelled along the coast. Once the radioactive plume does reach California, concentrations of radiocesium are predicted to increase to peak values between 2016 and 2019, declining gradually thereafter over the next several decades (*46, 52*). The actual concentrations remain unknown but, based on recent measurements elsewhere in the North Pacific, are likely to be on the lower end of the 0.003 – 0.02 Bq/L range bracketed by the predictions of Behrens et al. 2012 (*46*) and Rossi et al. 2013 (*52*), respectively (*41, 50*). It is important to note that even the higher estimated levels of radioactivity are dwarfed by naturally-occurring radioactivity (>400 times greater) and the ^{137}Cs "legacy" of atmospheric nuclear weapons testing (>30 times greater), and represent only a tiny increase in total radioactivity above the pre-accident background.

Fukushima Radioactivity in Seafood & the Marine Ecosystem

Generally speaking, levels of radioactivity in marine organisms will be proportional to the radioactivity of the water in which they live, with higher levels expected in organisms dwelling closer to the source of contamination. However, certain radionuclides which are chemically similar to nutrient elements can be preferentially absorbed by marine organisms and become concentrated in the marine food web. Strontium-90 (^{90}Sr), for example, mimics the

[11] Cesium-137 derived from atmospheric fallout of nuclear weapons tests in the 1940s-1960s is still present, at very low concentrations, in the world ocean. Recent measurements off the California place the "background" level of ^{137}Cs at 1.3 – 1.9 Bq/m^3 (*50*).

chemical behavior of calcium, and if taken-up by organisms is concentrated in calcium-rich structures such as shell and bone, where it delivers a sustained dose of radiation over time. Cesium is also highly bioavailable, but is distributed more evenly throughout the body and is removed more quickly ("biological half-life" of ~ 70 days in humans) (*53*).

Impacts to marine life from the Fukushima disaster are most evident in the coastal ocean nearby the nuclear power plant. Fish caught in the Fukushima area, in particular bottom-dwellers which may be exposed to high radionuclide concentrations in seafloor sediment, have had levels of radioactivity well above the Japanese regulatory limit of 100 Bq/kg (in an extreme case, >100,000 Bq/kg) (*54, 55, 56*). In 2011 alone, the closure of local fisheries is estimated to have resulted in $1 – 2 billion in economic losses (*54*). Other species, with different life histories and occupying different ecological niches, were less consistently contaminated (or at lower levels), and a few appear to have escaped contamination entirely (e.g., squid, octopus) (*54*, *56*). Sampling in June 2011 at locations 30-600 km offshore of Fukushima prefecture found total radioactive cesium ($^{134+137}$Cs) levels of 0.3 – 102 Bq/kg in zooplankton and fish (below the 100 Bq/kg limit in all but one case) (*10*).

Along the West Coast, Fukushima-derived radionuclides were fleetingly detected in giant kelp off of California (^{131}I) (*57*) and in Alaskan salmon (trace amounts of ^{134}Cs and ^{137}Cs) (*58*), reflecting the "pulse" of atmospheric fallout immediately after the accident. Subsequent sampling of kelp and fish local to the eastern North Pacific has not detected further contamination (*37, 58, 59*). However, a study by Madigan et al. (2012) demonstrated the potential for highly-migratory species, in this case Pacific Bluefin tuna, a species that spawns and rears in the western Pacific, to transport radionuclides over long distances. Pacific Bluefin tuna caught off of California in August 2011 contained an average of 10 Bq/kg of radioactive cesium ($^{134+137}$Cs) from Fukushima, which the fish accumulated in contaminated western Pacific waters prior to migration (*59*).[12] A 2012 follow-up study found that radiocesium levels in Pacific Bluefin had decreased by more than 50% (*60*).

When the plume of radioactivity currently spreading across the North Pacific reaches the California coast, local marine life will accumulate Fukushima-derived radioactive cesium (and other radionuclides present at much lower levels, such as ^{90}Sr). The low radiocesium concentrations currently observed in seawater off of British Columbia (*41*) and in the central Pacific north of Hawaii (*50*) suggest that the level of exposure will be quite low, and that marine organisms are unlikely to accumulate dangerous quantities of radioactivity. However, on-going monitoring of the situation is clearly warranted.

Risks & Health Implications of Fukushima Radiation

It is clear from the available data that people living on the West Coast were exposed to Fukushima-derived radiation in the days and weeks following the disaster, with lower levels of exposure (from radioactive cesium) continuing to the present. Environmental and public health agencies at the state and federal levels have issued repeated assurances that the levels of exposure are "safe", "not harmful" or present "no risk" to the public (e.g., EPA RadNet, Oregon Health Authority, etc.), often citing regulatory standards or exposure limits that are higher than

[12] For comparison, post-accident concentrations of $^{134+137}$Cs in Pacific Bluefin caught off Japan were in the range of 61-168 Bq/kg, 6-17 times higher than those caught off California (*56, 59*).

the measured levels of Fukushima-derived radiation. Though the basic message is likely to be accurate, such assertions are probably best read as "shorthand" for a more nuanced reality: The levels of Fukushima-derived radiation detected in North America are unlikely to cause significant harm to the public at large, and the risks posed by Fukushima radiation are small in comparison to other things that threaten public health (e.g., air pollution, smoking, obesity, etc.) (*53*). This more circumspect assertion of safety does not rule out adverse impacts to individuals, and more accurately reflects the current level of scientific uncertainty about the health risks of low levels of radiation. Individual risk is influenced by multiple factors, including the strength and length of exposure, the particular radionuclides involved, and the age, health and susceptibility of the individual, to name a few. Moreover, the health effects of long-term exposure to low-level radiation are a matter of on-going scientific debate. The canonical, precautionary view, which extrapolates from studies of the health impacts of high doses of radiation, is that any increment of increased radiation exposure, no matter how small, increases an individual's chance of developing cancer or other health problems, and that even unavoidable natural background radiation can contribute to health problems (*53*). However, the relationship between radiation dose and health consequences has not been established for doses below 100 mSv, and studies on animals indicate that much of the DNA damage done by low-level radiation can be undone by natural DNA-repair mechanisms in the body (*61*).

WHO Study

The World Health Organization (WHO) has attempted to estimate radiation doses from Fukushima to people living in Japan and other parts of the world, using both observations and modeling approaches (*8*). The resulting study considers the full range of exposure pathways, including external doses from radioactive contaminants in the atmosphere ("cloudshine") and deposited on the ground ("groundshine"), as well as internal dose from the inhalation and ingestion of contaminated air, food, and water. Within Fukushima prefecture, radiation doses from the accident were estimated to range from 1 – 200 mSv, depending on an individual's age, body-size and geographic location. Elsewhere in Japan estimated doses ranged from 0.1 – 1 mSv. Outside of Japan, the total radiation dose attributable to the Fukushima disaster was estimated to be less than 0.01 mSv (*8*). To put these numbers in perspective, the average annual dose in the United States prior to the accident, from all sources (e.g., natural background, bomb testing legacy, medical procedures), was 6.2 mSv (*19*). Doses from a number of sources of radiation are shown in **Figure 2**. The WHO analysis indicates that, outside of areas in close proximity to the nuclear power plant, the increase in radiation dose as a result of the accident was very small.

Radiation Exposure in California

Local-scale analysis of radiation exposure in California seems to bear out this finding. For example, if a person were to breathe the most radionuclide-contaminated air detected in California (single-day peak of 70.3 mBq/m^3 in Anaheim, 3/21/11) and the tap-water with the highest sampled level of radioactivity (0.09 Bq/L, Berkeley, 3/30/11) for an entire year, he would receive an additional dose of about 5 μSv (0.05 mSv), or less than 0.1% of the average annual radiation dose prior to the accident.[13] Given that these were peak values, not representative of

[13] Dose calculations follow the methodology of BRAWN (2011) (*37*).

air and drinking water over the full year, the actual dose received by Californians from breathing and drinking in the aftermath of the Fukushima disaster was almost certainly much lower.

Radiation doses in food are more difficult to estimate due to the wide variety of plant and animal products, sourced from various parts of the world, that are included in the typical American diet. A person consuming certain groundfish species or other embargoed food products from the area around Fukushima risks exposure to potentially dangerous levels of radiation, but these foods are difficult to acquire for the average Californian.[14] Fukushima-derived radionuclides were detected at low, but variable levels in locally-produced foods in California in the weeks after the accident (*23, 37*), but as with the cases of air and drinking water, it would take consuming the most contaminated of these foods, at their peak levels of radioactivity, for long periods of time to accumulate even a modest dose of Fukushima-derived radiation. For example, a recent study examined the radiation exposure of a hypothetical subsistence fisherman consuming only Pacific Bluefin tuna in amounts five times greater than the average total seafood consumption in the U.S. Based on observed levels of Fukushima-derived cesium in Pacific Bluefin tuna (~10 Bq/kg of $^{134+137}$Cs), such a fisherman would receive a 4.7 μSv (0.0047 mSv) radiation dose in a year, or 0.1% of the average pre-accident annual dose (*55*).

External doses of radiation from the environment (cloudshine and groundshine) in places outside of Japan were very small in relation to internal doses (*8*), and thus are not expected to add much to an individual's total radiation dose. Likewise, radiation doses from contact with seawater will also be extremely low due to low radionuclide concentrations expected off the California coast (<0.02 Bq/L) (*46, 52*) and the fact that even the most vulnerable populations (e.g., surfers, fishermen, etc.) spend only a minor fraction of their time in the ocean. In summary, the radiation dose to Californians from the Fukushima disaster is very unlikely to amount to more than a few percent of the average annual dose from the natural background and anthropogenic sources, and overall the Fukushima disaster presented (and continues to present) a low risk to public health relative to other concerns. However, it is worth reiterating that the health implications of exposure to low levels of radiation remain incompletely understood, and that the incremental impacts of the radiation released at Fukushima may be very difficult to separate from those of other radiation sources (e.g., bomb-testing legacy) and the many other causes of disease (*61*).

On-Going Monitoring Efforts

Existing, government-supported environmental monitoring networks appear to have performed reasonably well in the immediate aftermath of the Fukushima Dai-ichi nuclear accident. Air and precipitation monitoring networks managed by the U.S. Environmental Protection Agency (EPA RadNet)[15] and Health Canada detected arrival of the atmospheric plume, and increased their regular sampling frequency for several weeks to months in order to document the declining levels of atmospheric radioactivity as the plume was dispersed and

[14] U.S. FDA has banned certain food products from being legally imported into the United States from Japan (*62*). The WHO has tested thousands of Japanese food products that continued to be exported after Fukushima, and found detectable levels of radionuclides in only a small handful of samples (*8*).

[15] EPA's RadNet network includes 100 stations nationwide, including 11 in California, for the monitoring of radiation in air, precipitation, milk and drinking water.

individual radionuclides were removed through fallout and radioactive decay. These federal agency efforts were supplemented by monitoring undertaken by national laboratories (e.g., *23*, *26, 37*), state governments (e.g., *24*), academic institutions (e.g., *22, 23, 37, 58*), and government-university partnerships (e.g., *21*) at other locations, cumulatively providing a fairly detailed view of atmospheric fallout following the accidents. Many of these monitoring programs are on-going, and can be expected to detect and quantify and future large-scale releases of radiation to the atmosphere.

Radioactivity in drinking water and food products is also routinely monitored, with limited frequency, as part of the EPA RadNet program. In California, the EPA tests for radioactivity in drinking water and milk at least several times a year in Los Angeles and the Bay Area. EPA's sampling frequency temporarily increased in the months following the Fukushima disaster. While it does not itself measure radioactivity in imported foods, the Food & Drug Administration (FDA) maintains a list of Japanese food products subject to detention (Import Alert 99-33), which is informed by radiation testing conducted by the Japanese government (*62*). A limited amount of testing of food and drinking water was also performed by academic researchers in the first two years following the accident, but many of these efforts have ended or were never intended as comprehensive monitoring programs (e.g., *23, 58, 59*).

Outside of Japan, ocean monitoring of Fukushima radiation has received much less attention and support from government agencies. Though the Canadian government is actively monitoring for the arrival of the radioactive cesium plume off the coast of British Columbia, and the state of Oregon is collecting seawater samples at several coastal locations, neither the U.S. federal government nor the state of California is currently testing for Fukushima-derived radiation off the California coast. Instead, most of what we know about the spread of the radioactive plume in the North Pacific is due to the efforts of a handful of academic researchers, a sub-set of whose work is cited in this report. At present, the only network for monitoring ocean water along the California coast is a citizen-science effort spearheaded by Dr. Ken Buessler of the Woods Hole Oceanographic Institution, to date consisting of 11 sampling stations spread between San Diego and Trinidad, with samples collected by volunteers (the network also includes sites off Oregon, Washington, British Columbia and Alaska) (*50*). A similar effort to monitor radionuclide levels in kelp along the Pacific coast (including 32 sites in California) is being led by Steven Manley (CSU-Long Beach) and Kai Vetter (UC Berkeley) (*63*). These efforts are critical for monitoring the spread of Fukushima radioactivity along the coast, for understanding the degree to which radionuclides enter and affect marine ecosystems, and for confirming the expectation that radionuclide concentrations will remain below levels of health concern. In light of the high level of public concern surrounding the effects of the Fukushima disaster on marine ecosystems and on-going confusion about the risks posed to human health, a greater level of involvement in coastal ocean monitoring by government resource management agencies would be desirable, particularly in light of the somewhat precarious dependence of the existing academic and citizen-science monitoring programs on volunteers and occasional funding sources (e.g., sponsors, grants) (*50, 63*).

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Table 1: Selected radionuclides released during the Fukushima Dai-ichi nuclear accident. Radionuclides discussed in this report are highlighted in **bold**. Blank cells indicate a lack of data rather than no release.

Radionuclide		**Half-life** ($t_{1/2}$)	**Environmental Characteristics** (phases, behavior, mode of release)	**Estimated Release** (atmosphere) PBq	**Estimated Release** (ocean – direct discharge) PBq	**References**
Xenon-133	**^{133}Xe**	5.25 d	inert gas atmospheric release	5,950 – 20,000	n/a	*3, 7, 8, 9* (& refs. therein)
Iodine-131	**^{131}I**	8.0 d	particulate, gas phases volatile atmospheric release	106 – 380		*7, 8, 9* (& refs. therein)
Iodine-132	**^{132}I**	2.3 hr		0.013 – 56.4		*8, 9* (& refs. therein)
Iodine-133	^{133}I	20.8 hr		42.1		
Iodine-135	^{135}I	6.6 hr		2.27		
Tellurium-132	**^{132}Te**	3.26 d	particulate somewhat volatile atmospheric release	88.0		*8*
Other tellurium	^{127m}Te ^{129m}Te ^{131m}Te	1 – 109 d		9.4 x 10^{-14}		
Cesium-134	**^{134}Cs**	2.1 yr	particulate somewhat volatile water soluble bioavailable atmospheric release & direct discharge	16.5 – 50[#]	4 – 40[#]	*6, 8, 9* (& refs. therein)
Cesium-136	^{136}Cs	13.2 d		3.8 – 9.8		*9* (& refs. therein)
Cesium-137	**^{137}Cs**	30.1 yr		6 – 50	3.6 – 41	*3, 5, 6, 7, 8, 9* (& refs. therein)
Strontium-89	^{89}Sr	5.5 d	particulate, refractory bioavailable direct discharge			*42*
Strontium-90	**^{90}Sr**	28.9 yr			0.09 – 0.9	
Barium-137 (metastable)	^{137m}Ba	2.6 min	particulate, refractory	4.1 x 10^{-4}		*9*
Barium-140	^{140}Ba	12.8 d		3.13		*8*
Cerium-141	^{141}Ce	32.5 d	particulate, refractory	0.018		*8*
Cerium-144	^{144}Ce	285 d		0.013		
Ruthenium-103	^{103}Ru	39.3 d	particulate, refractory	7.5 x 10^{-6}		*8*
Ruthenium-106	^{106}Ru	1.02 yr		2.1 x 10^{-6}		
Plutonium-239	^{239}Pu	24,110 yr	particulate, refractory	trace quantities		*43, 44*
Plutonium-240	^{240}Pu	6,561 yr				

[#]The range of release estimates for ^{134}Cs includes both direct estimates and inferred amounts assuming a 1:1 ratio with ^{137}Cs (e.g., *10*).

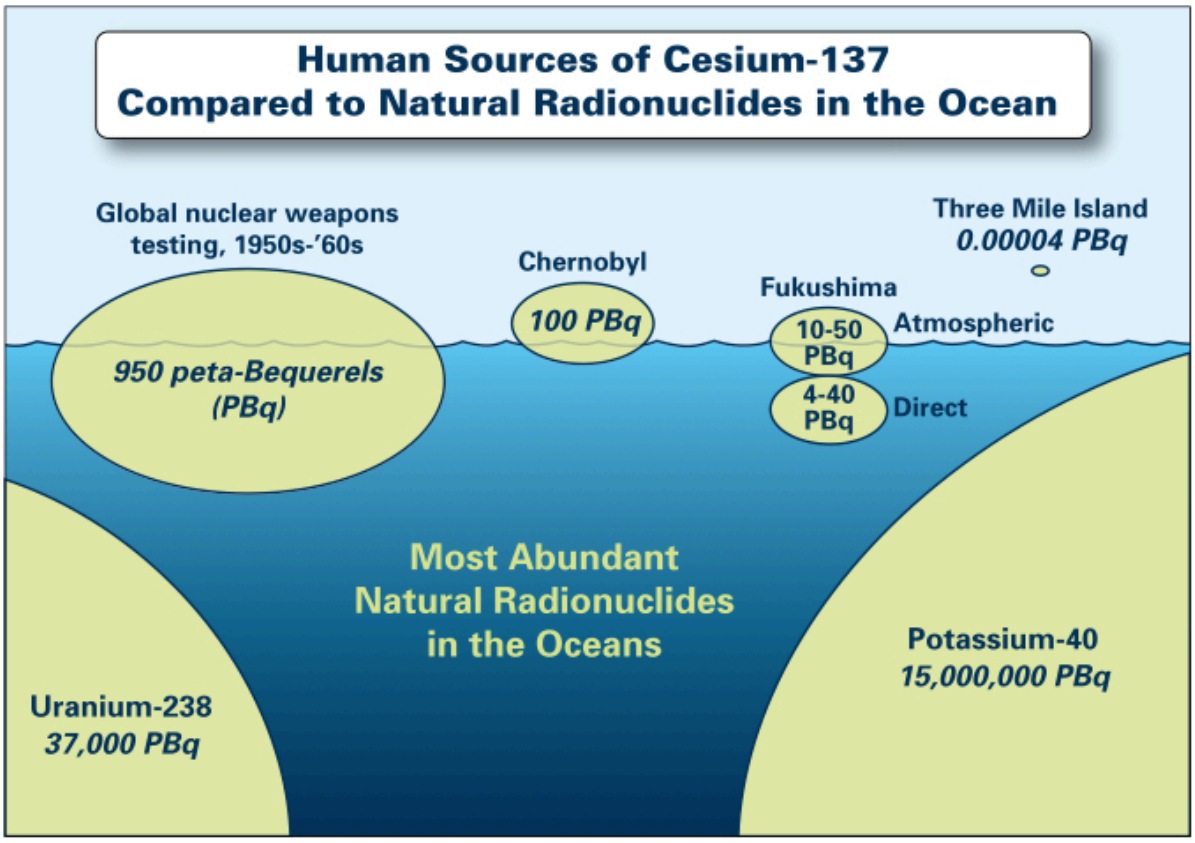
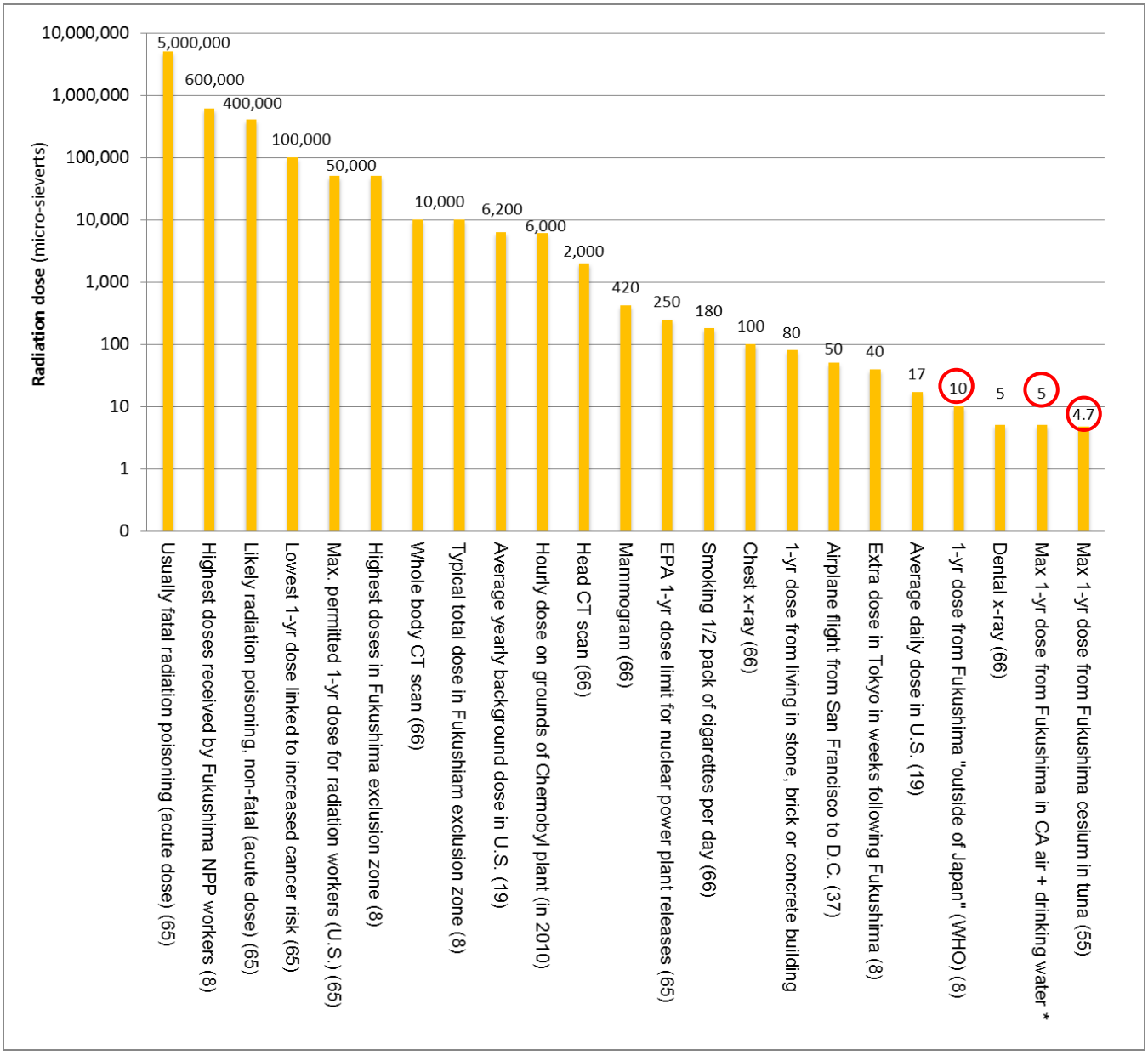


Figure 1: Comparison of the inventories of two common natural radionuclides in the ocean, potassium-40 and uranium-238, with anthropogenic cesium-137 from several different sources. Inventories are calculated for the entire ocean for the natural radionuclides, and at time of delivery for cesium-137. One PBq = 10^{15} Becquerels. Reproduced from Buessler (2014) (*6*).

Figure 2: Estimated radiation doses (in micro-Sieverts) from a variety of radiation sources and scenarios. Doses relevant to exposure from Fukushima-derived radionuclides in California are circled. Sources are indicated in parenthesis.



* Dose calculated in this study based on the methodology of BRAWN (*37*).

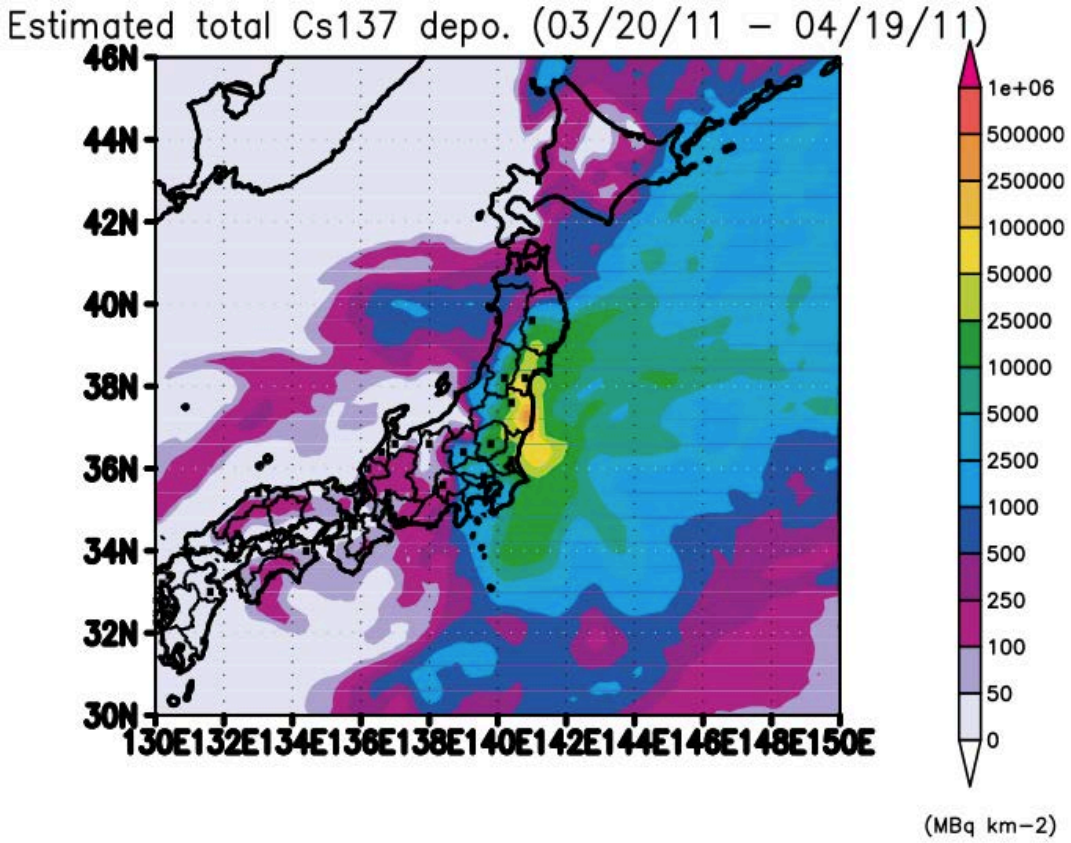


Figure 3: Estimated total deposition of cesium-137 (MBq/km^2) onto Japan and the western North Pacific Ocean in the month following the Fukushima disaster. Based on observations and modeling. Reproduced from Yasunari et al. (2011) (*29*).

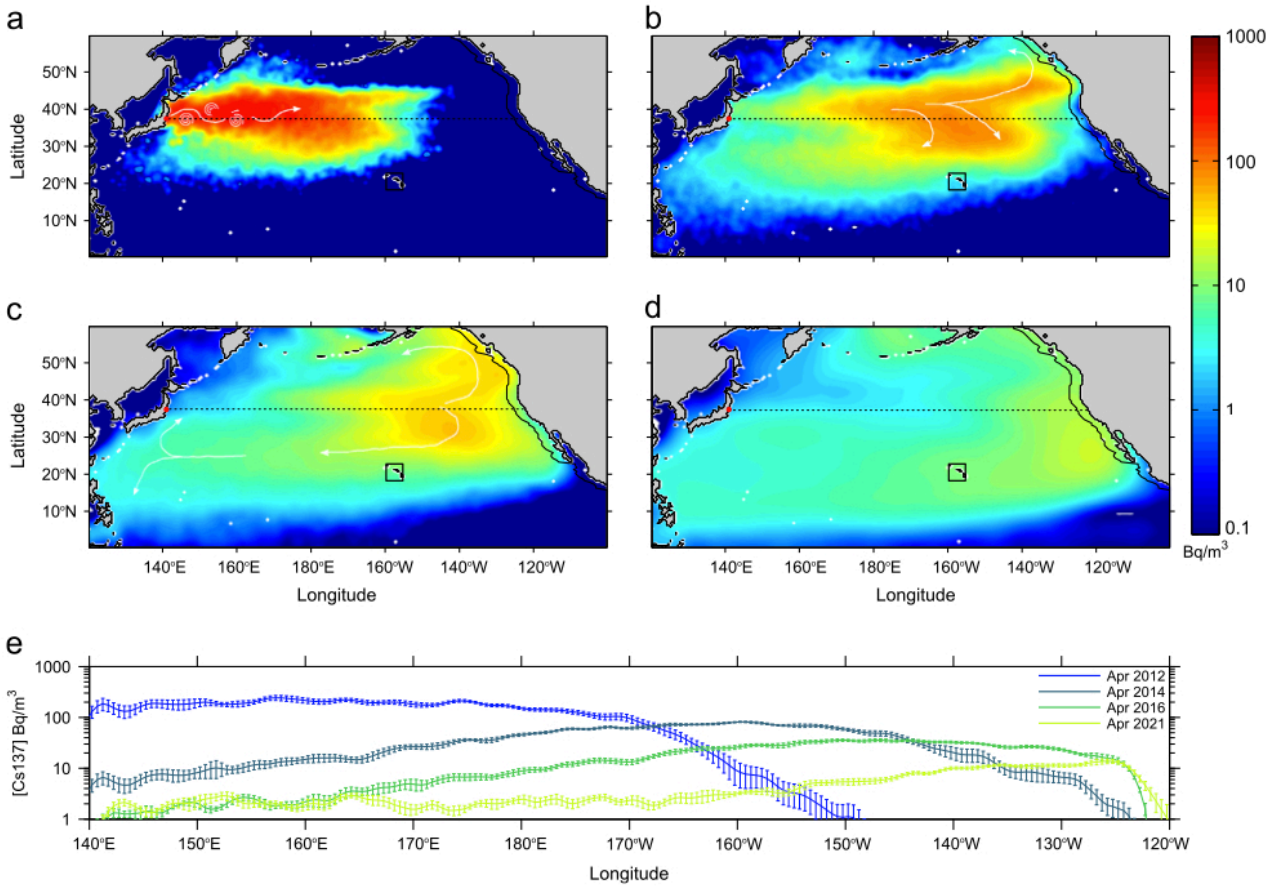


Figure 4a (above): Model simulation of the evolution of the Fukushima-derived radioactive surface water plume (shown as activity concentrations of cesium-137) in the North Pacific in (a) April 2012, (b) April 2014, (c) April 2016, (d) April 2021, and (e) along 37.5º N latitude. White flow vectors (arrows) illustrate the large-scale surface circulation at various locations. Reproduced from Rossi et al. (2013) (*52*). Ocean monitoring results indicate that the simulated concentrations of radioactive cesium shown in the figure are overestimates, and that actual concentrations off the California coast and elsewhere are likely to be substantially lower.

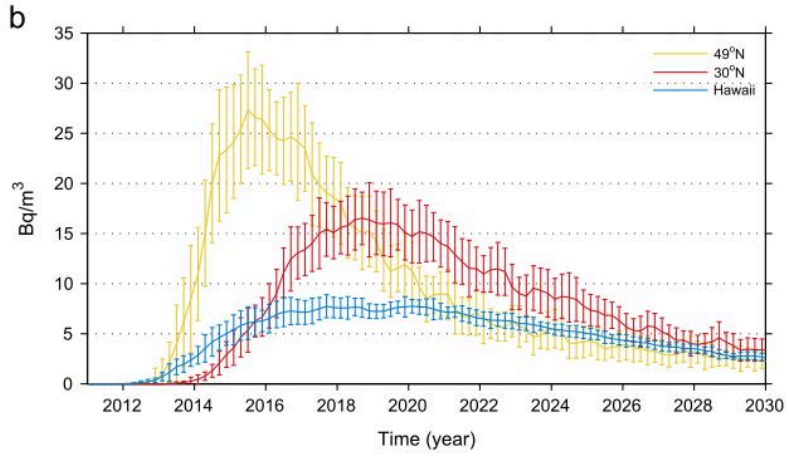


Figure 4b (left): Simulated time evolution of cesium-137 activity concentrations on the Pacific Coast of North America at 49º N and 30º N, and near the Hawaiian Islands. Reproduced from Rossi et al. (2013) (*52*). Concentrations are likely overestimates.