An international research team is reporting the results of a research cruise they organized to study the amount, spread, and impacts of radiation released into the ocean from the tsunami-crippled reactors in Fukushima, Japan. The group of 17 researchers and technicians from eight institutions spent 15 days at sea in June 2011 studying ocean currents, and sampling water and marine organisms up to the edge of the exclusion zone around the reactors.

一個國際研究小組正在報告他們組織的一次研究巡航的結果，以研究日本福島海嘯受損反應堆釋放到海洋中的輻射量、擴散和影響。 2011 年 6 月，來自 8 個機構的 17 名研究人員和技術人員在海上度過了 15 天，研究洋流，並對反應堆周圍禁區邊緣的水和海洋生物進行採樣。

Led by Ken Buesseler, a senior scientist and marine chemist at the Woods Hole Oceanographic Institution (WHOI), the team found that the concentration of several key radioactive substances, or radionuclides, were elevated but varied widely across the study area, reflecting the complex nature of the marine environment. In addition, although levels of radioactivity in marine life sampled during the cruise were well below levels of concern for humans and the organisms themselves, the researchers leave open the question of whether radioactive materials are accumulating on the seafloor sediments and, if so, whether these might pose a long-term threat to the marine ecosystem. The results appear in the April 2 online edition of the journal *Proceedings of the National Academy of Sciences* (*PNAS*).

在伍茲霍爾海洋研究所 (WHOI) 的高級科學家和海洋化學家 Ken Buesseler 的帶領下，該團隊發現幾種關鍵放射性物質或放射性核素的濃度有所升高，但在整個研究區域內變化很大，反映了複雜的性質的海洋環境。此外，儘管在航行期間採樣的海洋生物中的放射性水平遠低於人類和生物本身所關注的水平，但研究人員仍然沒有解決放射性物質是否在海底沉積物上積累的問題，如果是，這些可能對海洋生態系統構成長期威脅。結果發表在 4 月 2 日的美國國家科學院院刊 (PNAS) 在線版中。

“Our goal was to provide an independent assessment of what the Japanese were reporting and also to get further off shore to sample in places where we thought the currents would be carrying most of the radionuclides,” said Buesseler. “We also wanted to provide as wide ranging a look as possible at potential impacts on the marine system to give a better idea of what was going on in the region, but also to provide a stronger baseline from which to measure future changes.”

“我們的目標是對日本報告的內容進行獨立評估，並在離岸更遠的地方在我們認為洋流攜帶大部分放射性核素的地方進行採樣，”布塞勒說。 “我們還希望盡可能廣泛地了解對海洋系統的潛在影響，以便更好地了解該地區正在發生的事情，同時也提供更強大的基線來衡量未來的變化。”

On March 11, 2011, a magnitude 9.0 earthquake caused a tsunami that devastated the northeast coast of Japan and severely damaged the Fukushima Dai-ichi Nuclear Power Plant. In the weeks following, emergency crews poured tons of water directly onto the reactors to keep them cool and prevent them from going critical. Much of the contaminated water washed directly into the Northwest Pacific or collected in the basement of the reactor buildings and seeped slowly out, carrying with it a number of different radionuclides. In addition, several explosions in the reactor buildings sent additional radioactive materials into the atmosphere, much of which eventually landed in the ocean.

2011 年 3 月 11 日，一場 9.0 級地震引發的海嘯摧毀了日本東北海岸，並嚴重損壞了福島第一核電站。在接下來的幾週內，緊急救援人員將大量的水直接倒在反應堆上，以保持它們涼爽並防止它們變得臨界。大部分受污染的水直接衝入西北太平洋或收集在反應堆建築物的地下室中，然後緩慢滲出，並攜帶許多不同的放射性核素。此外，反應堆建築物中的幾次爆炸將額外的放射性物質釋放到大氣中，其中大部分最終降落在海洋中。

Among the materials released were cesium-134 and -137, two radioactive isotopes that do not occur naturally in the ocean. Cesium-134 has a half-life (the time it takes for one half of a given amount of radionuclide to decay) of a little over two years, and so could come only from the reactors at Fukushima. Cesium-137 has a half-life of roughly 30 years and is known to have entered the Pacific as a result of aboveground nuclear weapons tests in the 1950s and 60s, providing a benchmark against which to measure any additional releases from the reactors.

在釋放的材料中，銫 134 和 -137 是兩種在海洋中不自然存在的放射性同位素。銫 134 的半衰期（給定數量的放射性核素的一半衰變所需的時間）略高於兩年，因此只能來自福島的反應堆。銫 137 的半衰期大約為 30 年，眾所周知，由於 1950 年代和 60 年代的地上核武器試驗，銫 137 已進入太平洋，為衡量反應堆的任何額外釋放提供了基準。

Buesseler, who began his scientific career studying the transport and mixing of artificial radionuclides in the ocean from sources such as weapons testing and the 1986 explosion at Chernobyl, recognized the importance of organizing an oceanographic research mission soon after events at Fukushima began to unfold. With primary support from the Gordon and Betty Moore Foundation and additional support from the National Science Foundation, he brought together an international group that included physical oceanographers Steven Jayne and Irina Rypina, also from WHOI, and marine biologist Nicholas Fisher from the State University of New York (SUNY) Stony Brook.

Buesseler 开始了他的科學生涯，研究來自武器試驗和 1986 年切爾諾貝利爆炸等來源的人工放射性核素在海洋中的傳輸和混合，他認識到在福島事件開始後不久組織海洋研究任務的重要性。在戈登和貝蒂摩爾基金會的主要支持和國家科學基金會的額外支持下，他召集了一個國際小組，其中包括同樣來自 WHOI 的物理海洋學家 Steven Jayne 和 Irina Rypina，以及來自紐州立大學的海洋生物學家 Nicholas Fisher 約克（紐約州立大學）石溪分校。

The group departed Yokohama, Japan, on June 6 aboard the University of Hawaii research vessel *Ka'imikai-o-Kanaloa* and sailed a saw-tooth pattern that began 600 kilometers (350 miles) offshore and came as close as 30 kilometers (18 miles) from the damaged power plant. Along the way, the group conducted extensive water sampling from the surface to as deep as 1,000 meters (3,200 feet) and made more than 100 net tows to collect samples of phytoplankton, zooplankton, and small fish. They also released two dozen drifters, instruments that move with ocean currents and report their position via satellite back to shore.

該小組於 6 月 6 日乘坐夏威夷大學研究船 Ka'imikai-o-Kanaloa 離開日本橫濱，並以鋸齒狀航行，從離岸 600 公里（350 英里）開始，接近 30 公里（18 英里）) 來自受損發電廠。一路上，該小組對從地表到深達 1,000 米（3,200 英尺）的水進行了廣泛的採樣，並製作了 100 多條網拖來收集浮游植物、浮游動物和小魚的樣本。他們還發布了兩打漂流器，這些儀器可以隨洋流移動並通過衛星將其位置報告回岸邊。

In addition to their own samples, the group also collected water that they later shipped to labs at seven other institutions. Together, the ongoing effort is examining 15 different radionuclides likely to have been released from Fukushima. Their initial results, detailed in the *PNAS* paper indicate that the combined amount of radioactive material from the damaged power plant constitutes the largest accidental release of radiation to the ocean in history.

除了他們自己的樣本外，該小組還收集了水，然後將其運往其他七個機構的實驗室。正在進行的工作正在共同研究可能從福島釋放的 15 種不同的放射性核素。他們在 PNAS 論文中詳述的初步結果表明，來自受損發電廠的放射性物質的總量構成了歷史上最大的向海洋意外釋放的輻射。

Despite this, analysis of samples from the study site show that the amount of radiation in the ocean fell well below EPA standards that would deem it unsafe to use as drinking water. “We knew that the radionuclides had to be moving off shore very rapidly once they entered the water,” said Buesseler. “Once they did, they quickly dispersed across a wide area and began mixing into the deeper layers of the ocean.”

儘管如此，對來自研究地點的樣本的分析表明，海洋中的輻射量遠低於 EPA 標準，認為將其用作飲用水是不安全的。 “我們知道放射性核素一旦進入水中就必須非常迅速地離開海岸，”布塞勒說。 “一旦他們這樣做了，他們就會迅速分散到一個廣闊的區域，並開始融入海洋的更深層。”

In addition, they found that concentrations of cesium isotopes varied widely from station to station. Data from the drifters helped shed more light on this. First, the region is dominated by the Kuroshio, a large, fast current much like the Gulf Stream that flows north near the coast of Japan before turning east along the shore of the Chiba Peninsula. At the same time, a smaller, nutrient-rich current known as the Oyashio flows south along the northeast coast and mixes with the Kuroshio offshore from Fukushima.

此外，他們發現銫同位素的濃度因站點而異。來自漂流者的數據幫助闡明了這一點。首先，該地區以黑潮為主，這是一種大而快速的洋流，很像墨西哥灣流，它在日本海岸附近向北流動，然後沿著千葉半島海岸向東轉。與此同時，名為親潮的更小、營養豐富的洋流沿著東北海岸向南流動，並與福島離岸的黑潮混合。

“Having two strong currents in the region make this a very complex part of the ocean to study,” said Jayne, who had studied the region in the past. “It also makes this a very productive part of the ocean and a very active fishery. With all that water moving around in complex ways, areas that are low one day could be high the next.

過去曾研究過該地區的傑恩說：“該地區有兩條強大的洋流，這使得它成為海洋中一個非常複雜的研究領域。” “這也使它成為海洋中一個非常有生產力的部分，也是一個非常活躍的漁業。由於所有的水都以復雜的方式流動，一天低的地區可能會在下一天高。

As if to underscore that complexity, the group found that the Kuroshio acted as a barrier that prevented the movement of radionuclides to the south. In addition, they found the highest levels of radiation not in samples taken within sight of the reactors, but in those taken much further south along the coast of Ibaraki. The drifter tracks later revealed that an eddy, a swirling mass of water that sometimes breaks off from strong currents like the Kuroshio, had formed in the area and hugged the coast, likely drawing in contaminated water and maintaining higher concentrations of radionuclides.

似乎是為了強調這種複雜性，該小組發現黑潮充當了阻止放射性核素向南移動的屏障。此外，他們發現最高水平的輻射不是在反應堆可見範圍內採集的樣品中，而是在茨城縣海岸以南更遠的地方採集的樣品中。漂流者的踪跡後來顯示，在該地區形成了漩渦，一種有時從黑潮等強流中分離出來的漩渦狀水體，並環繞著海岸，可能會吸入受污染的水並保持較高濃度的放射性核素。

As a result, radiation levels in the eddy were as much as 1,000 times higher than those before the start of the accident, but these remained well below levels of concern for humans and marine organisms and were approximately one-sixth the level of radiation that marine organisms receive from naturally occurring radionuclides such as potassium-40.

結果，渦流中的輻射水平比事故開始前高出 1,000 倍之多，但仍遠低於人類和海洋生物的關注水平，大約是海洋輻射水平的六分之一。生物體接收天然存在的放射性核素，如 40 鉀。

Samples of plankton and small fish confirmed this. Levels of cesium isotopes and another, faster-decaying isotope of silver found in the organisms collected during the cruise ranged from below detection level to levels that, while elevated, remained within standards set for human consumption.

浮游生物和小魚的樣本證實了這一點。在巡航期間收集的生物體中發現的銫同位素和另一種更快衰變的銀同位素的水平從低於檢測水平到雖然升高但仍處於人類消費標準範圍內的水平。

“The radioactivity of the fish we caught and analyzed would not pose problems for human consumption,” said Fisher. “It does not mean all marine organisms caught in the region are perfectly safe to eat. That’s still an open question. There are still likely to be hot spots in sediments close to shore and closer to the power plant that may have resulted in very contaminated species in those areas. Further study and appropriate monitoring will help clarify this issue.”

“我們捕獲和分析的魚的放射性不會對人類消費造成問題，”費舍爾說。 “這並不意味著該地區捕獲的所有海洋生物都可以安全食用。這仍然是一個懸而未決的問題。靠近海岸和靠近發電廠的沉積物中仍然可能存在熱點，這可能導致這些地區的物種受到嚴重污染。進一步的研究和適當的監測將有助於澄清這個問題。”

Another open question is why radiation levels in the waters around Fukushima have not decreased since the Japanese stopped emergency cooling operations. According to Buesseler, it may be an indication that the ground surrounding the reactors has become saturated with contaminated water that is slowly seeping out in to the ocean. It may also be a sign that radionuclides in ocean sediments have become remobilized.

另一個懸而未決的問題是，自日本停止緊急冷卻操作以來，為什麼福島周圍水域的輻射水平沒有降低。根據比塞勒的說法，這可能表明反應堆周圍的地面已經被污染的水浸透了，這些水正在慢慢滲入海洋。這也可能表明海洋沉積物中的放射性核素已被重新激活。

“What this means for the marine environment of the Northwest Pacific over the long term is something that we need to keep our eyes on,” said Buesseler.

“從長遠來看，這對西北太平洋的海洋環境意味著什麼，我們需要密切關注，”布塞勒說。